Properties and Applications of Double-Skin Building Facades

by

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ABSTRACT

A new era of commercial buildings is emerging in Europe, driven by innovative designs in Germany, Britain and the Netherlands. Engineers and Architects are collaborating to design a new typology of buildings that are energy efficient, environmentally friendly, and architecturally sleek. The common elements are double-skin facades (DSF's) that employ sun shading and air movement between inner and outer glass membranes. The double-skin or "airflow" façade is tied to mechanical systems either physically with ducts or by significantly affecting the performance of those systems by reducing building loads. As compared to conventional façade systems, DSF's are credited with providing a 30% reduction in energy consumption, providing for natural ventilation even in skyscrapers, and providing valuable noise reduction. They also create a visually transparent architecture that is impossible with conventional curtain wall facades with similar thermal properties. However, most building owners, architects and engineers do not have the language or analytical tools to analyze the appropriateness of this technology to buildings of varying occupancies and configurations and in various climates.

Double-skin facades are defined and a typological system is proposed as a quick reference tool that will aid in understanding and communicating about the family of solutions that lie within a family of technologies that fit the definition of DSF's. A series of case studies examines a range of DSF typologies and analyzes their goals, structure, and relative success.

An analytical model is developed and described to provide a flexible tool for evaluating energy impacts of a wide range of double-skin façade designs. A parametric analysis suggests how this model may be used as a design tool by emphasizing key properties of DSF systems. The analysis and model is applied to the potential technology transfer to Tokyo, Japan.

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Table of Contents

1.0 Definition and Goals of Double-skin Building Envelopes 13

1.1 Technological context of double-skin facades 17

1.2 Goals.. 19

2.0 Typologies 29

2.1 Classification of double-skin facades... 29

2.2 Primary identifiers.. 30

2.3 Secondary identifiers.. 31

3.0 Case Studies... 37

3.1 High-rise buildings: outside ventilated 37

3.2 High-rise buildings: inside ventilated.. 64

3.3 Low rise building – outside ventilated 69

3.4 Low rise building – inside ventilated 73

4.0 Energy Implications 81

4.1 Existing calculation methodologies.. 81

4.2 A Simplified model for energy performance evaluation... 84

4.3 Desired Output 126

4.4 Troubleshooting methodology 130

4.5 Implications and Analysis of Design Parameters 140

5.0 Design Implications and Technology Transfer 157

5.1 Aesthetics and day lighting.. 157

5.2 The Effect of DSF and MEP system interdependency on loads 160

5.3 Policy, operating and life-cycle costs 166

5.4 Control systems 167

5.5 Climate 170

5.6 Culture and economy 171

5.7 Building forms 174

5.8 Construction sequences 174

5.9 Integrated design 175

5.10 Applications to Tokyo, Japan 179

6.0 Conclusions and Future Visions 187

7.0 Appendices 189

7.1 Contacts 189

7.2 Thermal model data for verification 195

8.0 Bibliography 267

List of Figures

Figure 1: Noise reduction of various window systems 22

Figure 2 Veiling reflections at Helicon 25

Figure 3 Stadttor Dusseldorf 26

Figure 4: Ventilation strategies for double-skin facades 31

Figure 5 Operable exterior glass plates of double-skin facade for a bank in Munich 34

Figure 6 Debis building detail 35

Figure 7: Family of typologies 36

Figure 8 RWE Tower 38

Figure 9 RWE fish mouth air vent (left) and building section (right) 40

Figure 10 RWE airflow pattern [Detail 1997] 41

Figure 11 Pressure coefficients for RWE 46

Figure 12 Relative pressure regime due to northeast winds [Daniels 1994] 47

Figure 13 Midsection of RWE tower with distinctive mechanical floor 50

Figure 14 RWE facade and room control panel 50

Figure 15 Ingenhoven Overdiek model for Commerzbank 53

Figure 16 Commerzbank Floor Plan 54

Figure 17 Commerzbank Tower with winter gardens 55

Figure 18 individual windows at Commerzbank 56

Figure 19 Victoria Insurance overview 62

Figure 20 Victoria Insurance facade detail 63

Figure 21 ABN Amro exterior (at solid flaps) and interior (at transparent flaps) 66

Figure 22 View of Max Planck Gesselschaft 71

Figure 23 Max Planck Gesselschaft corridor-style cavity 72

Figure 24 New Parliament Building facade detail 73

Figure 25 New Parliament Building detail 75

Figure 26 Inland Revenue Building 79

Figure 27: Window system diagram 88

Figure 28: Model area definitions 89

Figure 29: Model convection, conduction and infrared radiation 90

Figure 30 Energy balance for cavity airflow 95

Figure 31 Surface conductance for surfaces with air movement 97

Figure 32 Comparison of Heat Transfer Models Airflow over Blinds 103

Figure 33 Heat transfer coefficient model effects on SHGC 104

Figure 34 Heat transfer coefficient models and blind temperature 104

Figure 35 Heat transfer coefficient models and U-value 105

Figure 36 Solar and infrared radiation models 105

Figure 37 Reflection of sunrays between blinds 107

Figure 38 Direct solar radiation: Fsol Definition 108

Figure 39 Division of blind into 4 "rays" 109

Figure 40 Direct solar radiation distribution 111

Figure 41 Blind geometry for direct solar "rays" 113

Figure 42 Configuration for "ray" bounces 116

Figure 43 Electrical analogies for infrared radiation 118

Figure 44 Geometries for blind view factors 120

Figure 45 View factors for glass and blinds 122

Figure 46: Moody Chart from Fox and McDonald 125

Figure 47 Comparison of model and simplified equations for U-value verification 131

Figure 48 Comparison of simplified calculations and worksheet model 132

Figure 49 Temperature distribution for temperature distribution verification 132

Figure 50 Cavity flow verification: temperature distribution 134

Figure 51 Cavity flow verification: Air and blind temperatures 134

Figure 52 Velocities in air cavities by iteration 136
Figure 53 the iterative process in low mass flow conditions 137
Figure 54 Relationship of buoyancy and forced convection 138
Figure 55 comparison of Hens and MIT nighttime U-values 139
Figure 56 Hens and MIT solar heat gain coefficients 140
Figure 57 Parametrics: Glass emissivity and SHGC 143
Figure 58 Parametrics: glass emissivity and U-Value 144
Figure 59 Parametrics: Blind angle and U-Value 144
Figure 60 Parametrics: Solar angle and SHGC 144
Figure 61 Effect of blind solar absorptivity and infrared emissivity on SHGC 145
Figure 62 Typical blinds by material properties 146
Figure 63 SHGC and related instantaneous heat gain 146
Figure 64 U-value comparisons of standard systems versus DSF 148
Figure 65 SHGC comparisons of standard systems versus DSF 149
Figure 66 SHGC of typical double-skin façade with low-E coating 150
Figure 67 Comparison of systems with cavity flow model and Hens' model 151
Figure 68 SHGC and Tvis for standard and DSF systems 152
Figure 69 Debis Building site plan 159
Figure 70 Loads for narrow floor plate building 162
Figure 71 Loads for deep floor plate: 162
Figure 72 Loads for narrow floor plate 163
Figure 73 Loads for deep floor plate 163
Figure 74 Equilibrium distance for room and window ventilation 164
Figure 75 Air change rates based on fixed volumetric flow through facade 165
Figure 76 Comfort zone expansion for Rogers' building 173
Figure 77 Joseph Gartner & Co. headquarters Gundelfingen 177

Figure 78 Resultant properties for windows with various blind positions 183

Figure 79 Energy consumption based on hourly weather data 184

Figure 80 Hourly average energy consumption for typical month 184

Figure 81 Tokyo: winter conditions for interior ventilated façade 186

Figure 82 Tokyo: Summer conditions for exterior ventilated façade 186

1.0 Definition and Goals of Double-skin Building Envelopes

The building façade mediates between interior and exterior thermal conditions. Its primary goal is to provide a comfortable working environment for building occupants. This can be achieved by allowing the passage of air, sunlight and energy when it is desirable and blocking their passage when it is undesirable.

Internal heat loads such as computers, lighting and people are increasingly dominating institutional and commercial buildings. Particularly in American-style buildings that have a large ratio of floor area to façade area and in moderate climates, the internal loads outweigh external loads. In moderate and even in reasonably cold climates, cooling the occupied space may be required for much of the year. To minimize the primary energy required for cooling, these loads can be minimized at their source. Office buildings have increasingly been clad in glass. This creates a problem because once solar radiation passes into the building it is absorbed by the building fabric and re-radiated as high-frequency long wave, infrared energy that does not pass back through the glass. Instead it heats the air by convection in the occupied space making it difficult and costly to mitigate its negative impacts.

The primary forms of heat transmission into a building through the façade are by direct solar radiation through windows, as described by the solar heat gain coefficient (SHGC) and by conductive and convective transfer due to a difference in temperatures from the inside to the outside as measured by the U-value.

$$SHGC = \frac{Q_{room}}{Q_{incident}}$$

The solar heat gain coefficient is the proportion of radiation entering the occupied space to the incident solar radiation at the exterior of the assembly. The U-value is defined by:

$$U = \frac{Q_{room}}{A(T_{out} - T_{in})}$$

The combined US standard is:

$$Q = UA(T_{out} - T_{in}) + SHGCxq_{solar}xA$$

A European standard combines these into the g-value or g-factor. The equation has several forms but looks something like:

$K_{eq,f} = K_f - GS_f$ where

$K_{eq,f}$ equivalent K factor for fenestration, accounting for solar radiation.

K_f K factor for fenestration [w/k] equivalent to UA

GS_f Incident radiation factor [Gartner 1999]

Double-skin Facades (DSF's) also known as "airflow windows" represent the evolution of façade technology to include a specialized system for addressing the issue of heat gain through largely transparent facades without the use of exterior shading devices. DSF's are characterized by having at least two membranes between the interior, occupied space and the exterior environment. Blinds are located in the channel between the inner and outer leaf of the façade, and air passes through the channel.

This paper is concerned with those membranes that are largely transparent to visible light. They are constructed by mounting an additional layer of glass on either the inside or outside of the building façade. Opaque membranes are of interest as well but are not addressed in this paper.

DSF's are differentiated from conventional double or triple glazed facades by the intentional and controlled passage of air through the cavity between the inner and outer skins. The movement of air is an important departure from standard glazing systems such as sealed double and triple glazed insulating units, even if they have interstitial blinds. The thermal mechanisms are different as are the impacts on energy and comfort. With DSF's, the facade can no longer be considered as a static object. Air moves through it modifying and dominating its performance characteristics.

The characteristics of DSF's are dynamic because of the movement of air and movement of components such as sunshades. There is also a seasonal fluctuation in the facade performance. During the cooling season, air is introduced into the cavity to carry away heat that would otherwise accumulate in the cavity and be partially transferred into the adjacent occupied space. The temperature of the inner membrane is thus theoretically kept lower than without the airflow. This reduces the conduction, convection and radiation from the inner pane to the occupied space within. The result is that less heat is transferred from the outside to the inside, and less energy is required to cool the space. Building occupants are meant to be more comfortable because the mean radiant temperature of the space is reduced.

> *The double-skin window, with its Venetian blind, can be seen as a passive cooling device, easing the load on the chilled ceilings or other cooling means and therefore saving energy. The blind is effectively external and stops radiant heat before it can enter the building... the double-skin arrangement has other benefits. As the sun warms the air in the cavity, the 'stack effect' is improved, so that relatively cool air is drawn in at the sill at an ever faster rate as the temperature increases. Paradoxically, the heat of the sun thus contributes to the cooling of the facade. [Davies et al 1997 P 158-159]*

During the heating season there are two general scenarios: Scenario one has the system closed, with no air moving through the cavity. The cavity is allowed to heat up, increasing the temperature of the inner pane, and thereby reducing conductive, convective and radiant losses. In the second scenario, warm air is introduced into the cavity from the interior to warm the inner pane of glass and achieve the same results. The air is then ducted to the building systems plant where it may be run through a heat exchanger to pre-heat the incoming air. So far, it appears that no system has been developed that allows air to be warmed in the cavity and then returned directly to the occupied space. This would eliminate the transfer of the air all the way back to the plant. But would require local controls at the façade level. In situations where the air must be exhausted anyway as part of the fresh air supply, transporting air to the plant is required anyway. Depending on the depth of the building, the air volume being passed through the façade may be similar to the fresh air requirements of the space.

If air is being returned to the plant for heat recovery, there may be an energy penalty for nighttime and other times that there is no solar radiation on the façade because the air will lose energy as it passes through the window cavity. This energy penalty will be felt by the reduced stored energy arriving at the heat exchanger being used to preheat fresh outdoor air.

Solar shading devices are placed between the inner and outer skins. Typically this is an adjustable, horizontal Venetian blind that may be rotated and raised or lowered. During the cooling season, solar heating is unwelcome and must be removed by the building plant. The role of the shading device is to absorb or reflect unwanted solar radiation. Heat absorbed by the sun-shading device can be removed by convection if air is moved along the surface of the blinds and then removed from the cavity. The effectiveness of this heat removal is evidenced by a reduced solar heat gain coefficient (SHGC or solar factor, SF). If in addition, the air that passes through the cavity is cooler than the outside air, then the difference in temperature across the inner glazing will be reduced. This results in a lower heat flow across the inner pane as evidenced by a reduced u-value. In this way, DSF's facades act as heat exchangers [Saelens 1998]. The shading device acts as a solar collector and the captured heat may be controlled through the design of the façade system, its airflow and control.

During the heating season, some direct radiation will be desirable. Yet, it is still easy to overheat the area adjacent to the window. Therefore control of the position and deployment of the shading device is desirable. The SF can be adjusted by adjusting the blinds. The U-value will be improved if the blinds absorb some heat, thereby increasing the cavity temperature and reducing the difference in temperature between the cavity and interior.

A lot has been made of the impact of DSF's. The RWE AG building in Essen, Germany was touted as the first "pro-ecological high-rise [Pearson 1997]", and the Commerzbank building in Frankfurt am Main, Germany is said to use 30% less energy than a comparable traditional high-rise buildings [Preston Web]. Perhaps the most common acclamation of the double façade system is that they are energy efficient, but there is more to the story. They have also been installed for sound reduction, user control and comfort, noise reduction, pollution avoidance, and nighttime security of operable windows. Other reasons include capital cost savings of reduced mechanical plant, and reduced dependence on artificial lighting. Architectural benefits include transparency, and a "high-tech" image. Perhaps the most compelling reason which explains the boom in use of DSF's in Germany is that windows protected by an additional pane of glass on the outside may be opened, even when the building is subjected to high wind pressures, as is the case in high-rise buildings. Further supporting the use of this technology in high-rise buildings is that their use permits the activation of semi-exterior sun shading in adverse (windy, polluted, and rainy) conditions.

1.1 Technological context of double-skin facades

In order to have a good perspective on double-skin facades and the problems that they are designed to solve. Current trends in building technology began with the introduction of curtain walls and massive glazing to commercial buildings starting at the beginning with the industrial revolution and continuing through modernism with the increasing detachment of buildings from their environment. Curtain walls in general grew out of the evolution of structural systems from bearing masonry walls to steel and cast-in-place concrete structures. The newer structural systems do not have integrated walls, rather they are roughly post and beam structures that must be filled in with something that will moderate the climate and control the elements so that inhabitants will be comfortable and productive. Banham quotes Le Corbusier:

> *But now a house can be built of a few reinforced concrete posts... leaving total voids in between... What good is it, I ask, to fill this space up again, when it has been given to me empty? [Banham 1969 p. 154]*

According to Banham, Le Corbusier soon struggled with the void that massive walls left behind; how should sound be attenuated, and how should climate be controlled. For Cite de Refuge, the Paris hostel, Le Corbusier devised a system called *le mur neutralisant*, the neutralizing wall. It consisted of two layers of glass with tempered air circulating between, but was not implemented on that project due to budgetary constraints. While the *mur neutralisant* has been credited by Saelens and others with being the precursor to double-skin walls [Saelens 1997 p.1], it is worth noting that an air system separate from the conditioning system was envisioned that was meant to be a barrier between indoor and outdoor environments. There is no mention of sunshades except that bris-soleil were added at a later date to combat summer heat gain. The building was the first sealed building in the Paris area, and had mechanical ventilation and heating. It was not mechanically cooled, and overheated dramatically during the summer. It was designed for three air changes per hour [Le Corbusier 1936]. Rather than being the first double-skin façade, this is truly an early version of the sealed, mechanically controlled building. Indeed, Le Corbusier marveled at the lack of window operability. He speaks of America as a powerful and progressive country that developed a modern skyscraper with a sign next to each window stating:

> *Please do not open the windows so as not to disturb the proper functioning of the air conditioning. [Le Corbusier 1936 p. 20]*

Le Corbusier expands on his desire for the machine building to control the new environment regardless of local climate:

> *In the narrow space between the membranes* (of the neutralizing wall) *is blown scorching hot air, if in Moscow, iced air if in Dakar. Result, we control things so that the surface of the interior membrane holds 18°C. And there you are! [Banham 1969, p.160].*

Surely, this was not informed of the same spirit that would drive the Commerzbank away from the sealed building. Yet, it may well have been an early precedent for the sealed active facades. The flue-type double facades for low-rise buildings that have a cavity sometimes spanning 3 to 4 stories took a preliminary step.

The first patent related to airflow windows was received by the EKONO Company in Sweden in 1957. EKONO would build the first office building with airflow windows in 1967. The introduction of mass-produced active walls created a consciousness about the technology.

The Briarcliff House at Farnborough is the first widely publicized use of a double-skin façade. See [Hannay 1984]. It consists of a standard sealed office building with exterior automatically controlled sunshades, and a second skin about a meter outside the sunshades. The cavity formed between the skins open to the outside at the bottom, and connected to the air handling plant on the roof (three stories above). This building broke ground on mediating solar loads and noise impacts for low-rise buildings. A US building was also published in the 1980's; the Hooker building in by Cannon Inc. developed the Briarcliff model by adding adjustment to the intake with controllable dampers.

The Commerzbank and RWE would take the next step by opening the inner walls such that occupants would have more control of their environment, breaking the seal on the envelope so that natural ventilation would be possible again. Foster wrote about the Briarcliff House in 1993, and clearly takes some inspiration from it. The two German towers use double façade systems to solve evolving programmatic concerns. Pushes architecture to new paradigm. Foster is critical of architecture that seeks high levels of day light (as he does) but overlooks the need to control glare, overheating and heat loss. [Foster 1994 p. 674]

Meanwhile, the Active Wall proponents (particularly in Belgium and the Netherlands) would turn Briarcliff inside out, putting the seal on the exterior, and ventilating indoor air through the façade and up to the plant. While not extensively published in architectural journals, they may well be recognized as they are applied to high profile buildings such as the ABN Amro building by I. M. Pei.

1.1.1 Next generation

As the development of double-skin facades moves forward, some will be copying the innovations that have come before while some will be making incremental innovations on top of the basic innovations already implemented. In either case designers must understand what goals are realistic for DSF's, and what configurations are available. In order to adopt these facades or windows, one should first comprehend precedents, and the basic thermodynamics that motive their design strategies. Only in this way can the next generation of dynamic walls be contemplated.

1.2 Goals

1.2.1 Energy Savings and Ecological Responsibility

> *Intelligent facades achieve a significant reduction in emissions, and thus don't contribute to the greenhouse effect. Investment and operating costs are kept as low as possible [Campagno 1996].*

Energy savings attributed to double-skin facades are achieved by minimizing solar loading at the perimeter of buildings. Providing a low solar factor and low U-value minimizes cooling load of adjacent spaces.

The Gartner Company claims that DSF's save natural resources by reducing energy consumption during the operational life of the building [Gartner 1999]. However, there has been no study published of the relationship of operational costs to construction/embodied energy impacts. This is particularly important in the case of a high-rise building. High-rise buildings provide certain efficiencies during their life at the urban scale because they provide a density that can minimize transportation if walking and mass-transit are adopted. Of course, in some large cities higher density leads merely to congestion, reliance on automobiles, highways and parking structures, while mass-transit is shunned and pedestrians are in peril. The use of the building carries certain transportation-related burdens internally. The building is reliant on elevators that are energy intensive, and unnecessary or used at occupant discretion in lower buildings. The shear difficulty of maintaining and renovating tall buildings is much greater than for lower buildings.

1.2.2 *Natural Ventilation*

The surge of activity in designing double-skin facades that occurred in the mid 1990's can be attributed to the mandate in Germany to provide natural ventilation in skyscrapers. Two buildings competed to be the first naturally ventilated building (Commerzbank and RWE). The DSF was the common solution for allowing windows to be operable in a windy zone, high above the Frankfurt townscape. The buffering effect of placing a fixed plane of glass outside the operable window made this possible. Because other attributes were attached to the system such as transparency, a high level of control and energy efficiency, natural ventilation became the catalyst for the diffusion of DSF technology within the industry.

1.2.3 *Cost Savings*

Double-skin facades are significantly more expensive to install than conventional curtain wall systems considering only the cost of the installed façade. Most of the early implementation has been in the form of prototypical designs requiring extensive research and the development of unique extrusion dyes and numerous unique parts. Many of the designs were developed in parallel (such as the RWE and Commerzbank buildings) and did not benefit from cross-fertilization of ideas due to both simultaneity of design and the race to be labeled as the first innovator of the systems.

Additional installed costs for double-skin façades above typical static façade systems have ranged significantly from 20 percent to perhaps 300% [Arons 1999]. It is not always possible to obtain exact figures due to privacy concerns of the project owners. Examples of some of the costs will be discussed in chapter 3.0.

The incremental cost of airflow windows within largely solid walls would appear to be less significant than for larger airflow facades because of the smaller area, and smaller moving parts. Facades that may come pre-assembled to the site will tend to be more cost effective than facades that require site assembly. Double-skins with the inner skin being something other than glass may also be less costly; fabrics and flexible metallic screens may serve as well as glass but at reduced cost. There will be functional and aesthetic differences, however.

A designer should consider costs and benefits on a project-wide capital basis as well as on a life-cycle basis rather than looking at capital costs for the façade alone. Consideration should be given to operations and maintenance budgets. It has been claimed that the use of

DSF's can reduce the initial construction cost of buildings [Saelens 1997 p.1]. By reducing heating and cooling loads of the envelope at the source, the overall size of heating, ventilation and air conditioning (HVAC) systems can be reduced. In certain climates, particularly in mild European climates, the need for perimeter radiation may be eliminated as well. Any savings here will depend on the building type and occupancy as well as the meteorological zone. The actual up-front savings must also be part of a holistic design process. See section 5.9 for more on integrated design. Savings of this type have not been well documented to date, perhaps because they are difficult to trace to particular elements (such as the façade) in a complex building system.

While costs are quite exorbitant on certain high profile projects, there are buildings that use reasonably detailed systems that, while still costly, should not be unreasonable additional costs compared to the added value of the systems. Standard small-scale windows coupled with separate interior unframed glass have been used to create double-skin systems from low-cost, readily available components.

Even the sophisticated packaged systems have great potential to become cost effective. As manufacturers hone their ability to design, test, and manufacture the systems the uncertainty and risk associated with them will go down. As more projects utilize DSF's, the mass production segment of the market will grow, thereby giving the manufacturers economies of scale. Hence the installed costs will come down. A reduction in cost is predicated upon timely adoption of the systems.

1.2.4 Sound Reduction

Sound reduction is a principal concern in urban environments. The concern is intensified by the increased use of glazing that reflects sound. Ove Arup and Partners used a second skin over a conventional sealed 30% glazed façade for the Briarcliff House in Farnborough U.K. Its location in a noisy urban setting was a driving force for the design choice of perhaps the earliest double-skin façade [Holmes 1994 p.3]. A more recent development at the Max Planck Institute in Munich utilized a double-skin façade in a noisy setting as well. In that case however, both the inner and outer leaf of the façade were operable, providing greater potential to balance noise reduction with natural ventilation.

The degree of noise reduction varies with the specific details and operation of particular double-skin facades. Data provided by Permasteelisa (see Figure 1), a manufacturer of double-skin and conventional facades, indicates that the potential noise reduction is in the order of 9 decibels (dB). The difference is nearly enough for the perception of the noise to be halved, and more than enough for the difference to be "clearly perceptible" according to Stein and Reynolds [Stein and Reynolds 1987 p. 1329].

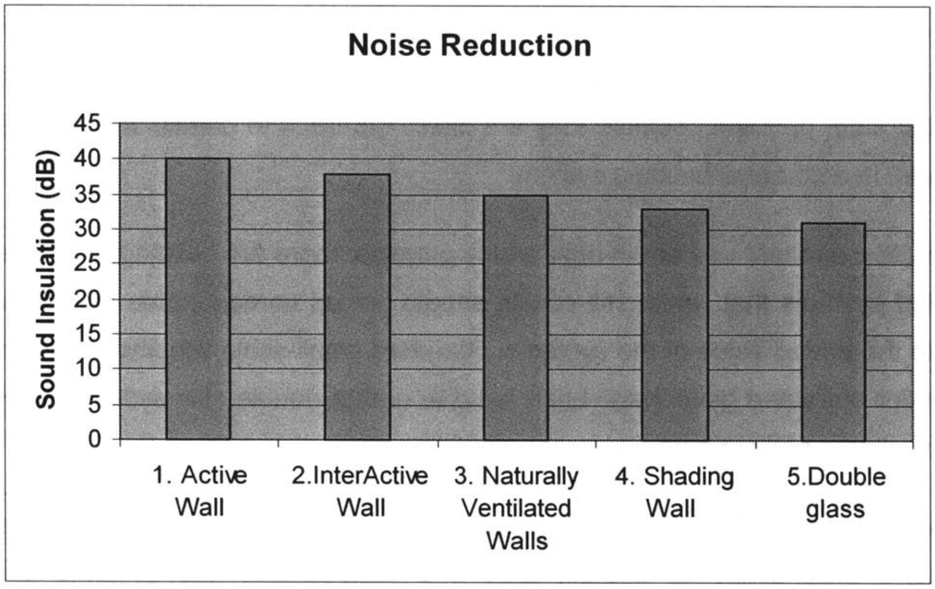


Figure 1: Noise reduction of various window systems. Systems 1-3 are double-skin facades.

1.2.5 User Control and Comfort:

Typically, designers must pay particular attention to the temperature of the inside surface of glazing systems. This surface is a source of infrared radiation during the summer, and a heat sink during the winter. Inadequate HVAC and façade design can lead to uncomfortable conditions, even when the air temperature of the space is within the comfort zone. DSF's are said to help with this problem.

Saelens states "The surface temperature of the inner pane is leveled with the room temperature, improving the thermal comfort near the window [Saelens 1997 p.3]." This claim is particular to inside-ventilated facades; because room temperature air is brought into the window cavity, the inner surface of glass should be close to room temperature. The findings of this paper will call this into question. The blinds in the window cavity are solar collectors by design. They are meant to collect incident radiation and are meant to dispatch it before it enters the occupied zone of the building. They also exchange energy via radiation with the inner pane of glass and the glass may climb well above room temperatures, particularly during the summer. Also, the higher the window or façade, the greater this effect will be felt because the difference in temperature between the blind and the air is reduced. Saelens and Hens show that increasing the height of the window from 2.0 meters to 2.4 meters increases the U-value from 0.44 to 0.48. They also indicate that the inner surface may climb by 10 degrees Celsius when the incident solar radiation is 500 W/m^2. DSF's may indeed created better comfort conditions by controlling radiation and indoor air temperatures. The radiation directly contacting occupants will be less when blinds are used. However, it is doubtful that better glazing temperatures are to be credited with the increased levels of comfort.

Control is closely linked to comfort. By providing occupants the ability to control light with louvers or shades and the ability to control air movement and temperature with operable windows, not only may comfort be enhanced, but the sense of well being that comes with controlling one's environment is also nurtured. The degree of user control, which may or may not coincide with improving actual comfort conditions or energy efficiency, must be reconciled with building management control systems that may more rigidly control these factors. The psychological benefit of varying the façade may come in conflict with the sense that one is occupying an automated machine that adjusts view, lighting, and thermal conditions from a central source.

1.2.6 Occupant Productivity and Contact with the Environment

It has been estimated that wages and salaries can represent about 95 percent of all costs of a typical office building [Ternoey, et al, 1984]. Certainly, in the commercial market, energy consumption is probably only one tenth the cost of personnel. For this reason, owners will be driven toward solutions that increase their return on investments made in people before those that are made in infrastructure. But the two are linked.

Reduced sickness, absenteeism coupled with increased performance would more than offset any increased initial costs or life cycle costs [Robbins, 1986] associated with providing more workers visual access to windows [Franta and Anstead 2000]. Given current trends, this will probably remain true in the US longer than it does in Europe because costs of energy are externalized from accounting ledgers. The depletion of natural resources including fossil fuels biological diversity and atmospheric and water quality are not translated to the costs to operate buildings. So, for the near and perhaps distant future, energy costs are probably less important than occupant productivity to the applicability of technology.

If a more comfortable, controllable and visually pleasing environment can be created, then workers may well be more productive.

"In 1969, in 'the Architecture of the Well-Tempered Environment', Reyner Banham spoke out against the high energy requirement of artificial air conditioning systems and against the separation of architecture from local climatic and regional conditions" [Campagno 1996].

1.2.7 Security

Many of the same building owners that can afford double-skin facades are drawn to high-end technologies and the high-tech image that they exude also have a practical concern for the security of their premises. These are establishments that have a particularly high cost associated with the personnel in their buildings. In Europe, these workers have demanded access to outdoor air and light. To have operable windows while maintaining security requires that some measure be made to protect the accessibility of windows from the exterior.

DSF's offer a relatively unimposing manner for achieving security. Rather than protect openings with bars or metal grating DSF's have a continuous sheet of glass with relatively small vents to allow for the entrance and exit of air. The result is a transparent barrier that breathes. Deep facades add a psychological level of security; there is a perception of protection that comes from having a thick façade system. Just as a moat or wall give a sense (and physical) protection, so does the façade depth. Security was a chief concern for the Max Planck Gesselschaft, so they went one step farther by incorporating both a DSF and a moat along the primary street façade.

1.2.8 Aesthetics

Some double-skin facades and windows are very similar in composition to their traditional counterparts. The facades are crafted of glass and aluminum and other than the requisite addition of interstitial blinds to control solar radiation; they appear quite similar as well.

Transparency

Architects have been taking advantage of the sun shading ability of double-skin facades to make their buildings more transparent; having sun shades to deploy, allows the use of highly transparent glass because the glass does not need to reflect or absorb the radiation on its own. The use of "white glass", having less iron than standard architectural glass, changes the transparency to visible light from about 0.85 up to 0.90 for each pane. For a three-pane system the overall visible light transparency goes from 61% up to nearly 73%. The quality of the light reflected and transmitted is also improved. Standard glass has a greenish tinge to it, while the low-iron glass is whiter. This means that the psychological impact of the window will be lessened.

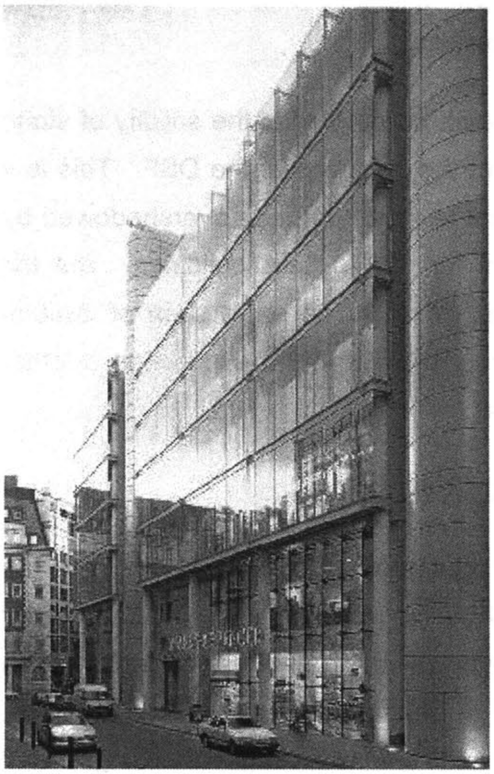


Figure 2 Veiling reflections at Helicon

A notable building that was designed with transparency in mind is the Helicon building in London. The building conveys a sense of transparency that is not necessarily borne out in fact. Housing retail shops on the bottom floors, it was critical to the leasers of the space that products being displayed within be visible from the exterior. Indeed, the displays are visible, but the success of the facades is not clearly due to transparency. The DSF's were meant to minimize the reliance on electric lighting, but retailers being who they are, the lights may be found illuminated even on sunny days. This ensures product visibility. The walls are 100% glazed; yet the image from the exterior is not necessarily one of transparency. Direct sunlight and reflections of neighboring buildings in its very urban context can throw concealing glare across the façade. The essential point is that the façade is more transparent than any other that would provide the same level of energy transmission. It is not physically more transparent than a single or double layer housed in a structural glazing system or a thin-member curtain wall, though the perception may be there.

Depth

Double-skin facades offer a tremendous design opportunity that no other building system has offered before: depth. The thick walls of load-bearing masonry structures is tied to conveying massiveness. When punctured by windows, they tend to seem still heavier. To the contrary, double-skin facades tend to defy gravity. The thicker models such as the Stadttor Dusseldorf create space within the cavity that has no visual weight. Most of the buildings employing thick (0.5 ~1.5m deep) facades are nearly entirely glazed. This is true of the Stadttor Dusseldorf, the RWE tower and the Victoria Insurance building. These buildings offer the opportunity to view through the edge or corner of the building skin without having the sight line blocked by opaque surfaces. This lends a transparency to the whole building. Depending on the color of and geometry of the inner skin, the inner surfaces may be well lit and reflect enough light out to lighten the building.

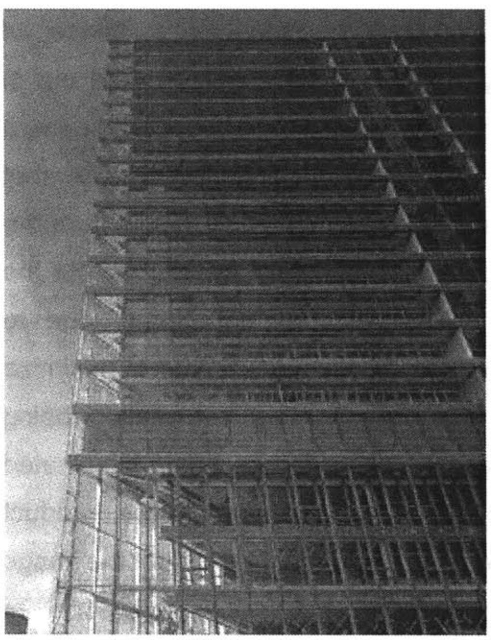


Figure 3 Stadttor Dusseldorf

The Max Planck building adds the solidity of stone walls to offset the lightness of the DSF. This is a technique that to date has been overshadowed by the penchant for 100% glass buildings. But the opportunity is great for an exploration of double-skins as a counterpoint to the expression of other technologies.

Layering and Movement

Most commercial buildings that are designed in the vein of the US office building forego blinds, exterior louvers and other shading devices. While European cities have a tradition of exterior roller blinds, sunshades and shutters, larger buildings, and particularly towers have followed the US model of glass-only fenestration. Double-skins do not compete with exterior shading devices for shedding solar radiation, but DSF's are possible to incorporate into tall and large buildings without the same penalty for maintenance and operation; the outer glazing protects the blinds in double facades so they are not vulnerable to precipitation or wind. The result is that DSF's are highly layered creations. The sleek outer surface gives way not only to the active workspace within but also to the subsequent layers of blinds and an inner layer of glazing housed in it's own frame. In some cases, such as the RWE tower, there may be a layer of shades within the inner glazing. These components of the system add to the visual interest of the façade and enhance the perception (and reality) of depth within the façade.

Normally, the appearance of glazed walls varies frequently with changing interior and exterior lighting conditions. This aspect is enhanced by the multiple layers and physical depth of DSF's. In addition, DSF's physically change. Blinds go up and down, and rotate from open to closed. Doors or windows within the inner and sometimes outer skin open and close for natural ventilation. These variations add to the activity and excitement level of the façade making it a dynamic mechanism, changing with weather conditions, time of day, and internal use a dramatic rather than static object in the urban landscape.

High-tech or ecological

DSF's are taking hold of the German and Dutch façade markets. In some cases they are being used for their efficient performance, but just as often it appears they are being chosen for their high-tech look. These are not only high-cost but also high-style facades. Banks, insurance companies and other high-profile institutions have used them extensively. These are institutions that desire not only performance but also the appearance of performance and desire to carry the environmental banner. This is not to say that the facades are not performing well but that this performance may be secondary to the aesthetic message that the facades brings. This means that some of these innovative owners are really follow-on implementers of the technology; picking up the technology without necessarily doing the elaborate design, modeling and testing that the earlier executors of the technology were required to do. This may not have a dramatic impact on the functionality of the facades, but in other cases it may.

2.0 Typologies

2.1 Classification of double-skin facades

It is useful to categorize different types of advanced envelope systems that can be considered "double-skin". For the purposes of this paper, double-skin will be restricted to those, which have significant air movement between the various planes of the facade. Much as 'Trombe Wall' describes the operational and physical conditions of a particular passive solar wall, the emergent technology of double-leaf walls will benefit from a common language. The classification system will benefit the design community if it offers quick identification of the functions and construction of DSF's.

One difficulty in labeling a rapidly evolving technology is that each new building is a departure from the previous one with its own variations and innovations. It would be most effective to label the wall types by the building name. This method would give us the RWE Wall and the Commerzbank Wall. Unfortunately, too much prior knowledge about these systems is required for these definitions to be meaningful. It also does not serve as a generally applicable language. Rather it will be beneficial to create generic terms that apply universally and provide a hierarchy of terms based on relevance to the designer.

Some distinction between terms will be useful. The details of the distinction will become clear when they are described in detail later on.

Double-skin, double leaf façade or simply double façades: a façade that consists of two distinct planar elements that allows interior or exterior air to move through the system. This is sometimes referred to as a "twin-skin".

Airflow façades: a double-leaf façade that is continuous for at least one story, with its inlet at or below the floor level of one story and its exhaust at or above the floor level above.

Airflow window: a double-leaf façade that has an inlet and outlet spaced less than the vertical spacing between floor and ceiling.

The term airflow façade or airflow window is commonly used for windows that are dominated by forced convection whereas the term double-skin façade is more commonly used for those dominated by natural convection. The distinction comes from the largely regional development of systems. Facades exchanging air with the internal environment have been developed in the UK and the Netherlands and are termed "airflow facades (or windows)", and those exchanging air with the external environment have been developed in Germany and are termed simply "double-skin facades" or, in the UK, "twin skins". For this paper, the term "double-skin facades" has been used to describe airflow facades and windows in the generic sense.

2.2 Primary identifiers

Saelens and Hens identify three primary identifiers for DSF's: The nature of airflow (inlet and exhaust same side, supply from exterior to interior, and exhaust from interior to exterior); the generation of airflow (natural or forced convection); and *horizontal* partition of the façade (window or façade). These are valuable ways of distinguishing the type of façade for engineers [Saelens 1997 p.2]. However, to bridge the gap between engineering and architecture, and more specifically between those with a detailed understanding of the function of these systems and newcomers to the field, a more descriptive system is proposed.

There are two primary categories of double facades. The first, similar to Saelens and Hens, defines the way that air moves through the cavity between the skins. The second separates mid-rise to high-rise buildings from low-rise buildings. The distinction is that mid-rise to high-rise buildings have restrictions on the operability of windows due to wind pressure (typically associated with height above terrain).

2.2.1 Airflow Patterns

Walls with double-skin facades or windows can be thought of as "ventilated" facades or windows. There are three breathing modes that are identified by Permasteelisa: outside ventilated, inside ventilated and hybrid ventilated. Outside-ventilated walls bring outside air into the interleaf cavity and vent it back to the outside. Inside-ventilated facades bring air from the occupied space through the cavity and exhaust it to the plant. Hybrid systems bring air in from either the interior or the exterior and vent it to the opposite side. See Figure 4. Saelens' distinction of forced versus natural convection is not addressed herein because typically those systems that are outside ventilated driven by natural buoyancy and inside ventilated facades are driven by forced convection. Saelens points out "small fans could be built in the façade or in the window." This is absolutely true, and will probably be the future of outside ventilated facades. This is a perfect application for photovoltaic power assisted fans that would function when air currents are needed in the façade, i.e. when the sun is shining. For now, this distinction is for future consideration.

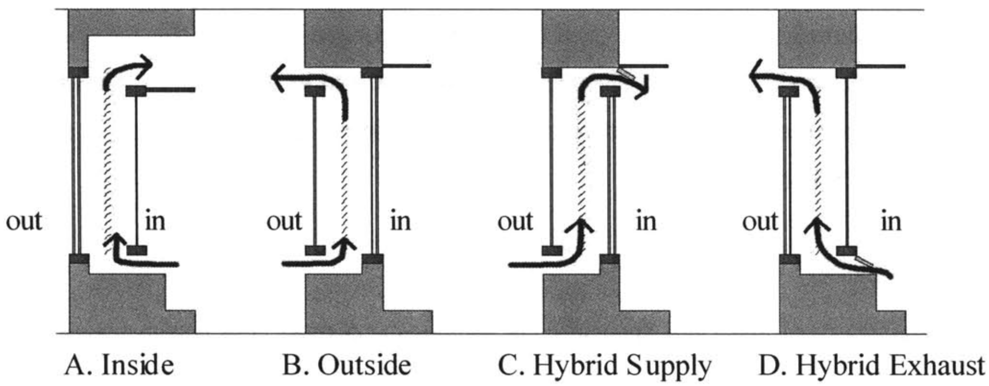


Figure 4: Ventilation strategies for double-skin facades

2.2.2 Building Height

The goals of double-skin facades apply to both low and mid- to high-rise buildings. They do not, however, apply equally. The dominating reason for using double-skins in high-rise applications is that they allow windows to be operable, even when the exterior of the building is subjected to quite forceful wind pressures.

2.3 Secondary identifiers

There is a wide range of other characteristics that can be used to categorize double-skin facades, but the nature of the field is such that no two facades are the same, and they differ enough that they tend to fill-in the spaces between distinctly different schemes. In other words, there tends to be a spectrum of solutions rather than orderly groupings of solutions. Some of these categories are described below as a reference point for examining case studies.

2.3.1 Layering Composition

Facades are composed of a series of planes that are layered from the exterior to the interior. In the case of DSF's, the layers consist primarily of glass (supported in a variety of ways), gases, and shading devices. There are infinitely many variations on the construction of these layers. For example, glass may be low-E coated, hardened, laminated, low iron content, or fritted. Shading devices may be metal, plastic, painted or polished, perforated or solid. Insulating glass may be filled with air, argon, krypton, or vacuum-sealed.

Usually the general arrangement of layers is closely tied to the air movement strategy. If the façade is outside ventilated, then there is usually a pane of single glass on the exterior, and insulated glazing to the inside. The system is reversed for inside ventilated systems; the insulating glazing is placed on the exterior, and a single, possibly unsealed, glass is located to the interior of the air cavity.

2.3.2 Depth of Cavity

The range of cavity depths varies significantly. In existing buildings, the range tends to be between 200mm and 1400mm as measured face to face between the inner and outer skins. There are three predominant styles: The compact style is usually from about 200mm to 500mm, the latter allowing enough space to allow for maintenance occupation of the cavity primarily to accommodate cleaning of the surfaces within the cavity. The wide style is typically about 1m wide. This allows for the space to be used as a fire egress corridor. There are also architectural and day lighting implications. The third style is the expanded style that includes atrium spaces and buildings-within-buildings.

2.3.3 Horizontal Extent of Cavity (Length along the facade):

Cavities may be divided in relation to interior partitions. This extends the sound barrier of the partition to the outside face of the façade. But this is not always the case. Where the interior façade has windows within opaque walls, the exterior skin may mirror that form, creating a "box window". In other cases, particularly in renovations where a second skin is applied over an existing building, the inside may be a window, but the exterior skin may be continuous glass. The cavity may be continuous as well. In a deep façade with such an uninterrupted cavity a 'corridor façade' is created. When it is intended to use the corridor as a walkway, the floor/ceiling may be either a grate, open to air movement, or closed, but the horizontal length of the cavity must be uninterrupted.

2.3.4 Vertical Extent of Cavity:

The vertical extent of the cavity refers to the distance between air supply to the cavity, and ultimate exhaust from the cavity, without intermediate interference such as a floor plane.

There may be operable windows or other vents along the height of the cavity. There are multi-story facades that are referred to as “atria” if they are relatively wide or “flues” if they are narrower. Among single story double facades there is an array of styles. If the cavity extends for the full height of the story, it may be called a double-skin façade. If it is only partial height with spandrel panels or other windows between, then it may be called a double-skin window. Practitioners that design and build inside-ventilated facades tend to call them “airflow facades” or “airflow windows”. Still, they are double-skin assemblies with air moving between the skins.

2.3.5 Operability

The inner pane of double-skin facades tends to be operable. That is, it can be opened either by occupants or by automated means. What you see when you open the window is less certain. In some cases, the inner pane opens, giving full access to another, fixed pane of glass and a narrow space that is ventilated through slots at the top and bottom. It may also open onto an outer skin with its own operable “flaps”, as is the case in the Max-Planck Gesselschaft building in Munich. Another building in Munich uses exterior flaps to redefine not only the function, but also the entire character of the building (see Figure 5).

The form (and operability) of the inner window is varied. Some options are tilt-turn windows that may be inset windows or full height doors. There are also full height doors that slide or pivot. An aspect of the relationship between window operability and comfort is not addressed in the literature: There are serious implications of the functionality of windows on the comfort conditions that are achieved within the room. Windows that open mostly at the top (full height inward-tilting hopper windows) will tend to let in the hottest air from the cavity if the air within the cavity is passing from the bottom to the top, collecting solar heat as it goes. Doors that slide give access to the full height of the window, (but must be restricted if occupants shouldn’t have access to the cavity). Pivoting windows/doors provide a large open area (either top and bottom or side to side). They may restrict sun shading options or effectiveness. Consideration should also be given to possible impacts on usable space within the building.

Figure 5 Operable exterior glass plates of double-skin facade for a bank in Munich

2.3.6 Materials

The materials for the supporting the glass are almost as varied as with any window system. There are some differences; the choice of materials for the inner skin of double facades is more forgiving because it is protected by outer skin that handles the most punishing and demanding part of climate control. There are several buildings that take advantage of this by having wood frames on the inner façade. There is a restrictive aspect to double facades; they act as solar radiation collectors so they are likely to have high temperatures in the cavity. This can be damaging to glazing seals, frame finishes, and can even damage the glazing itself.

Exploration is just beginning into the integration of double-skin facades into architectural design. Early versions, while elegant, are highly impersonal as well. Renzo Piano's Debis building and BT 2000 incorporate terra cotta, which creates a wider palette of texture and color.

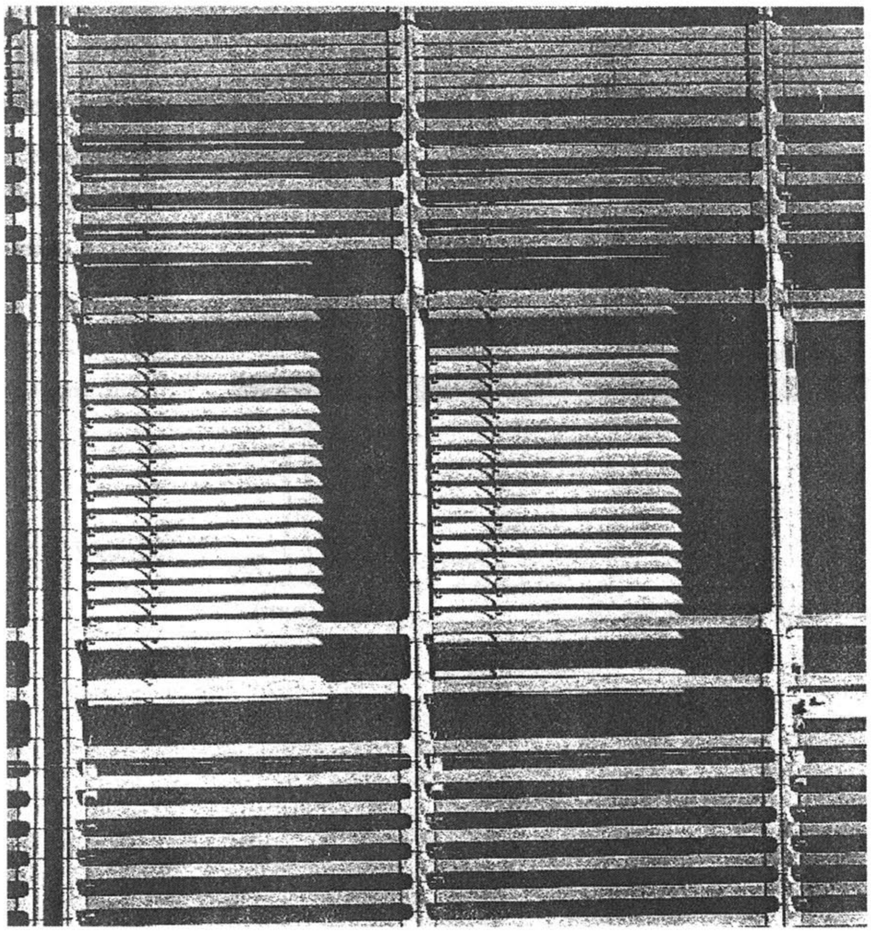
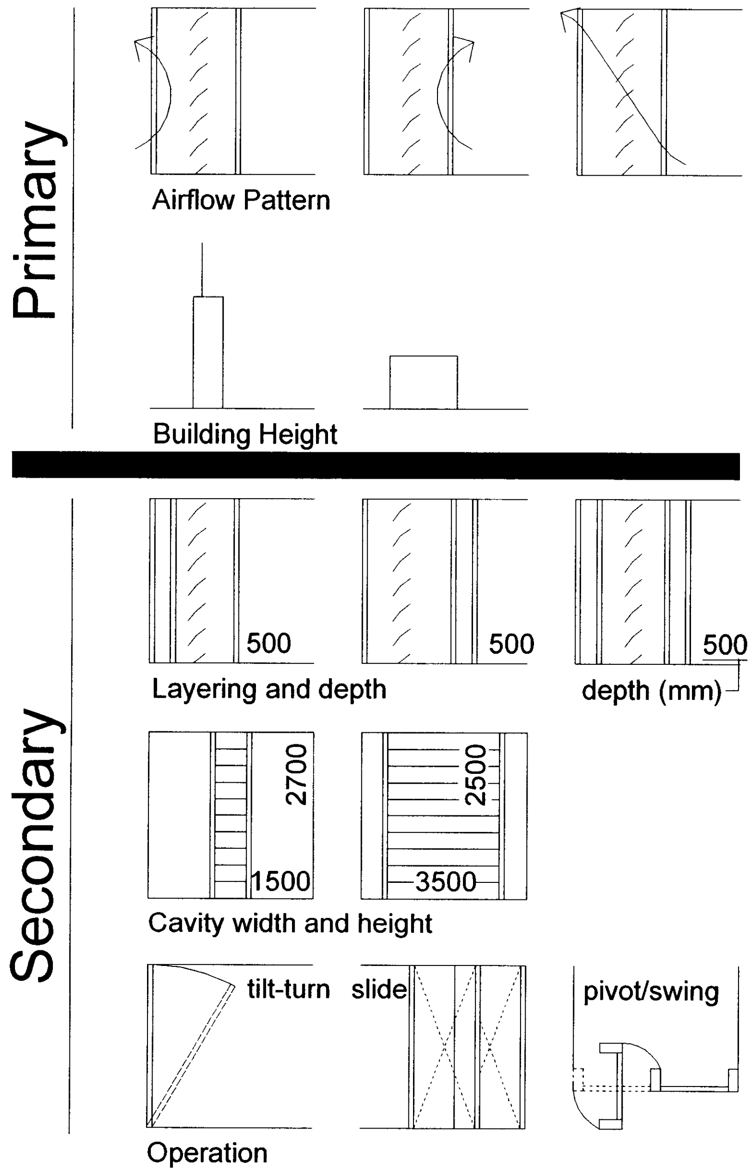


Figure 6 Debis building detail: terracotta glass and aluminum articulate a diverse architectural palette.

2.3.7 *Graphical Representation of Typologies*



A quick reference device for building types has been developed. This system may be used to quickly identify the key elements of an advanced façade system described by primary and secondary identifiers. This system is illustrated by the legend shown in Figure 7.

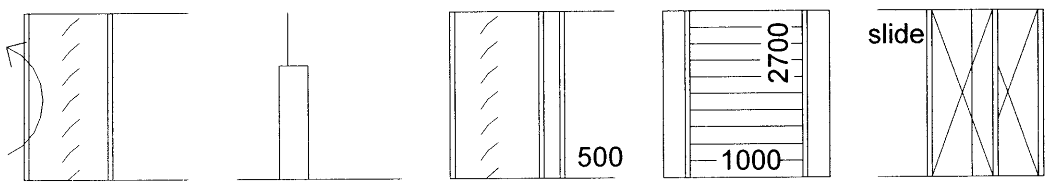
Figure 7: Family of typologies

3.0 Case Studies

3.1 High-rise buildings: outside ventilated

In Germany, a race to create the first ecologically sensitive high rise in the world resulted in the construction of two highly innovative structures, one for Commerzbank in Frankfurt, and the other for RWE in Essen. Both of them include double-skin facades that are naturally ventilated to the exterior.

3.1.1 The RWE AG Tower, Essen, Germany



3.1.1a INTRODUCTION

> *"The RWE AG building in Essen, [Germany] can be described as the first ecologically oriented administration building ever built. A second skin in the form of a circular glass cylinder 120m high, which allows the natural exchange of air and also roof-top terraces at this height, marks the decisive turning-point in high-rise building, which up to now has been dominated by the American principle of the strict separation of interior and environment. The building is "...no longer closed to the conditions imposed by nature, but takes them up and realises them both architecturally and technically. Architecture is not about form, but about contents and meaning (theory). -- Christoph Ingenhoven, building architect. [Hochhaus]*

With these words, the architect proclaims that a new typology of buildings has been created based on the development of new construction technology -- the double-skin façade. It appears that the technology is creating a new architectural expression, or at least that it represents a departure from standard practice.

The owner of the project, RWE, an energy utility and conglomerate, was looking to the new technology not just to save electricity but also to "benefit the tower's "inhabitants", RWE's staff, who can enjoy fresh, naturally conditioned air, individual control of air-conditioning and lighting, the benefits of natural daylight, and an unimpeded view of the outside world." [RWE web]

In many ways this is true. The extent that the building (completed in 1996) and its technology successfully satisfy these ambitions will be evaluated below. First is a description of the system and its design.

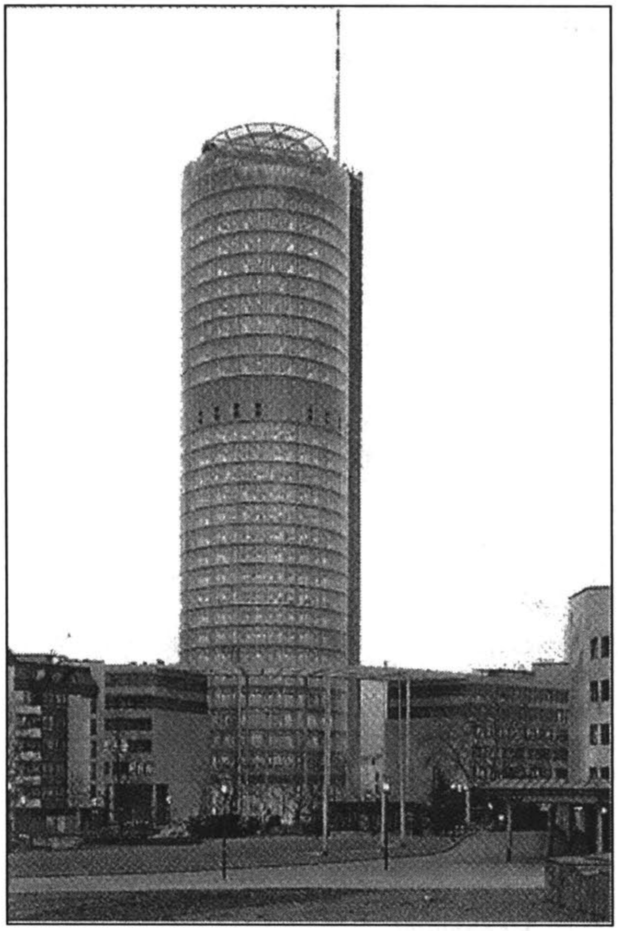


Figure 8 RWE Tower

The RWE tower designer, Ingenhoven Overdiek und Partner, IOKP (later renamed Ingenhoven Overdiek, Kahlen und Partner) was chosen from a competition in 1991. The design for the

162 m high (including antenna), 300 million DM would make it is the tallest building in the North Rhine-Westphalia state. The competition came on the heels of a competition for the design of the tallest building in Europe to date for Commerzbank in Frankfurt in which IOKP placed second.

IOPK's Commerzbank competition entry featured a cylindrical glass tower with interior offices pulled back in opposing arcs that created a void between the inner and outer skins (see Figure 15). In the intermediate space were envisioned planted garden spaces that would assist in conditioning outside air that could be admitted to the offices. The transparency of the skin was of great importance to the image of the building as shown in the competition model.

3.1.1b Building Layout

The cylindrical form reappeared for the RWE solution, in part because it provides the largest floor area to façade area ratio. This means that the impact of external loads – radiation, conduction and convection through the façade – will be minimized. [This is accomplished in the western style buildings by having deeper floor plates, but this means less human access to the façade as well]. The diameter of the 30 story tall cylinder is 32m. "The modest size of the floor-plate (about one-third the size of typical American 'developer specials') means that this 30 story tower is not the hulking presence that skyscrapers often are [Pepchinski 1997]." Limiting the depth of the building and maximizing the height of glazing at the perimeter also means that natural daylight is available for most of the office space. Maximizing daylight is beneficial both to the occupant's well being and because electric lighting will be used less. In terms of surface to volume ratio, wind pressure coefficients heat losses structural cost and day lighting, the cylindrical form is claimed to be the "optimal form" [Detail 1997 p. 358] Of course, it may be true that the form minimizes wind pressure and heat losses, but is it equally clear that heat losses should be minimized? With internal loads of computers, this may not always be the case. Also, this means that there is only an average amount of west glass, perhaps not ideal compared to a typical passive building that faces north and south. This seems to be an example of fitting the perceived performance to the design idea, rather than the inverse. The simplicity of the form may imply incorrectly that there is simplicity in the thermal and day lighting problem that is insensitive to cardinal directions.

Yet, the high envelope-to-occupant ratio increases the importance of the façade and emphasized the need to minimize summer heat gain and winter heat loss. The requirement for natural ventilation and minimal electric light load further increased the demands on the façade.

The relationship between building envelope and floor plate is examined below in Section 5.2 below. Leaving exposed the bottom of the structural concrete slab above the ceiling plenum also minimizes peak loads. The concrete absorbs some heat from the air to minimize instantaneous loads before exhaust air is removed. But, nighttime ventilation for 'free cooling' is apparently not practiced at RWE, so the potential of exposed concrete is not met in the control sequence for this design. The design approach can be contrasted to the almost single-minded approach that Michael Hopkins and Partners applied to the New Parliament Building in London. There, nighttime ventilation is used and every square centimeter of concrete surface is accounted for.

At the RWE tower, the core area on typical floors contains utility space such as mechanical chases, bathrooms and storage and a conference room. A circular corridor separates the core from perimeter offices leaving slightly wedge-shaped offices that are 5.85 meters deep [Evans 1977]. The outer perimeter is completely glazed from below floor level to above the ceiling level. The ceiling actually slopes upward toward the perimeter to allow more daylight into the space.

Glazing in the corridor walls is intended to allow light to pass from the offices to the interior, but Evans feels that this is not enough to give one a connection to the outside world. Certainly he is correct to some degree. The Commerzbank is more successful with its (expensive) glass partition walls, but a degree of privacy within the offices is achieved at RWE that is apparently valued by the corporate culture. Also, there is intentionally little life within the core space. Activity is focused on the offices, the façade and the views beyond.

3.1.1c FAÇADE COMPOSITION

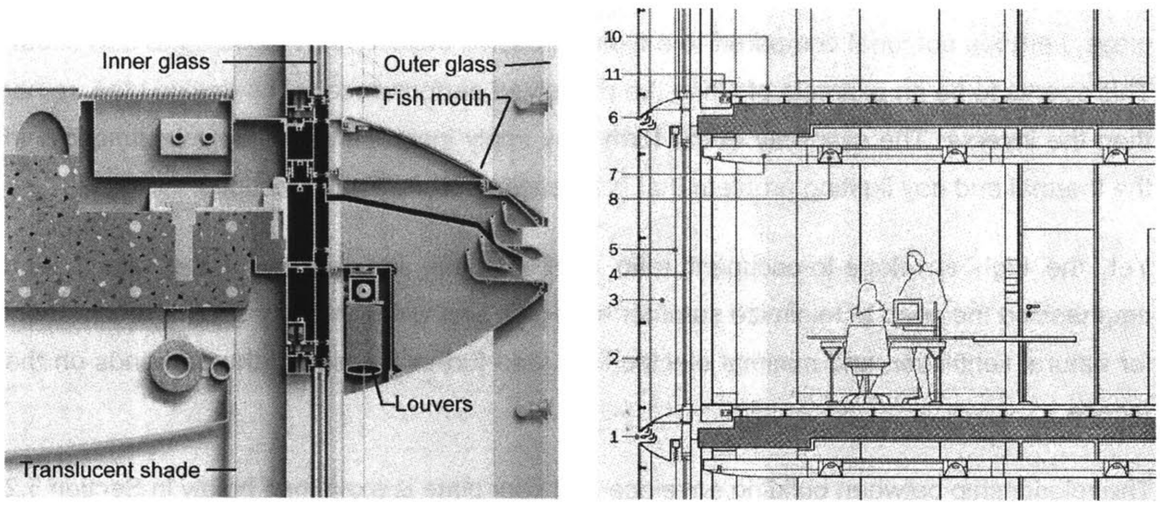


Figure 9 RWE fish mouth air vent (left) and building section (right)

The façade consists of full height doors that are fully glazed with insulating glass set in an aluminum frame. To open the door, one turns a crank to pull the door into the space. Once it clears the face of the adjacent door, it can be slid to the side. During normal operating conditions, the door opens just 15cm. The window can be opened fully for maintenance and cleaning.

Mounted 500 mm outside the first skin, is a second skin of approximately 12mm thick toughened "OptiWhite glass" supported with stainless steel point supports and butt sealed. The cavities are divided with vertical glazing that is aligned with the axial office partition walls. These are adjustable so that, theoretically, walls can be moved to modify the configuration and sizes of offices. The glazing serves as a smoke and sound barrier. It also impacts the movement and pressure of air that may conflict with other design aspects.

The cavities are also divided at the slab level with an aluminum device called a “fish mouth” for its curved and tapering faces and gill-like fins. See Figure 9. This is an exterior ventilated cavity; air enters by natural convection through openings in the outside wall of the building, moves through the cavity within the wall, and exits at the top of the cavity. The fish mouths have multiple functions: They house the horizontal aluminum blinds that may be deployed within the cavity. They hold a walkway that may be used when cleaning the cavity space and adjacent faces by lifting the top of the fish mouth out of the way. Finally, they house the horizontal louvers that admit and direct air into and out of the cavity. All of these systems were combined into a modular element that could be incorporated into prefabricated stand-alone window boxes [DeutscheB 1997 p. 58]

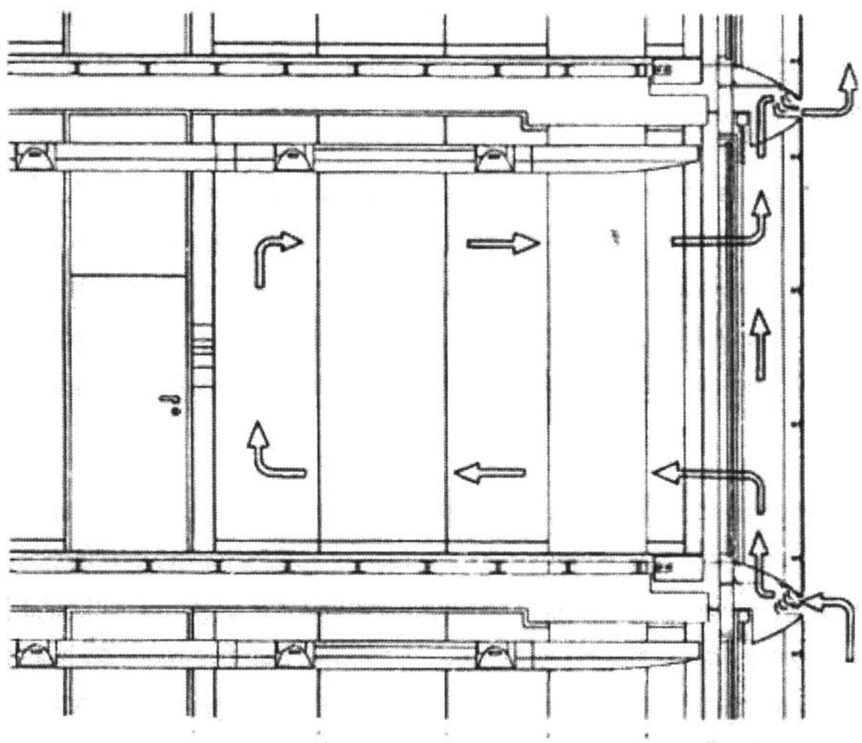


Figure 10 RWE airflow pattern [Detail 1997]

The design of the fish mouth assembly was an iterative process. Airflow behavior was tested in a wind tunnel to establish coefficients of pressure for the tower. Joseph Gartner & Co. also did a 1:1 mockup of the façade. The fish mouth design was studied to see what the air change rate in the cavity would be. Air is meant to pass through the "gills" without creating a lot of noise. It then enters the cavity, is heated by convection along the blinds, and rises to next level where it exits through another fish mouth. The inlets and outlets are offset along the face of the façade to minimize re-entrainment of exhaust air by adjacent intake louvers. This means that window panels are grouped together. In the case that two panels are grouped between vertical dividers, one will contain the intake and other will contain the exhaust. This implies a diagonal movement of air through the pair of panels. When three panels are grouped, there will be two intakes and one exhaust or one intake and two exhausts. A proponent of this system states that "diagonal through-ventilation [along the façade] is guaranteed and there is no danger of a re-entry of stale air [Detail 1997 p.359]." The guaranty should surely be dependent on wind velocity and direction, for if inlet and outlet are side by side, and the wind flows along the face of the building, it doesn't seem altogether improbable that re-entrainment may take place. This doesn't imply that this is a critical flaw in the design, but that designers might be overstating the reliability and accuracy of their designs. The issue is more critical where contaminants are present in volumes greater than are encountered in office buildings.

Ineffective cavity ventilation has not been addressed in the literature to date. Clearly there will be dead zones in the cavity that will be prone to both overheating, and ineffective thermal performance. Stagnant air will create hot zones during the cooling season that will increase the conductive and radiant heat transfer through the inner glass panel. It will also increase the temperature of the glass, increasing therefore, the mean radiant temperature of the space.

The impact of wind direction and velocity on the effectiveness of the cavity is largely overlooked in current literature and calculations. The effect of modest wind pressures is enough to overshadow any buoyancy effects. Therefore, typical calculations will tend to estimate incorrectly the cooling effects during the summer and the buffer effects during the winter. The models also over simplify the degree to which airflows are one directional. Opening windows for ventilation will dramatically complicate the formulas.

3.1.1d MEP Systems

The high thermal performance of the façade coupled with high transmittance of daylight led to the minimization of cooling loads. The exposure of concrete mass in the beams and (to some degree) ceiling aided in the reduction in cooling capacity of the central plant.

Cooling is supplied to the space via hydronic radiant panels in the ceiling. Heating is supplied by hydronic fin tube radiation near the windows at floor level. Ventilation is provided from diffusers in the ceiling. The air is apparently exhausted through the plenum and back to the plant.

Lighting is arranged in rows of three recessed linear fluorescent lights running axially to the center of each window. One additional daylight quality fluorescent down light is also provided in each bay. There are no light sensors for dimming the lights. This means that the building energy system does not fully take advantage of the extreme degree to which daylight is transmitted by this façade. The only way that an energy benefit is when occupants think to turn off the electrical lighting all together or in banks.

A control panel mounted by the office doors has an acoustic warning system that advises occupants to close exterior windows if winds or outside temperatures are too high. The windows may also be controlled by "hand, by infrared or PC" [DeutscheB 1997 p. 58] See Figure 14 below.

Opening or closing windows does not influence the controls for mechanical ventilation air supply. Air is supplied at all times, at levels that supply minimum hygienic requirements. According to several sources including the architect, the building can be naturally ventilated (and 'aired') for 70% of the time.

The previously mentioned wind tunnel tests were essential in predicting the wind pressures on the facade. While the wind speeds were measured as being above 8 m/s for only 230 operating hours (about 11%) during the course of a year, this is a ground level measurement. Velocities exceeded these measurements by 5% midway up the tower and 20% at a height of 110m near the top occupied floor [Daniels 1994]. The wind tunnel indicated that the pressure coefficients would be in the range of +1.0 to -2.3 (suction), and that the maximum negative pressure would normally be offset from the incident wind by approximately 80 to 90 degrees. There is some difficulty in modeling the internal forces that result from such external wind forces, even if the wind is considered to be of static velocity and direction; there are many variables for the interior as well. Doors may be opened or closed and partitions may be rearranged over time. Additionally, assumptions must be made regarding the interior skin window panels and the sunshade.

'Supporting air' [mechanically supplied air] is provided but that is considered 'belts and braces' by the designer". The architect feels that there were extra safety factors in the building due to owner concerns, and that his firm, IOKP would be trying to get away from this type of reaction on future projects [Hochhaus]. Beyond the unfortunate inclusion of this system in the building if indeed it is unnecessary, is the more unfortunate fact that the ventilation air is always on whether needed or not. Cutting corners on the control of the mechanical system may cost the owner even more than putting the system in the first place. That the system truly is "belts and braces" may be as much a question of the designer's optimism as it is of fact. Natural ventilation or 'airing' is possible 70% of the time. Airing means a brief opening and closing of the window to let fresh air in. This would be done when it is too cold to leave the window open, but not so windy that it causes other problems such as disabling office doors from opening or scattering papers on the work surface (although the outside second skin is meant to protect against this). There is a cultural aspect to the potential success of the control system; Germans are accustomed to 'airing' of spaces even when it is quite cold by American standards. The danger here is that this interaction between occupant and façade may not translate to other cultural settings.

3.1.1e Operability of Windows

To predict performance, Gartner and HL-Technik modeled the building using the TRY03 weather data from the Essen Muhnheilm station. There are times that in spite of the damping effect of the second skin, winds will still sometimes be too strong to allow opening of the windows. They found a 60-70% open window possibility with a wind speed of 8.2 m/s as the maximum allowable speed. This created a 0.16m/s air speed in the room and a 0.50 m/s air velocity at face of window and 0.6m/s in the cavity. This outside wind speed was set to result in a 10 Newtons opening force at the door to the corridor [Arons 1999 p.9]. According to Daniels of the consulting firm HL-Technik, door-opening forces should not exceed 40N (4kg) for continued operation or an "intermittent" force of 60N. The "top" limit for operability is a force of 100N. The box windows did very little to reduce the wind pressure on the office doors as compared to the 'double-skin' option. [Daniels 1998 p.159]

A further assumption was that no door closers would be used. Door closers would exponentially increase the door-closing force if the wind force were applied to the side opposing the motion. Paradoxically forces on doors are less if all of the doors are typically closed because cross ventilation is eliminated. The control sequence is therefore dependent on occupants to regulate the airflow through their individual spaces by closing doors and adjusting windows. The result is that when doors in offices with high positive air pressure on the windward side are closed because the air velocity in the room is too high, then offices on the leeward side may lose the source for their natural ventilation. From experiencing the space in person, it would appear that the default scenario will probably be doors closed, and one-sided ventilation rather than cross-ventilation.

3.1.1f Two Scenarios Compared: Box-Window and Double Façade

HL-Technik describes the study of two facade models during the building design: The box window (which was how the building was constructed) and the Perimeter double-Leaf Facade. They differ in the degree to which there are vertical (glass) dividers separating one segment of the cavity from the next. The box window scenario has dividers approximately every 2m along the circumference of the facade. The double-leaf facade is divided only twice for the entire circumference of the cylinder, so that there are two sectors in the facade at each floor level. Air can then circulate along the perimeter of the building, leveling pressure differentials. This reduction in pressure can be translated into a reduction in pressure coefficient at the face of the inner skin of the building. The studies looked at the number of air changes per hour that would result from given wind conditions if corridor doors were held open.

Air Changes per Hour

It was found that air change rates would be lower for the box-type windows than for the Double Façade. A lower boundary for comfort was established at airflow velocities of 0.15m/s combined with air-change rates of 25 per hour. These conditions will occur approximately 50% of the total operating period for box-type windows and 58% of the period for the perimeter double façade. These percentages represent worst-case conditions in which windows and doors are open to maximize cross ventilation.

The reality is that doors are probably more often closed. Closing the doors leads to drastically reduced exchange rates because ventilation becomes one-sided. Airflow, theoretically, can be controlled by leaving doors open and throttling the flow by adjusting the openness of the windows at the inner skin. But this works in theory only because occupants control only their own windows and doors, and do not optimized the entire system. Thus, they may optimize their own sub-system and preclude the possibility of neighbors down the hall being able to optimize their conditions.

Door-Opening Forces

Daniels concludes that the perimeter façade is preferable to the box-type window solution with regard to door-opening forces. He recommends that for the box-window scenario, windows remain closed on the upper floors when there are outside wind velocities exceeding 8 to 9 m/s so that doors will remain operable.

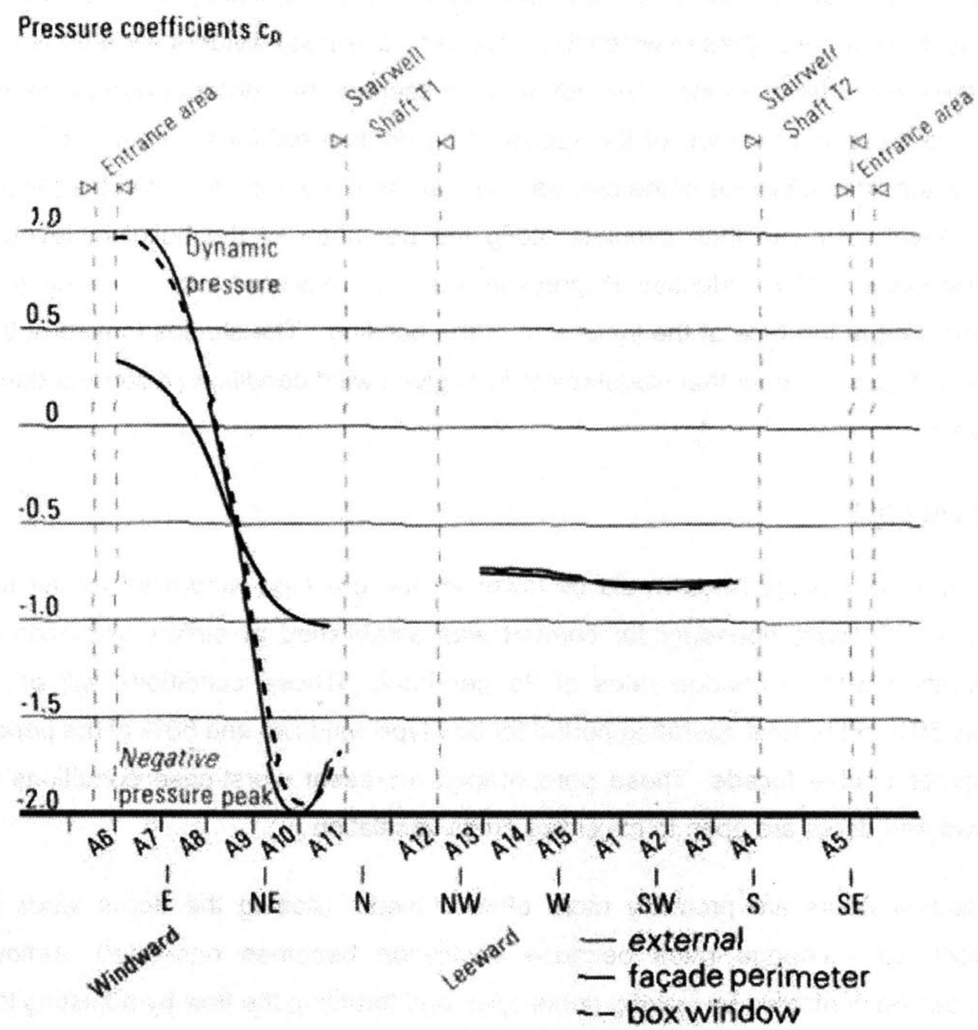


Figure 11 Pressure coefficients for RWE. Facade divisions (box-type) reduce pressure by about 50%.[Daniels 1994]

Most notable from this study is that the difference in pressure between the outside and the inside is remarkably small for the box window case. For the 'double-leaf facade, pressure coefficients at the extreme positive point could be reduced by over 50% and for the extreme negative side by a similar value (See Figure 11) [Daniels 1994 p.113]. The double-leaf facade without dividers has the pressure equalization benefits of a rain screen system design for a solid wall. The scenario may be more dramatic because of the cylindrical shape of the RWE building than it would be on a long rectangular building where there is more resistance to air movement around the perimeter cavity.

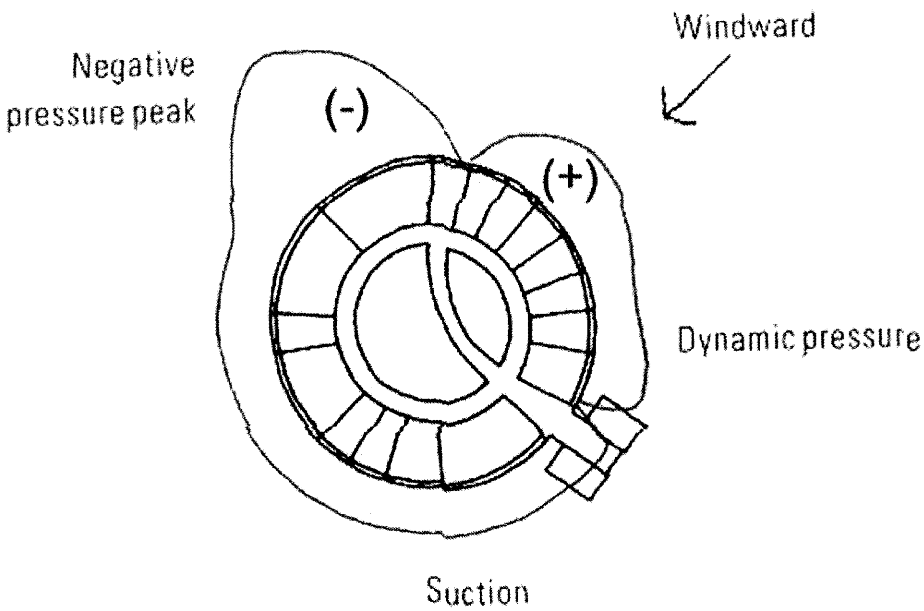


Figure 12 Relative pressure regime due to northeast winds [Daniels 1994]

The literature does not explicitly state why the box-type window was selected instead of the double-façade. Most probably, human-interfaces took precedent over the thermodynamic performance of the façade. The need to control sound transfer between neighboring offices was paramount for a successful building system. In addition, the box-windows will be more successful at containing smoke and fire.

Gartner also found by way of wind tunnel testing and analysis that the allowable exterior temperature range for opening is between 15 deg C and 27 deg C for opening the window. Combining wind velocity and temperature cut-off the weather data indicated that at 100m above ground, the windows can be opened for a short period of time 69% of the time, and left open for an extended period for 22% of the time. At 50 m above the ground the windows can be opened for a short period of time 75% of the time, and left open for an extended period for 24% of the time [Arons 1999].

Cavity Temperatures

The temperature of the cavity is important both for the operability of the window and the heat transfer across the inner windowpane to the space and occupant. The solar shading device may be adjusted according to the incident radiation. HL-Technik simulated the conditions within the façade for a (maximum) 32° C sunny July day. The temperatures within the box-type window and perimeter double-façade are comparable. A northeast-facing envelope peaked at 36°C and a southwest-facing envelope peaked at 42°C. When average winds are applied, the perimeter double façade has the ability to self-cool by dispersing heat within the cavity. In this case, while the northeast envelope peaked at 32°C for both facades, the southwest envelope was in the range of 36.0 to 39.5°C for the box-window and 33.5 to 37.5°C for the perimeter double façade. This indicates that the box-window will impose higher loads on the internal space and present a higher component to the mean radiant temperature. Further, it will impact the operability period of the window. The Perimeter Double-Skin Façade has the potential to create discomfort due to excessive air change rates because it allows less restriction on airflow paths. This, however, can be managed by closing windows.

An annual simulation of the cavity temperatures indicates that the frequency that cavity temperatures rise above 30°C is greater for the box-type windows than the perimeter double-leaf façade. The frequency varies by façade, but tends to be 15 to 30% higher for the box-type windows [Daniels 1994 p 121].

3.1.1g Interdependent Mechanical Systems

Mechanical ventilation air is conditioned to approximately room temperature, but is not designed to provide heating or cooling to the space. The humidity of ventilation air can be controlled according to a project manager for Hochtief the RWE-owned construction manager/facilities operator. The engineer also indicated that he believes ventilation air can also be reheated in the local plenum by an electric heater prior to distributing the air to the room. [Arons 1999]. This air is provided beginning at 4:00am to be 'ready' for occupation at

7:00am. Ventilation is turned off at night. There is no manual over ride. There is no adjustment of air volumes; it is either on or off. Special zones for the conference rooms (in the core) have higher supply air rates when they are activated. There appears to be no 'occupied/unoccupied' mode for rooms as was the case in the Commerzbank and Victoria Insurance. There is an 'in-use' button at the conference rooms, though so that more fresh air can be provided during meetings.

Nighttime set points are lower during the winter and higher during the summer. Heat from used air is exhausted. 100% fresh outside air is supplied. A heat wheel is utilized for heat exchange.

Cooling water is used for the radiant ceilings, but the architect (Webber) wasn't sure of the chilling source or location, but it appears that outside air plus water from 'public water supply' is used for cooling [Arons 1999 p. 17].

The mechanical plant has its own floor midway up the tower (see Figure 13). The wind direction determines the side of the building that supply air is received and exhaust air is ejected. The ductwork is configured so that the air can be taken in on the windward side of the building and expelled on the leeward side. The location of the plant was selected for several reasons. First, it allows the top floors of the tower, which have a symbolic power, to be used for corporate executives and board members. There they enjoy the best views in the city and outside terraces that are made habitable by the continuation of the outside skin of the facade up past the terraces to buffer the wind. This enhances the architectural quality of the tower as a transparent cylinder, something that may have been far more difficult if the bulk of the mechanical plant was located at the top of the tower. Finally, Mr. Nagel states that the mid-tower plant location is a preference to minimize the length of mechanical runs, thereby making the system more efficient.

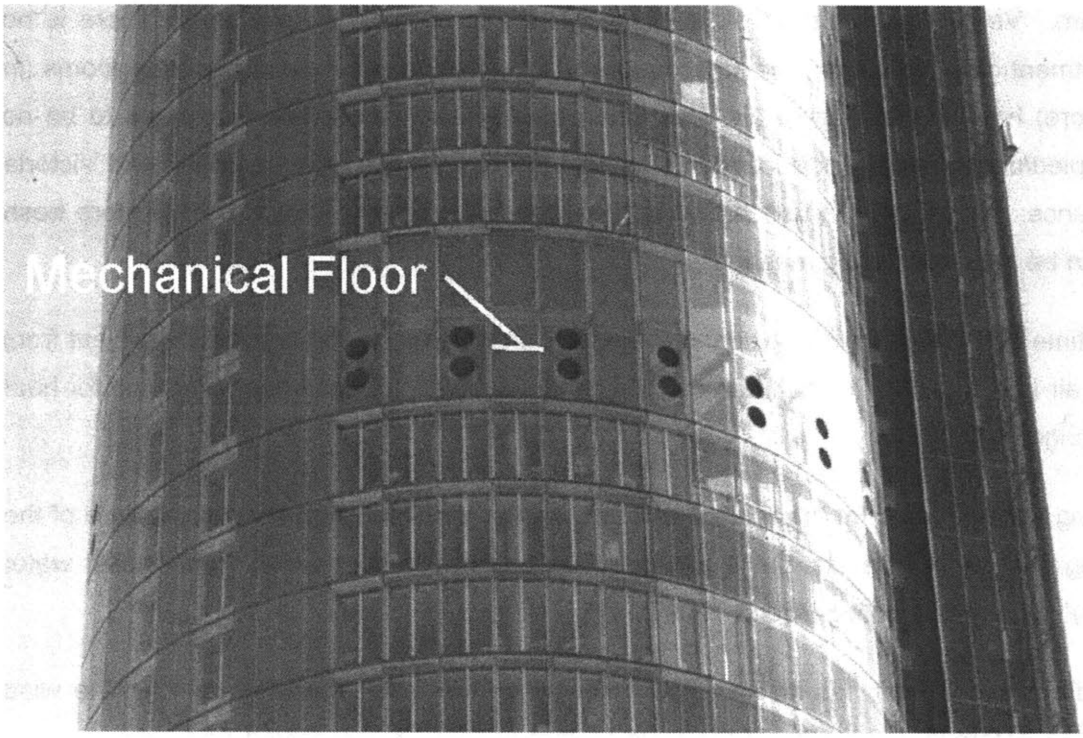
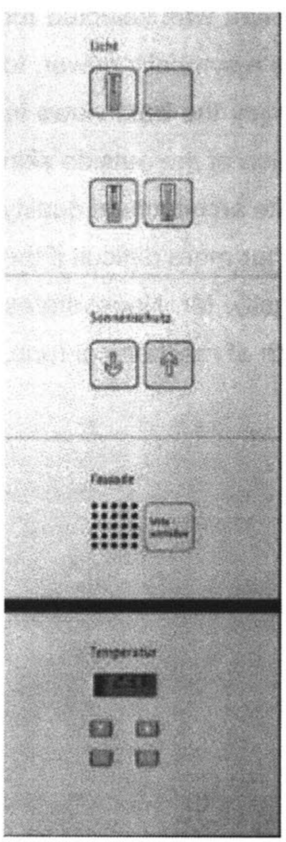


Figure 13 Midsection of RWE tower with distinctive mechanical floor



As can be seen in many European buildings, there is a raised computer floor to make wiring flexible over the life of the building. One outlet 'tank' for electrical, data, and telephone connections is provided per one-meter bay.

3.1.1h MECHANICAL AND FAÇADE CONTROL

Control of the façade is by the building management system (BMS) and by the occupant. There is an interface between the two as well; when the window is opened, cooling water for the chilled ceiling is turned off. Energy control systems, at the building management level, are now being installed, (about 2 years after occupancy).

Temperature control in the rooms can be adjusted to +/-3 degrees Celsius from the standard set point, and can be adjusted digitally (to 1/10 of a degree C). If an occupant adjusts the temperature to +3

Figure 14 RWE facade and room control panel degrees Celsius, the cooling will turn off and heating may be turned on. This is apparently a 3 or 4 pipe system. If the occupant adjusts the temperature to -3degC (summertime), then the valve to the hydronic ceiling is opened, supplying more chilled water to the radiant panels. The Hochtief engineer wasn't sure if the panel directly controlled the perimeter heating. Control of the blinds is 'continuous', allowing any position to be set by the occupant. The blinds may also be repositioned to preset positions by the building management system. There are 'at least' two zones for general control of the building [this may be north south plus the central core] [Arons 1999 p. 16].

3.1.1i Cost

Even though it is often the goal to minimize overall costs by using double facades, the cost of the facade is more than traditional curtain wall systems. According to Daniels, the idea that the façade will reduce overall costs is "in simple terms, a misconception"[Daniels 1994 p. 153]. RWE is perhaps the most expensive of the double facades. This is because of the complexity of the fish mouth (including moving parts) and because it was an early prototype. The Commerzbank facade cost 1200 to 1300 DM/m^2, (currently about US $71.00 per square foot) a 20-30% increase over conventional curtain walls according to the manufacturer of the systems. Meanwhile, the RWE facade was “certainly more.” Daniels notes a cost *surcharge* in the range of 800 to 3000DM/m^2 (about US $45 to US $ 168) as compared to single-leaf facades. The average cost of double-glazed (single-leaf) curtain wall facades in the United States is $30 to $50. Daniels states that the energy savings compared to single leaf facades amounts to only 1.5 to 2% of the extra investment. The design team is said to have claimed that the building will use 22 per cent less

Life spans are meant to be about 50 years for conventional facades, but the double facade is a mixed bag. The inner facade may last longer because they are protected from UV and weather. On the other hand the sunshades and motors probably won't last that long. The outer may also be shorter lived than conventional curtain walls due to the increased cavity temperature.

Ernst also says that paybacks don't make sense from an energy savings standpoint alone. This is the case even in Germany where fuel costs are three to four times that in the United States. The reasons, other than architectural, that he gives for using the double-skin are: 1, Comfort and 2, the fact that you can't sell a building without offering natural ventilation, and in some locales or with tall buildings, the 'only way' to offer natural ventilation is with a second skin.

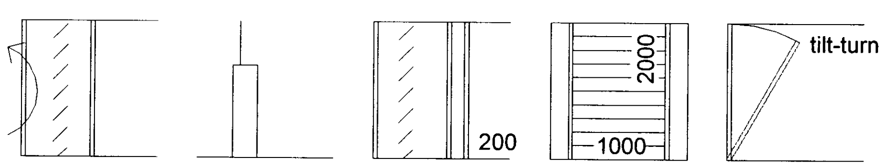
It is not a forgone conclusion that double facades are the only solution to ventilation in high-rise buildings. The ABM Amro building in Amsterdam uses an interior ventilated façade in combination with small (about 20 x 20 cm) ventilation flaps. See a further description of ABM Amro in section 3.2.1 below.

The architects of RWE argue that the additional costs of the façade will have a very quick payback period due to the energy savings they create. But independent testing has not yet been done, nor do we know over the long term whether such a complex façade can be readily maintained. Considering that back-up cooling and ventilation systems were also installed [although perhaps at smaller capacities] it is difficult to take this at face value. Additionally, the façade and cooling system must both be taken into account.

3.1.1j MEASUREMENT

Researchers at the University of Dortmund say that the energy consumption is significantly less than an 'ordinary façade'. At the time of the author's visit to the building, the Dortmund researchers had two temperature sensors (high and low) in the room, and an additional two pairs of temperature sensors in the cavity. Outside temperature, air changes in the room, and on/off conditions of the radiation were also being measured.

3.1.2 The Commerzbank Building



3.1.2a INTRODUCTION

"The building, completed in 1997, has 63 stories and a height of 299 meters including antenna. Revolutionary engineering and technology makes the office tower the world's first ecological skyscraper." [Frankfurt web]

With these words, quite similar to those describing the RWE tower, it is (again) proclaimed that a new typology of buildings has emerged. The driving force is a combination of the development of new construction technology -- the double-skin façade, and the location of enclosed winter gardens in a high rise.

The architect, Sir Norman Foster and Partners departed from its previous design for the Hong Kong Bank by incorporating issues of global ecological importance. The building is intended to minimize energy consumption by shunning the deep-planned, air conditioned format. Instead, an approach was sought to maximize the use of natural ventilation and day lighting. This strategy dovetailed neatly with the owner's desire for a humane and socially responsible image and the need to satisfy social and political pressures that were particularly strong because this is the tallest building in Europe.

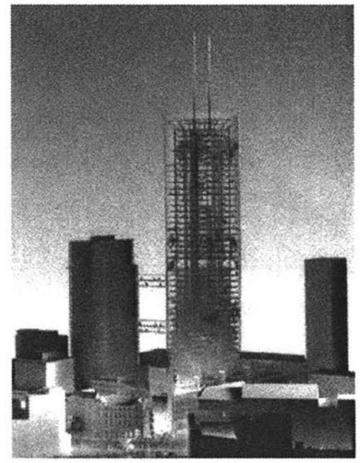


Figure 15 Ingenhoven Overdiek model for Commerzbank

The success of the Foster design and the entry by Ingenhoven Overdiek and Partners was based in their satisfaction of guidelines set forth by the owner. The competition brief called for an environmentally and socially responsible design. Along with low energy consumption, every workstation was to be close enough to the window to have a view out. This eliminated the deep plan layout and resulted in compact plans.

Colins and Lambot stress the important role that the owner had in setting the philosophical underpinnings of the project:

> *Architectural design was only one of many criteria for judging the entries. Environmental friendliness, energy efficiency, urban planning goals, space requirements and economic viability had all been analyzed in advance and expressed in the form of clear quantitative and qualitative parameters which were to be applied strictly and objectively by the competition jury. In short, the Commerzbank project management team had done its homework, knew exactly what it wanted and would not be content with a decision based solely on architectural or stylistic prejudices. [Colin and Lambot 1997 p. 39]*

3.1.2b BUILDING LAYOUT

Foster's plan is nearly triangular in form with rounded corners and gently curved sides. A full-height atrium at the center is a pure triangular form. The atrium is divided into 12 story segments with glass planes dividing them for smoke and heat control. A corridor divides the office space into perimeter offices and central offices. The latter of the two faces onto the atrium space. These central offices are meant to get daylight from the atrium, but this is clearly a second-class situation. Each bar connecting two corners of the triangle is 16.5 meters deep so that the German regulations that occupants be within 7 meters of a window is satisfied.

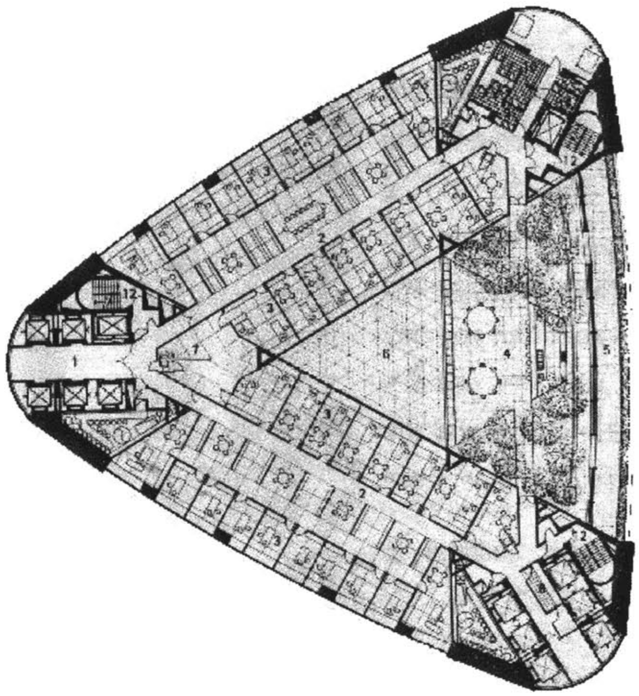


Figure 16 Commerzbank Floor Plan

One-third of the floor plan is given over to a winter garden. The offices and central atrium on one side and a full height single glazed wall on the other enclose the three story winter gardens. Glass flaps in the wall are used to admit fresh air. The flaps are automatically controlled by the building management system (BMS) so that they are open when it will be beneficial from a heating and cooling standpoint and otherwise closed. The BMS used weather station inputs to make such decisions. The offices facing the atrium and winter garden have conventional double glazed tilt-turn windows set between opaque glass spandrel panels. Since they are so far away from the face of the building, sunshades are not required. The winter garden space acts as a four-story cavity within the double leaf façade composed of inner double-glazing and outer single glazing. Air can circulate into and out of the space via the flap windows in the outer façade. If the temperature in the atrium drops to 5 degrees Celsius, air from the offices is cycled through the atrium to keep it warm enough. This is done with the help of the building weather stations [Evans 1997c].

The gardens are repeated every four floors in a position four stories above and rotated 120 degrees from the previous garden. This means that in twelve stories, there are three gardens filling out a complete rotation around the triangular building. It also means that one third of each façade is comprised of winter gardens, giving an important symbolic position for these features. Even though the building form is ostensibly structurally efficient, sacrificing this much space is a very expensive way of planning a high rise in terms of materials and space per building occupant. This must be reconciled with the social and corporate benefits. There may be benefits in terms of ventilation strategies, but it has not been proven that the energy or environmental benefits of the system have a reasonable, if any pay back.

Figure 17 Commerzbank Tower with winter gardens

The perimeter offices have a window-type, compact double-skin façade, as described below. The offices are separated from the corridor with nearly fully glazed walls. This allows daylight into and a view out from the corridor. This is far less disorienting than the RWE building, even though the Commerzbank has a bigger floor plan. It is difficult to say if Commerzbank takes advantage of a large area to façade ratio; while it is nearly circular in form, a large piece is cut out for the atrium and winter gardens. This would tend to make the effective surface area quite large, and especially so if the floor and ceiling of the winter gardens are taken into account; only a single layer of glazing protects them.

The elevator core was originally located in a bump-out attached to the main building. According to Colin Davies and Ian Lambot this was eliminated because it contained too few elevators and because it increased the surface to volume ratio [Davies et al 1997]. This was probably an aesthetic decision as well.

3.1.2c Façade Composition

The primary focus of this section is on the double-skin façade that is used for the envelope at the perimeter offices. This comprises approximately two thirds of the building. Unlike the RWE tower, transparency of the building was not a primary goal of the façade. Instead

Foster created an elegant patchwork of transparent windows and glazed gray spandrel panels. Rather than the windows being 95% of the façade area, they account for only about two thirds, exclusive of the one third that has the windows onto the winter gardens. See Figure 18.

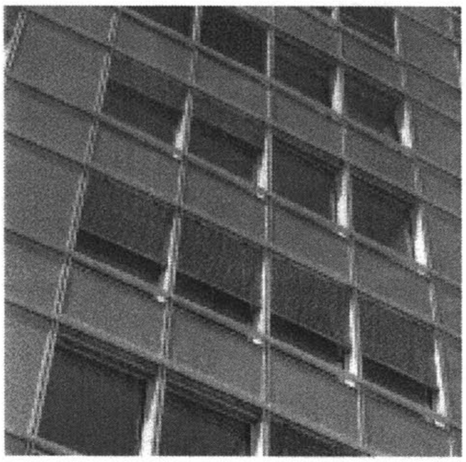


Figure 18 individual windows at Commerzbank

Rather than a double-leaf façade, we have a double-leaf window. Each window is approximately 1.2 m wide by 1.75 m high. The inner window sits on a kind of stool or seat that houses a steel spandrel beam and a perimeter radiant heating device. The window spans from the top of the stool to the ceiling. They are aluminum tilt-turn windows. Under normal operation, they open at the top, tilting back into the room. Control is by the BMS or from local control panels in the room. These double-glazed windows form the main weather barrier. A first line of defense is a second skin of single toughened glazing that is set 200mm in front of this panel. The two skins were pre-assembled in a single unit with an aluminum frame. This frame creates a solid vertical barrier between the units. An aluminum sunshade of non-perforated lamellae is set between the two skins, and is operated in the same manner that the window is operated.

The outer skin has open, non-louvered slots at the top and bottom that are about cm high. Outside air can freely enter these slots. On still days, it enters through the bottom, is heated in the cavity, and exhausts through the top. On windy days, this buoyancy flow is likely to be overpowered by wind forces. The flow patterns are more complex when the interior window is open.

A different strategy for avoiding re-entrainment is used than was designed for the RWE building. Rather than the complex, louvered fish mouths that were offset to separate intake and exhaust, the Commerzbank solution is to use protrusions, or aerofoil strips, that direct exhaust air away from the façade (and also break up the hot boundary layer at the exterior face of the façade). Another important feature is that intake and exhaust are separated by the +/- 1.3 m high spandrel panels at floor level.

Designers placed a lot of emphasis on the design of RWE's fish mouth, and its ability to direct, silence and maximize the effectiveness of air patterns. By contrast, the Commerzbank is a simple opening in the curtain wall, with a stainless steel wire across it, apparently to keep pigeons from taking up residence.

It is unclear to what degree RWE benefited from their study, or to what degree Commerzbank could have done so. Guiding the air stream with some type of louver or scoop (as in the case of Stadttor Dusseldorf) will make the air movement more efficient by eliminating friction and eddies. A larger opening will allow more air to enter the cavity with the potential to remove more solar heat gains. This can become a very expensive proposition both in terms of the complexity of the element (see RWE detail in Figure 9) and in terms of design and simulation time. Some uncertainties will remain. It is possible that the lack of efficiency of air movement at the intake and exhaust of the cavity may be counter balanced by increasing the heat exchange area. Creating more surface area for the sunshades or selecting more absorptive materials may do this. See more discussion of this topic in Section 4.5. Issues to look at include pressure loss coefficients of entrance/exit, width of cavity (friction), angle of blind and heat transfer coefficient, etc).

Considering the effectiveness of the tilt-in window is interesting. It allows a reasonable amount of open area, but forced airflow is directed toward the ceiling. Evans is critical of the system, stating that the "bottom-hinged opening light is not ideal for fine ventilation control" [Evans 1997c]. If the incoming air is cooler than the room air (when radiation is not heating the cavity) then air will drop into the occupied space. There is a psychological handicap to this functionality, though. Users cannot look out of the opened segment of the window because it is too narrow in the occupied space, and it is also at the side of the window. This may contradict the design intent to give occupants access to fresh air and a connection to the environment.

3.1.2d Operability of Windows

Not only are occupants close to windows bathing them in daylight, but also the windows are operable. This is perhaps the most significant aspect of the tower. Normally windows in such buildings are not operable because of the high pressures associated with tall structures. According to Herr Ernst at Joseph Gartner and company, the maximum wind speed for opening the windows is 15 m/s. This is nearly twice the limit set for the RWE tower, although the actual effectiveness of the window systems at design conditions is unclear. When the outside conditions are too extreme to allow for opening windows, they are automatically closed, and the air conditioning system is turned on. Ventilation air is continually on [Buchanan 1998 p. 36].

3.1.2e Interdependent Mechanical Systems

As at RWE, Commerzbank is equipped with radiant panels in the ceiling for space cooling, and perimeter radiation for space heating.

3.1.2f Mechanical and Façade Control

The maximum temperature inside is meant to be 27° C in offices. Set points are 20 °C heating and for cooling, set points vary from 21 to 25°C, on a sliding scale, depending on outside temperature. When the outside temperature is at and below 26 degrees Celsius the set point is 21 degrees. From 26 to 32° C outside temperature, set points inside go from 21 to 25° C. Office ventilation air is inactive for outside temperature between 2 to 22°C.

For fresh air when the ventilation is off, occupants are relied upon to open their windows briefly to get a gust of fresh air. Radiant panels at the ceiling supply cooling, but no heating. Windows are closed automatically when winds exceed 15 m/s. Greater wind speeds overpower the motors that operate the windows. On hot summer days, people can still open windows. This introduces hot air into the room that must be conditioned by the ceiling. However, the ceiling panels are shut off when the windows are open, so the hot air remains until one of three things happens; colder air from outside eventually replaces it, the air is mixed with corridor air, and cooled remotely within the building, or the window is closed and the radiant panel extracts the heat. Ventilation in the corridors is always active.

Occupants control the temperature set point of their individual rooms. They may adjust the temperature within a range from the building set point minus one degree Celsius up to the building set point plus 3 degrees Celsius. A motion sensor, and in/out buttons on the room control panel allow the system to go into a stand-by mode.

The bank has implemented a program for communication between occupants and facility managers to fine-tune the building controls. There is a kind of 'buddy system', by which each group of 200 occupants has a liaison to report to the facilities department to communicate issue relating to building maintenance, operation and user comfort. There are approximately 1200 occupants in the building. There is also a "traffic light" system on the control panel that tells users when it is okay or not okay to open windows. A red light indicates that conditions are not appropriate to open windows.

Fluorescent lighting is banked. An exterior bank and an interior bank, each with two lights are switched independently. The outer bank has a light sensor that dims the lights when more than 500 lux is available on the work surface. The facilities personnel interviewed believed that the windows can be opened for some period during 10 months out of the year.

Weather stations are located at each of the winter gardens and on the roof. When summertime temperatures are 5° C colder outside than inside, the office windows are automatically opened. When it is too hot out to open the windows for an extended time, the windows are "rationed" to save energy. Occupants may open their windows for 1 hour in the morning and 1 hour in the afternoon for fresh air. Otherwise they must remain closed.

Sunshades are controlled by a system that monitors incident radiation. If radiation levels are high at 11 am, then the blinds are lowered, and set to at a 45-degree angle. The system may check at other times as well, and could be programmed to check continuously.

Measured radiation with the blinds at 45 degrees was 29.2 W/m^2 whereas with the blinds open, the radiation was 120.1 W/m^2 as measured at the inside surface of the inner pane of glass.

Facility managers believe that the DeutscheBank uses 30% more energy than Commerzbank. This would be interesting to verify because Gartner and Company installed both facades. According to Gartner, DeutscheBank has an air-extract window system. It is not clear what other factors could lead to such a difference in energy consumption. DeutscheBank is probably an all-air system. This suggests that the biggest difference may be the use of radiant panels rather than the use of one façade system or the other. The interdependency of systems is the critical aspect of obtaining benefits from DSF's and the aspect that makes their evaluation so difficult.

3.1.2g Energy, Economy and Ecology

Like RWE, Commerzbank is a top-notch building in terms of its materials, detailing and systems. To provide a double-skin with operable, motor-driven windows and motor-driven blinds in a highly monitored and controlled building is expensive to construct and to operate. The Commerzbank façade cost about 1200 to 1300 DM/m^2 (about US $71.00 per square foot). The hope of the bank is that the 20-30% additional investment in the edifice pays off both in increased staff productivity and in positive public relations for the owner of an "ecologically-aware, energy-saving and pollution-reducing" building. The motivation for this desire may come as much from the political pressures of the approval process as from internal motivation. But Davies asks, "what could be better for the public image of a commercial company than a humane and socially responsible skyscraper that also happens to be the tallest building in Europe? [Colin and Lambot 1997 p.10]."

Unfortunately, this remains largely unproven. There is no documentation of this claim. Davies claim that the building begins a new phase in building design may be true in terms of intent and awareness. Commerzbank (and RWE) are the first constructed skyscrapers to take these issues on in a series, integrated approach.

There are claims that the tower required only 90 percent of the cooling capacity and that it has only 50 percent of the energy cost compared to a "fully air conditioned high-rise building" [Preston Web]. Architect Spencer de Grey with Foster and Partners hoped that the building would *save* between 50% and 66% of the energy used in a comparable building [Davey 1997a p. 36]. The Commerzbank states that "thanks to all services provided by the building management system, 30% less energy is used than in comparable traditional high-rise buildings [Commerzbank web]." Surely some of the credit for such savings must go to the radiation-shedding double-skin windows. The challenge here is to compare internal loads to the radiation load, and to look at the capacity of radiant cooling. In fact, much of the economic feasibility may be owed to the radiant ceilings rather than the double façade. A detailed cost comparison here would include such implications as duct or plenum space requirements of the alternate systems.

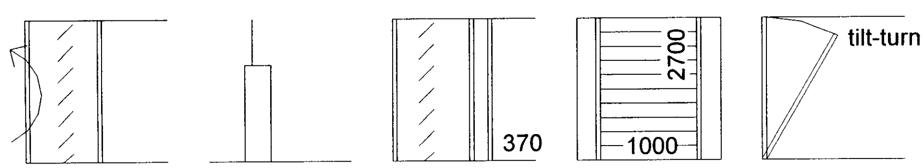
3.1.2h Measurement and Expectations

The Commerzbank was designed to have an optimal U-value and minimal solar gain. The use of computational and physical models to predict the extent to which natural ventilation of the offices would be possible aided the design. The modeling results predicted that natural ventilation would be available for approximately 60% of the year [Buchanan 1998 p.36]. Gartner predicted that an 800 w/m^2 incident radiation relates to a 10 deg C increase in cavity temperature and concluded that this would be 'not too bad'. [Arons 1999]

Both Commerzbank and RWE are similar in thermal performance. They each have a U-value of approximately 1.0W/m^{2}K. They are also said to have a G-value (shading coefficient) of approximately 0.10. This translates to 10% of incident radiation enters occupied space as compared to what would enter through a single layer of standard glazing. This relates to a solar heat gain coefficient of about 0.12. This is slightly better than the Permasteelisa manufacturer's data that states that the SHGC (or what is termed "shading factor" (SF%) in Europe) is in the range of 0.15 ~ 2.0.

Two designs were considered for Commerzbank according to [Evans 1997c p. 36]. The one that was later rejected had an exterior single pane and interior double pane, but the interior was fixed rather than operable. An operable flap was then created above the window to allow for natural ventilation. This system would have been more energy efficient, using about 140-150 kWh/ m^2/year.

3.1.3 The Victoria Insurance Building



3.1.3a INTRODUCTION

The Victoria Insurance campus, just north of the historic district of Dusseldorf consists of several low- to mid-rise buildings with a central cylindrical 29-story tower. The base building is approximately 100m long and is adjacent to Fisherstrasse, a heavily trafficked arterial street. This adjacency led to the requirement of a sound attenuating building envelope. The tower behind has less noise to mitigate, but the owner placed great importance on natural ventilation, day lighting, and energy efficient/ecological design. These criteria, along with the architectural desire for transparency and lightness led to the installation of double facades in both the tower and the low-rise buildings.

The building is a new landmark for the city and an advertisement for the owner.

3.1.3b BUILDING LAYOUT AND FAÇADE COMPOSITION

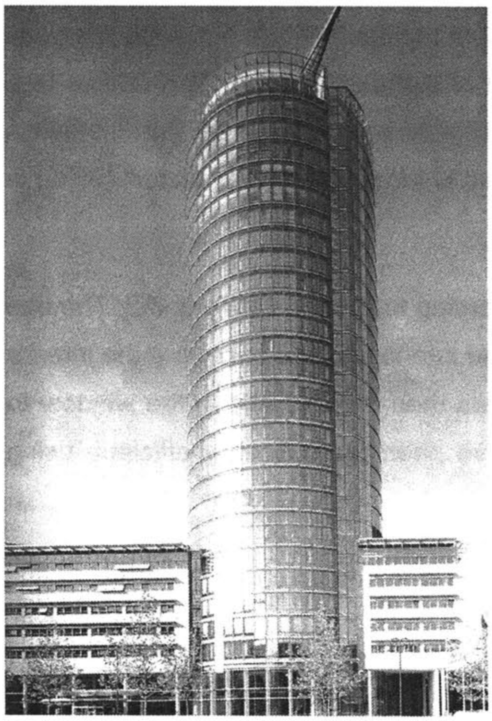


Figure 19 Victoria Insurance overview

The tower is just 34.4 m in diameter, just 2.4m greater than the RWE tower. The height (109m versus 120) is nearly identical as well. The perimeter offices are dominated by their view of and through the full height glazed wall. The inner facade consists of full-height tilt-turn double glazed windows that can be power operated either by occupants or by the building management system. 37cm outside of the inner skin is an outer skin of 8mm thick point-connected glass. The cavity contains perforated metal blinds that the occupant or BMS can adjust in rotation and up/down position.

Each panel with two tilt-turn windows is self-contained. Vertical dividers separate the panels. The dividers are roughly vee-shaped in plan with the open part of the vee to the outside of the building. 22 openings along the sides of this divider allow air to pass from the outside of the building into the cavity. Plastic inserts in the holes serve to keep out insects and birds

Air entering the cavity through the vertical dividers is heated by radiation within the cavity, and rises by buoyancy to the top, where it exits through 450 mm high horizontal, louvered gaps at the slab of the floor-level above. This system was simulated to provide 1½ air changes per hour for a 1°C difference in temperature between bottom and top. Joseph Gartner & Co. is reported to have verified this with a 1:1 scale mockup. Assuming a 3-meter high cavity, and perfect airflow, this represents an air velocity of only about 1.25×10^{-3} m/s (a volumetric flow rate of about 1.5 m^3 per hour). This seems remarkably slow, if it is to take away sufficient radiation. Most active systems are designed to move 20 to 80 m^3/hm.

The role of the double-leaf facade is primarily to provide noise control for the low-rise buildings, and allow for natural ventilation in the tower. The buildings benefit from an 18-19 dB noise reduction when the windows are open and a 45-46 dB reduction when the windows are closed. The noise reduction when windows are open is 100% better than if there were no second skin. The noise reduction for closed windows, however, is not as good as triple pane windows, but better than double pane windows.

As for natural ventilation, it is claimed that the windows in the tower may be opened for 60 to 70% of the operational hours throughout the year. The exterior temperature range for natural ventilation is from -5°C to +24°C. Mechanical ventilation is in effect when it is hotter than 24°C.

3.1.3c MEP SYSTEM INTERFACE

Victoria Insurance is, perhaps, the most sophisticated building with double-leaf facades in terms of its capacity to control the interaction of the facade and mechanical, electrical and plumbing systems.

Artificial lighting is controlled by the BMS. Light sensors in the room can adjust lighting levels with dimmers to maximize the use of day lighting, and minimize the use of electric lighting.

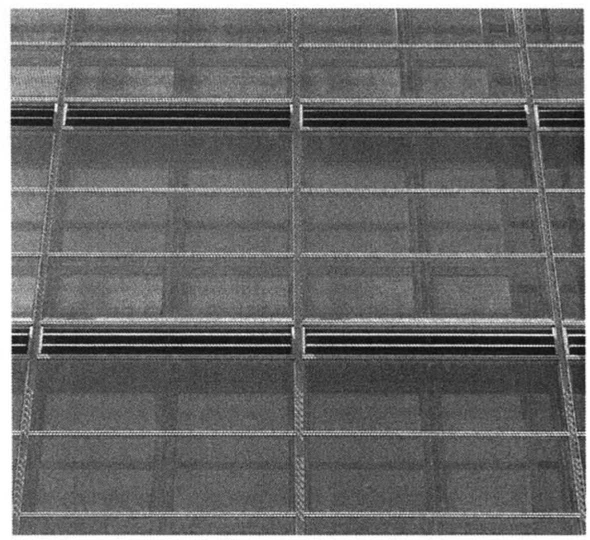


Figure 20 Victoria Insurance facade detail

The offices in the tower are provided with 2 to 3 air changes per hour mechanically to meet hygienic levels of fresh air. Air is supplied via the displacement technique; incoming air comes in near the floor and leaves near the ceiling along the interior (corridor) wall of the office. This ventilation air is supplied at 2 to 3 degrees Celsius cooler than the outside temperature. Water cooled in the plant by a steam absorption chiller is supplied to radiant cooling ceiling panels. An on-site cogeneration plant that is said to be 90% efficient produces the steam. Through reverse metering, Victoria sells electricity to the local utility when it produces more than can be used on-site.

Both the high- and low-rise buildings utilize “free-cooling” techniques. The low-rise buildings have radiant heating set in the concrete. The exposed concrete also serves as thermal storage, to minimize peak loads and allow for effective night cooling. The high rise has perimeter radiation, and doesn't have the same degree of exposed concrete for thermal storage. Because the floor in the tower is covered with carpet, the only surface available for thermal storage is the underside of the concrete slab above the radiant ceiling. This design approach should be critically compared to the one taken for the New Parliament Building and BT 2000, which circulate air within the raised floor plenum.

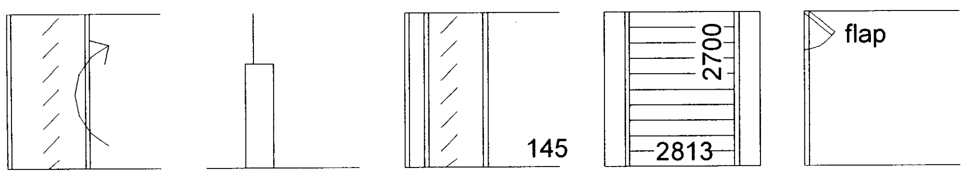
The refinement of the control sequence for the Victoria Insurance building is that the building monitors when workers enter the building. Each room on a given floor has a different solar orientation, and so, takes a different period to re-condition air from nighttime setback temperatures to operational temperatures. The BMS monitors this pre-heat/pre-cool time, and adjusts the time period according to orientation and user habits. If a user typically arrives at 8:00 am, then his/her office will be adjusted so that it is ready at this time. Vacation schedules can also be entered so that a particular office is not tempered if it is unoccupied.

Victoria's controls are designed so that each office is in its own zone. Opening windows will disable ventilation and cooling, and set back heating. Lighting is also automatically dimmed. These features combined in one office make this the most sophisticate tower from a controls viewpoint.

3.2 High-rise buildings: inside ventilated

The proponents for inside ventilated facades argue passionately for the cost savings, maintainability, and efficiency of their approach. As one engineer put it, "if we can control the movement in the facades, then we *should* control it. [The amount of air movement] should not be left to chance [Leijendeckers 1999]." The inside ventilated façade is designed to do exactly this. As described in 3.xx Typologies above, inside ventilated facades are tied to the mechanical ventilation of the building. Typically double-glazing is located at the outside of the façade. Single glazing is located to the inside, and sun shading is positioned between the two. Air is supplied to the room, either at the ceiling, or floor level. An exhaust duct located at the top of the window and between the two membranes draws air through the cavity. A simple opening in the inner façade serves as the link between occupied space and the cavity. This is an up-flow window; the air moves from the bottom of the cavity, past the sunshades to the exhaust at the top. Down-flow windows are also possible and have been executed. See section 4.1 below for a description of the DVV building.

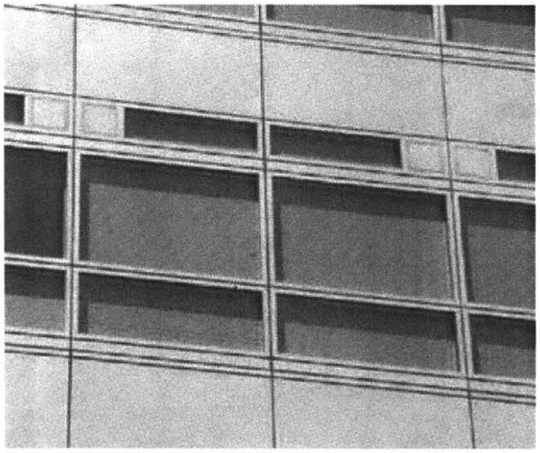
3.2.1 ABN Amro, Amsterdam, The Netherlands



3.2.1a SYSTEM DESCRIPTION

Construction of the ABN Amro building is currently nearing completion. Designed by Pei Cobb Freed Architects, the complex consists of several buildings, both mid-rise and high-rise. The same windows are used throughout. Unlike its German counterparts (Commerzbank, RWE and Victoria Insurance), this building is not meant to optimize natural ventilation. It is a sealed building with an interior vented double-skin façade. Small operable flaps are framed into the curtain wall to provide modest amounts of natural ventilation. ABN-Amro is similar to the German towers because it uses radiant ceilings for cooling. It is similar to Stadttor Dusseldorf in the use of radiant ceilings for heating. Raised floors are provided, the space within which is utilized for tel-data and electrical runs, and as a supply plenum for floor-supplied displacement ventilation.

The extent of windows on the façade is from floor to ceiling. This is somewhat less extensive than RWE, which spans from below floor level to above ceiling level, and more extensive than Commerzbank, which spans from approximately 0.4 meters above the floor to the ceiling level. The depth of the façade cavity is not as great as the German precedents.



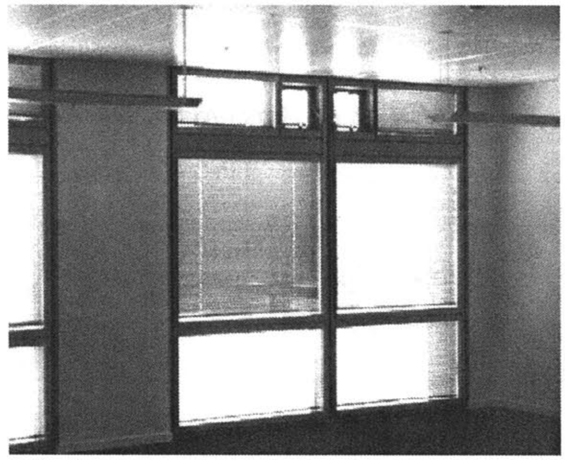


Figure 21 ABN Amro exterior (at solid flaps) and interior (at transparent flaps)

The distance from the inner single-pane glass to the outer double-pane glass is approximately 145mm. This distance is relatively small because the air movement through the cavity is mechanically fixed and controllable. This means that the cavity is not dependent on radiation driven buoyancy flows to control surface and air temperatures. It also means that there is the possibility of adjusting this airflow to tune the performance of the window system. Depending on budget and other design constraints, this adjustment could be made with individual fans for particular zones (i.e. by orientation). Such modifications could be made either as a commissioning activity (done once when the mechanical system is balanced) or as a building management strategy, (done on a continual basis by electronic monitoring and adjustment).

The window is divided into three parts by locating horizontal frame members at 0.2m above the floor and 0.2m below the ceiling, thereby creating a vision panel in the middle. Small slots run along the bottom of each section. Room air is drawn through these slots into the window cavity. Apparently, control of the blinds is possible only in the vision portion of the windows although this has not been confirmed.

As described earlier the upper segment of window has a small section at one end that is a flap. Sometimes transparent, and sometimes opaque, these small (about 20 x 20 cm) ventilation flaps have no second skin and no interstitial cavity for circulating air. They serve to allow a small amount of outside air and sound to be let into the room by occupants, and thereby provide a connection with the outside world. Space occupants manually operate these flaps. Some of the flaps are glazed, and others are opaque metal panels. Their design does not create the feeling of an operable window per se, particularly because they are located near the top of the wall. They do address ventilation for tall buildings. They do not have the benefit of a second skin to reduce pressure coefficients, but they do not have the same open area as the larger windows in RWE either. The lack of a second skin also does not have a detrimental impact on energy loads because the area is so small. Making the flaps opaque or glass can easily control radiation gains with special coatings without significantly reducing the overall transmissivity of the façade. One advantage of this method is that air entering the occupied space is never significantly hotter than outside air temperatures. It may be slightly hotter due to boundary layer heating along the face of the building, but not compared to the heating of a double-skin façade functioning as a heat collector.

The level of controls is unclear for this building. It seems that the blinds in lower and upper window segments are fixed (at an angle of 45° to vertical). This means that for summer sun will be largely blocked. Since east and west blinds are at similar angles, some radiation will bounce into the space, first hitting the front of one blind, then hitting the back of the blind above it, before entering the space. Blinds in this arrangement will not be optimal in terms of reflecting and absorbing radiation. Also, when direct beam radiation is bounced into the room in this way off of highly reflective blinds, a glare condition can be created. The bright reflection of the solar disc will be seen in contrast to the dark, shaded areas (such as the inside of the frame) adjacent to it.

Another important aspect of ABN-Amro is the plan configuration of the buildings. As opposed to the German towers, it is a series of relatively deep plan buildings. While not as deep as many American office buildings ABN-Amro is still a deep open plan layout. The importance of the façade in contributing to the building loads (in particular the cooling loads) is less significant than in shallower plans. See section 5.2 for more discussion on loads. The hope of providing natural ventilation is dim. Particularly when only small openings are provided. The flaps will be of even less usefulness near the ground as compared to higher in the tower where wind velocities will be greater. Opening the flaps will often be detrimental to energy conservation; ventilation will be on continuously because of the open plan layout. Small areas of the building cannot be portioned off mechanically. In a similar way, heating and cooling through the radiant ceiling panels is always on when the thermostats indicate they are needed. There is no interlock to turn heating off when the flaps are opened. This may lead to problems, especially during the winter. If flaps are left open on cold days, cold air may be drawn across the perimeter heating panels, and condensation could occur. Worst-case scenarios would have these panels freezing and bursting. The value of having some operation of the window may outweigh the risks to building energy and maintenance, but such risks must be assessed.

The chance of providing reasonable levels of natural day lighting to the inner reaches of the office is not particularly good. While the surfaces are somewhat reflective, no particular effort has been made to bounce the light to where it is needed most. From an energy standpoint, this means that automatic dimming of the lights would not be of great use, except perhaps near the perimeter. Even with a concerted effort, the occupied space is deep and so would be difficult to light from the perimeter.

3.2.1b Cost and Energy Implications:

The cost of this system has not been disclosed at this time. However, analysis of the façade shows that only limited cost factors are involved in upgrading to this type of airflow window. The complexity of the window can be compared to a standard double- or triple-glazed curtain wall. The ABN-Amro airflow window adds the inner pane of glass. This is simply framed in aluminum that snaps easily in and out of the main frame. This allows for maintenance of the cavity in which is placed the sunshades. The slots at the bottom of each frame require some additional labor, as do the slots at the top. Perhaps the greatest added expense is the connection of ductwork to the top of the window. The connections require some custom parts, and additional labor. This additional work may not be significant since the window exhaust will replace some or all of the standard exhaust diffusers.

In order to understand the accuracy of this assertion, one needs to look at the relative volume of air that is moved to maintain the minimum of about 2.5 air changes per hour in the occupied space. This volumetric airflow can then be compared to the volumetric flow that is required to make the window efficient. The latter is a variable concern because there is a relationship between cavity airflow, effective u-value of the window and fan power required. Consider that the cost effectiveness of the window is dependent on the relative volumes of airflow. It is also dependent on the relative importance of solar radiation loads to the internal loads of the space.

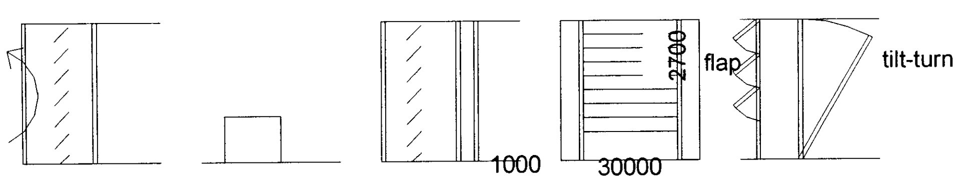
Similarly, the energy effectiveness depends on whether the window is drawing more air than would otherwise be drawn through the space. It will also depend on the effectiveness of taking solar heating away in the cavity before it can enter the space.

Finally, the effectiveness of the façade will be dependent on the potential use of heat exchangers to recoup heat from the air that passes through the cavity. While this heat will be largely undesirable during the hottest months, it will most likely be desirable during the short heating season. In more severe climates, heat exchange would potentially enhance the overall performance of the building.

3.3 Low rise building – outside ventilated

There are many recent buildings that have been constructed with double facades. The high-rise buildings have the clear advantage of taking on the challenge of providing naturally ventilated work places in skyscrapers. There is a reasonable argument that the technology is being applied because it meets a demand that cannot be met with other technologies. (This will be taken on in later chapters). The detachment of windows for view and windows for air should be considered. Air can be brought is either through baffled vent strips either driven by pressure differentials or fans, without doubling the façade. The strongest argument for the double façade is then taken away in the context of low to mid-rise buildings. The architect of the RWE tower, Achim Nagel states, "while the double-skin allows ventilation for 40-70% of the time, a seven story building can do that without trying [Evans 1977]." Yet by some accounts, double-skin technology is being used in as many as 80% of new commercial buildings in Germany [Arons 1999]. So what is the motivation? The answer can be found in a look at the Max Planck Institute headquarters in Munich.

3.3.1 Max Planck Institute, Munich, Germany



3.3.1a INTRODUCTION

The building is located in Munich, at Marstallplatz, next to the Bavarian House of Government. The architect, Mr. Post, felt the facade should have a large scale so the building would appear as one 'big building' [Arons 1999]. A second concern was to mitigate the effects of the building's noisy site (although it appears on-site to that environmental noise is only a concern on one side). Thirdly, there was a desire to reduce solar heat gains. All of these issues could be addressed with the double-skin facade. These factors pointed to the use of a deep double-skin façade.

3.3.1b BUILDING AND FAÇADE COMPOSITION

The five-story building is in the form of a U, with the open side to the south. A one-meter deep double-skin begins one floor above ground level. This deep cavity is divided at each floor level by a solid smoke-tight platform. The outer skin is single-glazed with horizontal aluminum dividers that incorporate open slots for the intake and discharge of air between the external environment and the cavity. There is one floor/ceiling level member and two intermediate members per floor. In this way, each floor of glazing is divided into three sections. The upper section at each floor is comprised of two rows of awning-style operable windows. These 'flap' open the outer skin to allow for more rapid and effective cooling of the cavity. The user can control them from a panel located near the door of each office.

Horizontal aluminum blinds are located at the inner edge of the meter-wide cavity. This is a good location for user control of light and view, but less desirable in terms of shedding heat gains. The inner insulated glazing unit has a low-e coating, and is comprised of full height tilt-turn windows.

Figure 22 View of Max Planck Gesselschaft: double-skin facade protrudes from building mass. Flap windows in open position are visible.

3.3.1c HVAC Design and Interface

The building has 100% natural ventilation. 40% of the ceiling is radiant cooling, and 60% is exposed concrete. The building is night ventilated so that when cool nights coincide with hot days, the building mass can be utilized to store excess heat during the day. The mass is then cooled at night to make storage capacity available for the next day.

3.3.1d Design Analysis

The Max Planck building was constructed before a fire in the Dusseldorf airport that prompted changes in the building code. Now the floor-to-floor separation in the cavity would need to be a "90 minute separation". This would have altered the design of this building. The floors in the walkways are light metal construction and offer little or no fire protection. The result of the new codes would have made the walkways thicker and heavier. Effects would be noticed in the depth of the façade elements at the floor levels and the weight or frequency of the walkway supporting elements. Little would need to change in terms of the functionality of the façade.

One user interviewed felt closed in by the second layer of glass, and wasn't happy with the amount that the windows open. Otherwise, a couple of users interviewed were happy with the overall style of window wall. A concern was voiced about interior glazing between offices. The control of the system for the user is on a panel located next to the office door. The user didn't mind going to the wall to adjust the window. On days with variable weather (partly cloudy) the window and shades would need to be adjusted more frequently, requiring multiple trips to the control panel. It was observed that when there is a light breeze outside, there is no palpable air movement in the office when the windows are open and the office door is closed. When the door is opened, then cross ventilation was noticeable. Rudi Marek, of H. L. Technik states that they often make blinds white on the outside and gray on the inside. According to Marek, making the blinds black on the inside worsens the overall performance. Forcing convection in this type of wall may be helpful. The Max Planck building has no mechanical ventilation and no dampers in the window system other than the operable flap windows.

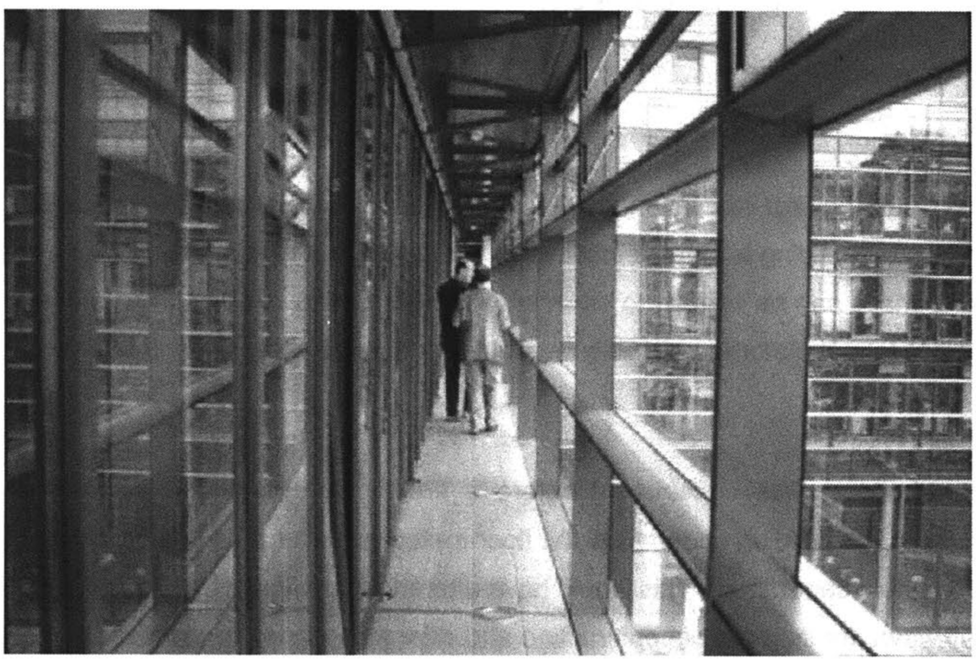
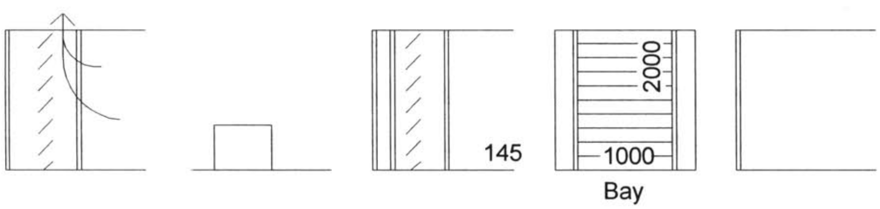


Figure 23 Max Planck Gesselschaft corridor-style cavity

Occupants will control the flaps in the outer façade. If they would like to have a breeze, the design concept suggests that they will open the flap and air will enter through their window. This logic seems weak if not faulty. The depth of the cavity and it's continuity along each floor means that the cavity is shared by all offices that open onto the cavity on a given floor level. If an occupant opens the flap opposite his/her office window, there is nothing to say that this adjustment will be appropriate for neighboring offices. Opening the window will drastically reduce the noise reduction properties of the façade, so any occupant can comprise the acoustical quality of his/her neighbors. The ability for occupants to open this flap also places the thermal efficiency of the façade in the hands of the occupants. There are not controls that allow the Building Management System to inform the occupant that opening the flaps may degrade not only the thermal efficiency, but also the comfort conditions of the space.

3.4 Low rise building – inside ventilated

3.4.1 New Parliament Building, London, England



3.4.1a Introduction

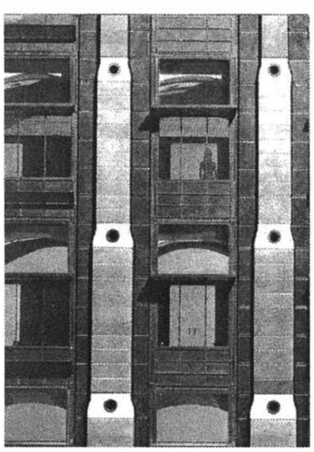


Figure 24 New Parliament Building facade detail

Nearing completion in 1999, the New Parliament Building was designed by Michael Hopkins and Partners with Ove Arup being the consulting mechanical (and structural) engineers. It is located near the Thames River, directly across the street from the House of Commons and Big Ben. It will house offices and conference rooms for Members of Parliament.

The requirements for a quiet building, safe from terrorist attacks were combined with the desire to minimize energy consumption within tight comfort range tolerances. Delays in the budgeting process conspired to give the design team extra time to develop an integrated approach to mechanical, structural and architectural design.

3.4.1b Building and Façade Composition

The building is a seven story square donut with an interior glazed atrium. The architectural design is a combination of solid masonry columns with bay windows between. The windows are separated vertically with floor level spandrel panels.

The columnar load-bearing stone gets smaller as they go up in response to decreasing structural loads. Ventilation air is supplied from roof level equipment down the façade. Located to either side of the structural columns, these ducts get smaller as they go down in response to decreased aggregated loads. The windows then fill a uniform width between these structural/mechanical elements. Due to architectural preference, the windows are in the form of bays that punctuate human occupancy within the facade.

The windows are an integral part of the mechanical system. They consist of an outer leaf of double-glazed insulating glass (that is meant to be literally "bomb-proof"). A cavity for air movement and a shading device is to the inside of this membrane, and a simple inner pane of glass is placed to the inside of these elements. A light shelf separates the lower two thirds of the window from the upper third. Air is drawn into the cavity through gaps in the inner glass at the bottom of either segment of the window (See Figures and further description below).

3.4.1c Mechanical System Integration

Chimneys at the top of the building have outside air intake vents at the bottom, and exhaust air vents at the top. The chimney also houses a heat recovery wheel consisting of rotating wire meshes. This large thermal exchange wheel has an efficiency of 84%. The six-meter height of the turret is designed to achieve separation of intake from exhaust. The two air streams do not meet. A small amount of fresh air is used to purge, or clean out, the exchanger in between cycles. Fresh air is supplied down the façade in the ducts along side the structural columns. The exhaust air returns up the façade to the exterior of the supply ducts.

Air from the perimeter supply airshafts is directed from the outside wall to the plenum space in a raised masonry floor. The air is then supplied to the occupied space at floor level. The air rises by buoyancy, and because the air is mechanically extracted by ducts attached to the cavity within the window. This is a modified displacement ventilation strategy. In typical displacement systems, air is supplied low and exhausted at the ceiling. In this case, to keep proper buoyancy distribution in the room, 20% of the air is drawn through the lower part of the window and 80% through the upper part. The author's understanding is that an ideal plunger type arrangement, having the air move uniformly from bottom to top, is not possible here because the exhaust portals are along the perimeter wall through the windows. This means that air that rises through buoyancy will also need to be pushed and pulled to the sidewall. It is easy to imagine that a layer of hot air will grow along the ceiling as it approaches the perimeter wall, potentially causing discomfort.

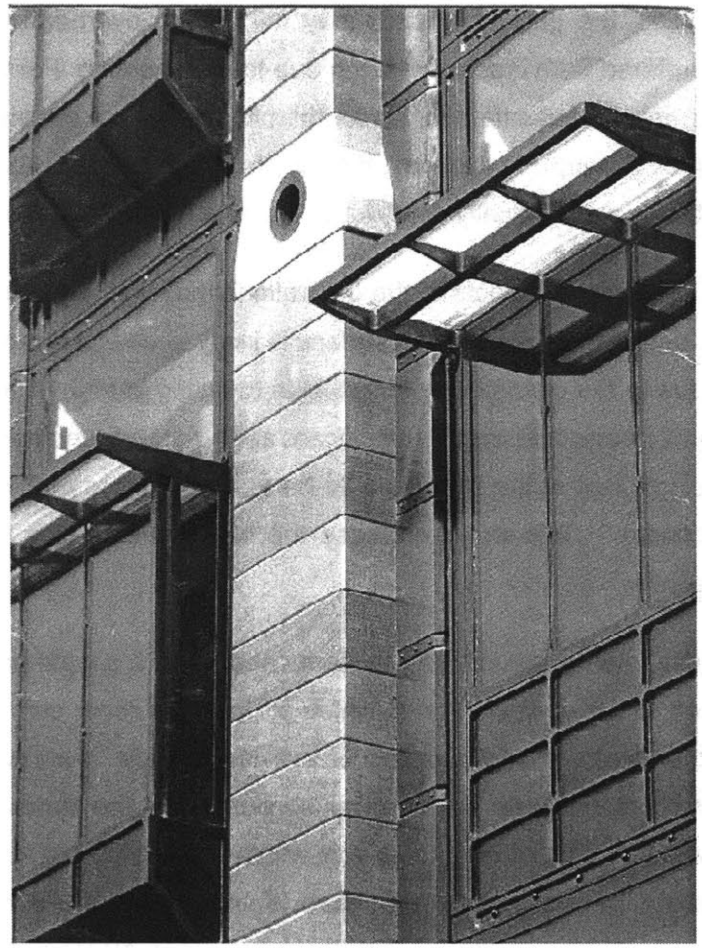


Figure 25 New Parliament Building detail

Rather than the typical aluminum sunshade, the louvers in the New Parliament Building are bronze to match the coloring of the roof and cladding of the building. The system is 95% effective at absorbing solar radiation because the dark blinds cancel internal reflections between the glazing and the blinds, and instead absorb the heat.

During the summer heat from the windows is 'thrown away'. During the winter heat is recovered in the turrets. The designers conceived of the windows as solar collectors. Because of intense absorption of blinds and subsequent heating of the cavity and adjacent glass, the glazing system may fail due to overheating. Test panels in an early mockup suffered from cracked glazing due to over heating. For this reason in the final configuration, there is a fail-safe position for the blind: They are stored at the bottom of the window (rather than the top). In this way, if power fails and the fans cannot bring air through the cavity, the blinds automatically drop out of the active portion of the window.

The energy impacts of the dark blinds may well be negative, particularly during the cooling season. The inner glass surface is likely to be significantly higher than it would otherwise be due to the absorption of the blinds resulting in high blind surface temperatures. To remove this heat would require significant airflow rates. Another option to increase the heat transfer coefficient of the blinds would be to create more surface area (larger blinds or roughened blinds). This would increase the effectiveness of a base level of air moving across the blinds.

The interior panel of the system consists of a simple pair of hinged glass doors with a gap left at the bottom through which air from the room can enter the window. The hinge makes maintenance and cleaning of the cavity easy. Airflow volumes are pre-set by sizing the orifices between the window sections and the ductwork. For calculation purposes, the window is considered as a duct with a given pressure loss. Frictional effects of the blinds are probably not considered. There is an element of thermal buoyancy in the facade. Air is pushed through the system; the pressure is 10 Pa in the ducts at the roof on the exhaust side, and approximately 90 Pa resistance on the supply side. This is done with hand calculations and then put into the computer model of the overall design.

Cooling of the air is accomplished by using 13.4 degrees C ground water that is sent to cooling coils. (The gray water from the coils is used to flush the toilets or is dumped to the Thames River about 100meters away). A tank holds the well water in a 'battery' tank for future use. Additional cooling is accomplished via night flushing of the building and cooling down the mass of the building. Design efforts were focused on maximizing exposed masonry. The raised floors allow air to pass between the top of the pre-cast floor slabs and the bottom of the raised flooring. The bottoms of the pre-cast slabs are open to the occupied space. In addition, a partition system was devised using exposed pre-cast concrete panels hung from the ceiling above. These were very expensive, and were targeted for cost savings during the value-engineering process. However, the engineers showed that the partitions could not be substituted with lightweight alternatives because the mechanical system was dependent on the storage capacity in the partitions.

Heating is accomplished mainly via passive solar means with the help of the large amounts of thermal mass. Radiant panels located on the inside face of the column supply additional heating. Some space heating is supplied by tempered ventilation air, but this has a minimal capacity.

An additional feature is the control of daylight. Perforated and corrugated aluminum reflectors between two sheets of glass form light shelves located at the bottom of the upper third of the window. The holes in the panels avoid the 'total obscurity' of solid reflectors. This helps to alleviate the negative feeling that one is wearing a visor when looking out the window. The glazing is meant to protect the aluminum, keeping it clean enough to bounce light deep into the room. Site observations indicated that the light shelves served to illuminate the ceiling adjacent to the window. Light colored surfaces, in general, help to illuminate the entire space.

3.4.1d DESIGN ANALYSIS

Holistic Design

The New Parliament Building is an example of integrated, interdisciplinary design. The architectural, structural and mechanical design have been integrated, and in an informal way, co-optimized. The windows are an active part of the mechanical system, serving as solar load control devices, mediating negative impacts and providing for redistribution of heat via the heat recovery wheels. In particular, windows on the sunny side of the building can collect heat that can be used to heat parts of the building that need heating while avoiding the need for cooling and the potential for discomfort on the sunny side. The ductwork also serves as part of the architectural finish on the exterior of the building. This is most likely not cost effective, but it does successfully express the functionality of the building for all to see. The building structure, consisting of pre-cast concrete slabs also serves as an architectural and mechanical system. The exposed panels at the ceiling and beneath the raised computer floor provide thermal mass to absorb excess heat from the occupied space. The local (London) climate is also advantageous for nighttime cooling of the structure to moderate diurnal swings. This combines with the impact of the DSF's to significantly reduce the overall load that the conventional mechanical system must mitigate.

Appropriateness of DSF to Building Program

There is a dialogue between the effectiveness of the windows and their architectural appeal. Hopkins uses the DSF's on every façade of the building, facing all cardinal directions. Double facades are most effective in controlling direct solar light, so this choice is a bit ironic. Even on the north face of the interior courtyard where direct sunlight may never shine the DSF's are used. This indicates an overriding principal on the architect's part to have a uniform building skin wrapping the building. It also muddies the reasoning behind having the ductwork exposed on the outside of the building -- it may be that the impetus came first from the engineer's need to locate the ductwork combined with the architect's desire to avoid interior shafts rather from an intent to express functionality on the façade. Note that the Inland Revenue Building does have exposed stack ventilators. Both projects exhibit an effective architectural resolution of mechanical elements on the façade regardless of the generating idea. Hopkins' earlier work at the Inland Revenue building exhibited a similar approach to having repeated facades in al cardinal direction combined with an integrated mechanical-architectural element. In this case the stair towers that double as stack ventilators. While DSF's are not used at the Inland Revenue buildings, the design approach is a similar one.

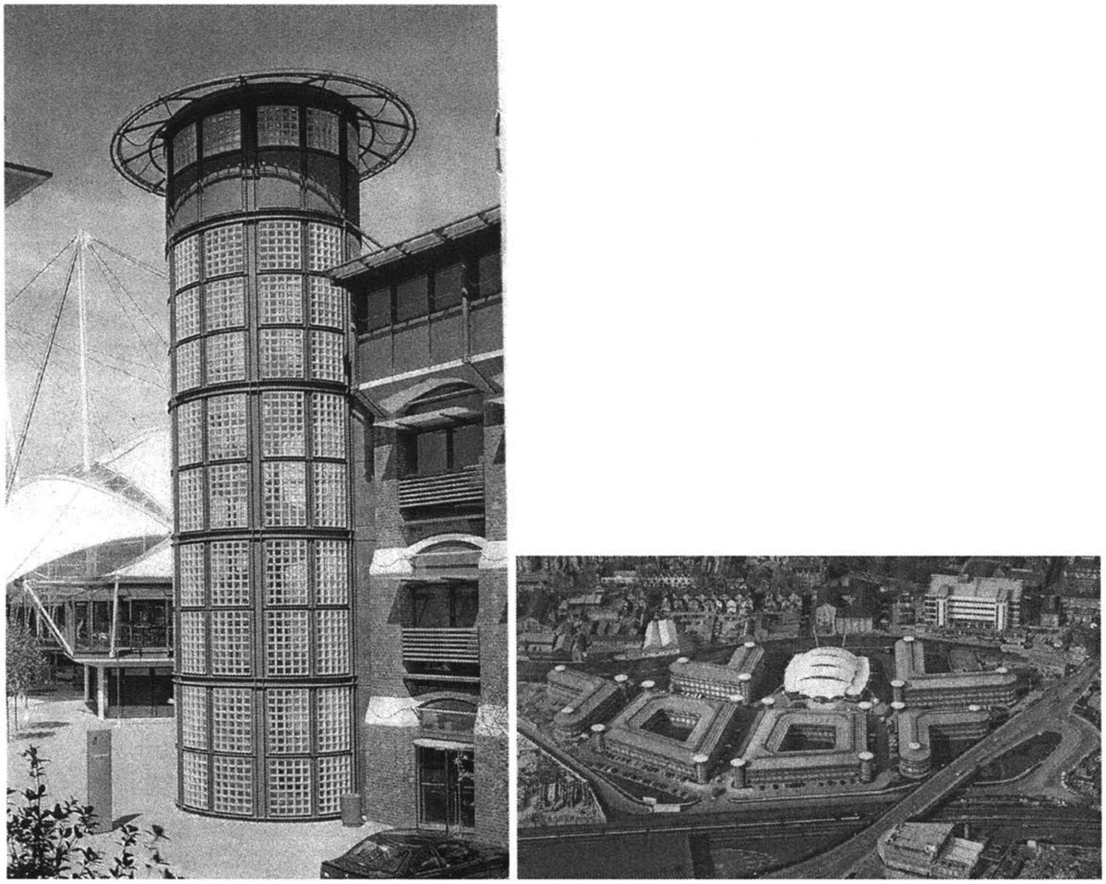


Figure 26 Inland Revenue Building, stack ventilator and aerial view with 20 ventilators shown on campus (images courtesy of Arup Engineering)

The design of the New Parliament building is interesting in the adaptation of the DSF's to Hopkins's architectural style. There is a large stylistic gap between the RWE building's sleek and transparent façade to the solid, human scale of Hopkins's work. Hopkins has chosen an internal ventilated system that provides the security required by the building program, and broken the façade into solid and transparent elements, the transparent ones in the form of bay windows. Rather than being sleek, the technology has a stately and somber quality. Perhaps it is even oppressive.

4.0 Energy Implications

The context for developing energy models is understood by considering the following quote:

> *The danger exists, of course, that spectacular structures will be erected in the name of solar, energy-saving, ecologically sustainable architecture, but which, in fact, do not meet these criteria. [Herzog 1996, p.19]*

The creation of mathematical models for the prediction of performance is part of a two-step process. The second would be measuring buildings to provide feedback for evaluating the accuracy of the models. The combination of calculated techniques with intuitive and human understanding is essential. This chapter describes the development of calculated techniques. The previous chapter looked at the built forms, and the following chapter considers the process more holistically.

4.1 Existing calculation methodologies

The literature encompasses various approaches to the problem, and it is beyond the scope of this paper to summarize all of them. However, a synopsis of the leading papers is made in this section so that the state of the science will be described.

Saelens and Hens have put together a series of useful papers on airflow windows that consider theoretical calculations as well as site measurement and analysis and speculation concerning system construction and performance. They set forth equations that separate effects of solar radiation from the combined influences of convection and infrared radiation. Their calculations show that effective U-values and Solar Heat Gain Coefficients are inversely proportional to airflow through the window cavity. More particularly, they show that both U-values and Solar Heat Gain Coefficients are reduced with decreasing effectiveness by the airflow, approaching a minimum value asymptotically.

Their experimental work focused on the case study of the DVV Building in Brussels, Belgium. The DVV is an unusually configuration for airflow windows. The air is ducted from exhaust grills at the lighting armatures through the ceiling space to the window heads. It is then down-fed through the window cavity that contains Venetian blinds and is exhausted from the windowsill. This configuration is meant to be beneficial because it removes some of the interior heat load component from the lights before it is introduced into the occupied space. The authors show that this heat is lost in the plenum, possible near the window head where insulation or thermal bridging introduce a cold source (heat sink), thereby cooling the air before it is introduced into the windows. This configuration also suffers from the counter-flow of the buoyancy effect pushes air up from the sill to the head. In the end, the authors found that even though the window cavity heats up significantly, the temperature of the exhaust air is not significantly higher than room temperature, indicating that energy is not being removed from the window. In fact, the authors conclude, "The active window always loses energy. This shows that heating the air while passing through the cavity in this case is fiction". The authors cite the need for heat absorption within the cavity. "Active envelopes without absorption do not collect solar energy nor have a good SHGC."

The authors have neither measured nor calculated the airflow volume within the cavity. They point out very clearly that, "...the performance of the window (e.g. the equivalent U-value or SHGC) should be distinguished from the overall performance (e.g. the overall energy consumption)."

Yoon and Lee evaluate annual energy performance of a three-story building with a full height, double-skin facade containing a vertically continuous window cavity. The building also has a ground-coupled heat exchanger, also referred to as a "cool tube". The "experimental" building is in Korea. The double-skin (DS) provides "integrated heating and its control logic is reported in a previous paper."

The authors modeled the building and systems using ESP-r (ESRU 1996). Korean weather data was loaded into the software. Cooling and heating loads were determined from sensible and latent gains and losses from occupants, lighting and equipment. "However, energy consumption for fans, lighting and energy losses due to plant inefficiencies are not included here."

The DS consists of a single 6mm, tinted leaf. It appears that this is outside typical external windows that are double glazed units (6mm glass on either side of a 12mm air space). During the heating season, fresh air passes through the DS after being pre-heated by the ground coupled heat exchanger. During the cooling season, the fresh air is pre-cooled by the heat exchanger but bypasses the DS, and the DS cavity is simply vented at the top.

The report indicates that a 12% annual energy savings is achieved due to the DS system compared to not having the system. It is somewhat unclear whether this is relative to the heating season or the entire year.

The report by Wiart and Suvachittanont analyzes the use of airflow windows in tropical climates by measuring windows in a small test chamber. The chamber can be fitted with either standard or airflow windows. The authors also cite analysis of a 6 story building in Thailand, equipped with airflow windows.

The study concludes that airflow windows are economical in the hotter localities such as Singapore. In Thailand, triple glazed AFW are not economical. The authors recommend doubling the inner glazing in climates that are hotter than Thailand's in order to minimize gains to the conditioned space.

"In air-conditioned buildings, the heat absorbed by an internal blind increases the temperature of the air in the channel and reduces its insulating effect." Rather than blind in the window cavity, heat-absorbing (gray tinted) glass is used on the outside. The portion of the heat that is retransmitted to the window cavity is evacuated with approximately 20 m^3/h airflow through the space.

The authors also conclude that the fan power used to evacuate the window cavity creates an undesirable payback time of approximately 20 years.

Tanimoto and Kimura have investigated the possibility of replacing the inner light of a traditional airflow window with a "roll screen". This study begins from the assumption that airflow windows are highly energy efficient. The limiting aspect of these windows in Japan is the cost of glass. The common window solution there, according to the authors, is single glazed windows with a Venetian blind on the inside. The proposed solution involves a roll screen that apparently has reasonably high air permeability. This permeability makes the system relatively leaky – creating cold drafts during the winter, and unwanted heat during the summer.

This article seems to be the only one that considers the stack effect numerically. The authors are concerned with understanding the flow across the roll screen. Yet it seems that the buoyancy effects should be considered in any vertical cavity with air flowing. Saelens and Hens allude to this fact by suggesting that the DVV building should have reversed airflow directions, but this was not considered in their calculations.

Tanimoto and Kimura have done both iterative numerical simulations using the finite difference method, and physical experimental modeling. The authors note the difficulty of creating truly accurate CFD calculations due to the variability of conditions including convective heat transfer coefficients, possible airflow short circuits near the ends of the device and local effects of the exhaust fan. Issues of workmanship are also of critical importance. [Tanimoto and Kimura 1997]

4.2 A Simplified model for energy performance evaluation

4.2.1 Reasoning for and Description of a Simplified Mathematical Model

Researchers have recently developed a handful of numerical tools to predict the performance of various configurations of double-skin facades. Some reasonably holistic approaches have been taken. The focus has been on determining the effective U-value and solar heat gain coefficients of the windows.

The models that have been developed have remained as backup to individual papers. They are not accessible in the public domain. For this reason, a new model has been developed that may be a stepping-stone to a public domain tool. This tool would have the potential to be run either on a personal computer, or via the World Wide Web.

The end user is meant to be the designers of buildings incorporating double-skin facades rather than researchers. This community of end users -- architects, engineers and students-- will have specific needs in terms of interface, level of complexity and output from the program.

The author has developed a simplified numerical model of a typical double-skin façade. This model is intended to predict the energy performance of multiple types of double-skin facades. The platform for development has been a spreadsheet utilizing iterative calculation methods. The basic configuration for the window under study has a layer of insulating glass on the exterior, an air cavity and a single interior layer of glass. An inlet is assumed at the bottom, and an outlet at the top.

Two-dimensional heat transfer, neglecting edge effects are considered. The system is considered in the steady state condition, with constant temperatures throughout. Conduction and radiation are considered in the horizontal plane (one-dimensional) and convection is considered in the vertical direction (also one-dimensional).

Solar Radiation:

- For the calculation of reflected and absorbed (and transmitted) solar energy at the blinds, the true solar altitude is used in conjunction with blind angle and geometry to determine passage of solar energy. Both diffuse and specular reflections are considered and material properties of the blinds are input.

- For the purposes of calculating the *quantity* of solar energy transmission, it is assumed that solar radiation will be converted to normal solar radiation prior to entry into the model. The model takes normal radiation (perpendicular to the window) as its input in W/m^2. So if weather data is used to determine solar energy input, the solar azimuth, altitude and direct normal (to the sun) radiation must be converted to direct normal (to the façade) radiation for the model. A separate spreadsheet has been developed to facilitate this conversion.

Infrared Radiation:

- Infrared radiation is evaluated based on the surface temperatures and geometries of the model.

Convection:

- Interior and exterior heat transfer coefficients may be input if desired, or defaults will be used.

- Heat transfer coefficients within the double-glazing unit are calculated based on the spacing of the glazing and the surface temperatures.

- The model for convection is one dimensional, and it is assumed that the air stream in the two cavities do not mix with each other. Also, within each cavity the air is well-mixed, constant temperature at each vertical tier.

- Heat transfer coefficients in the cavity are determined from correlations for forced convection flow in a long channel with smooth walls.

Conduction:

- Conductivity of glass is based on input properties.

- Conductivity of blinds is ignored due to its relatively small impact on the overall energy balance and temperature distribution.

Gas conductivity:

- Gas conductivity is input as a constant term that is used in calculating the heat transfer coefficient within the air cavity. Gas-filled double glazed units (with argon, krypton etc. in place of air) are not considered in this model.

The model may be adjusted in many ways. The airflow cavity may be opened to the interior or exterior and the flow rate of forced convection may be assigned. Alternatively, buoyancy in the cavities may be analyzed. The geometry of the window is flexible; the height and widths of the cavities as well as the dimension and spacing of the blinds may be selected. The properties of all of the materials is also flexible: The reflectance, absorptivity, emissivity and transparency may all be adjusted, or selected from a fixed set of glass or blind types imported from Lawrence Berkley Lab's Window 4.1 program.

The intent of the program is to virtually assemble a particular system by specifying the geometrical and physical parameters of the window. The model will calculate the energy balances and provide results in terms of energy flow into the occupied space or ductwork. This data can be compared to building loads to evaluate the efficiency or cost effectiveness of various double-skin systems. Inside surface temperatures may be used to analyze impacts on comfort.

The design may be refined and optimized for specific conditions to minimize energy consumption. Comparisons may be made to traditional static systems or to other dynamic systems to evaluate selection criteria.

Cost is not part of the model, but may be incorporated in terms of basic cost of energy calculations. Cost of fabrication and installation is too dependent on idiosyncrasies of site, geography, economy and technical expertise.

Future enhancements may include:

- Weather data integration: Currently the properties determined may be used to input into an energy analysis worksheet. Determining annual impacts on energy consumption is essential to holistic design. Evaluating one instance in time is not sufficient for window selection. Ideally, the window should be tested against hourly weather data.

- Building interaction: As with weather, the isolated effect of windows on energy transmittance is not sufficient for window selection. Interactions with thermal mass, electric lighting, perimeter radiation, and radiant hydronic heating and cooling must be considered.

- Evaluation of condensation potential: Transferring the technology to climates other than the climate for which they were originally designed (typically northern Europe), may introduce new criteria such as condensation. Linking the model to weather data, and being able to define interior air moisture content will allow the tool to warn its user when condensation of moisture on the interior pane or in the interstitial cavity may be a hazard.

- Input of gas-filled insulated glazing units

- Window frame and edge of glass analysis: The effects from conduction will be less because of the expanded depth of the frame, but thermally breaking the frame is more difficult for the same reason. Conduction may also be minimized in the case of bolted glazing on the exterior, although this is difficult to achieve with double-glazing.

- The effective solar shading due to the depth of the frame considered as a light shelf and fins because of its depth. This relative impact will depend on the frequency of frame elements.

- Effects of inlet and outlet configurations

- Frictional effects of the entry region may have significant effects on buoyancy flows and fan power

- Temperature variations of the cavity air stream, as it moves from the inside or outside into the base of the cavity have been ignored so far. Saelens and Hens have done some work with two-dimensional solid thermal modeling to evaluate this effect. Additional work on the fluid dynamics of the entry region is required to evaluate the heat transfer coefficients between air and frame.

- Fan power analysis for active façade: Especially at higher forced convection velocities, fan power may decrease the overall efficiency of the system. In order to evaluate this, one must compare the fan power to the fan power that would be used to exhaust/supply the room if the air were not moving through the window. (See Figure 74 on page164). The fan power will be accounted for against the benefits of reducing cooling/heating loads.

4.2.2 The Heat Transfer Model

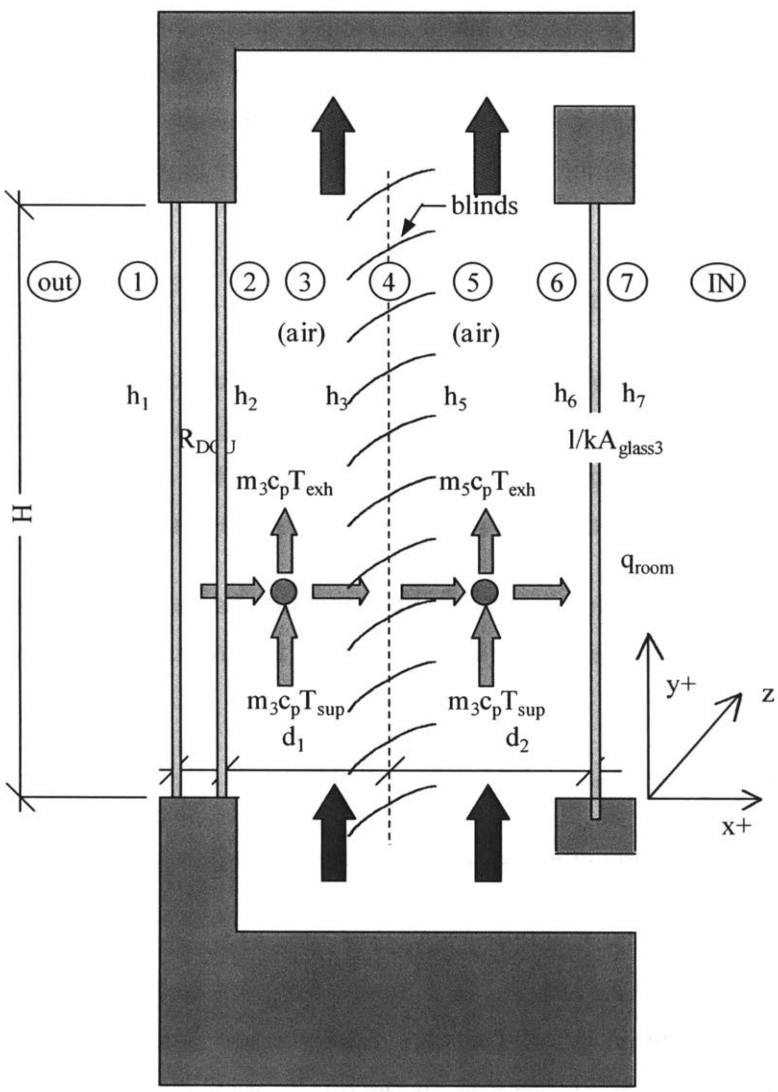


Figure 27: Window system diagram

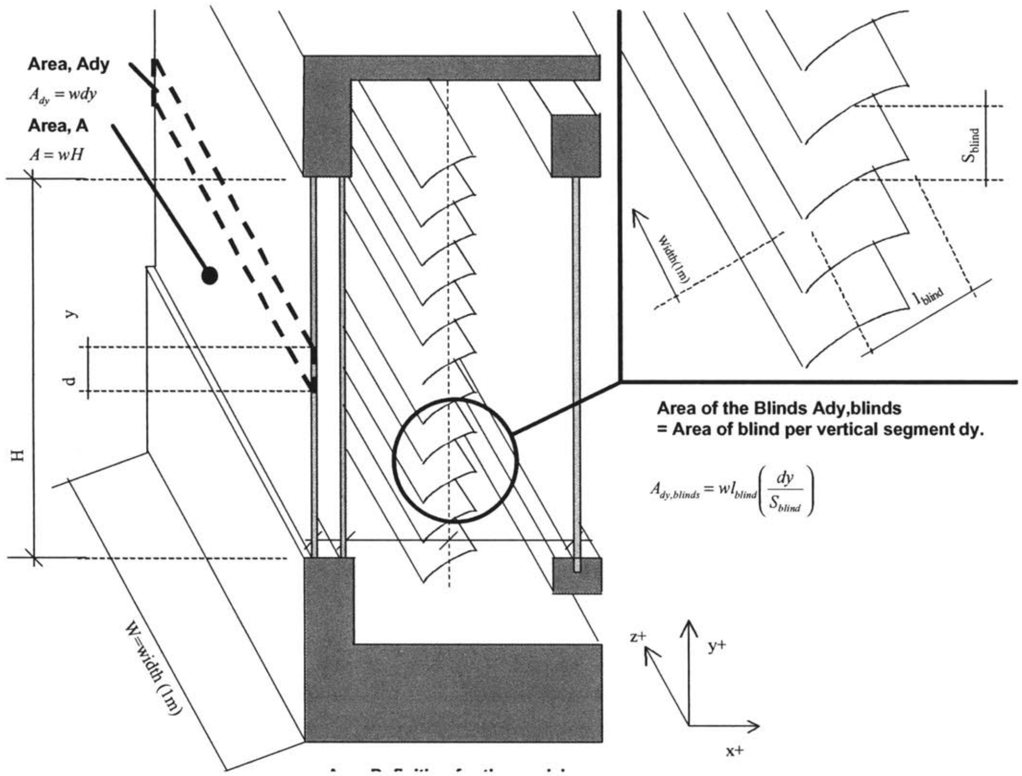


Figure 28: Model area definitions

4.2.3 The Electrical Analogy for Interior Vented Forced Convection Façade

The electrical analogy for energy transfer within the system has been the basis for the model design. Figure 29 shows the overlay of solar radiation with convective transfer and infrared radiation transfer. The diagram is for the simplified infrared transfer, which applies when the sunshade blinds are in the fully closed position. When they are open, a more complex relationship exists because there is a view factor between the glazing on one side of the blinds and the glazing on the other side. Also, the blinds may see either layer of glass. For a comparison of the infrared models, see comparison in Figure 43 on page 118 below.

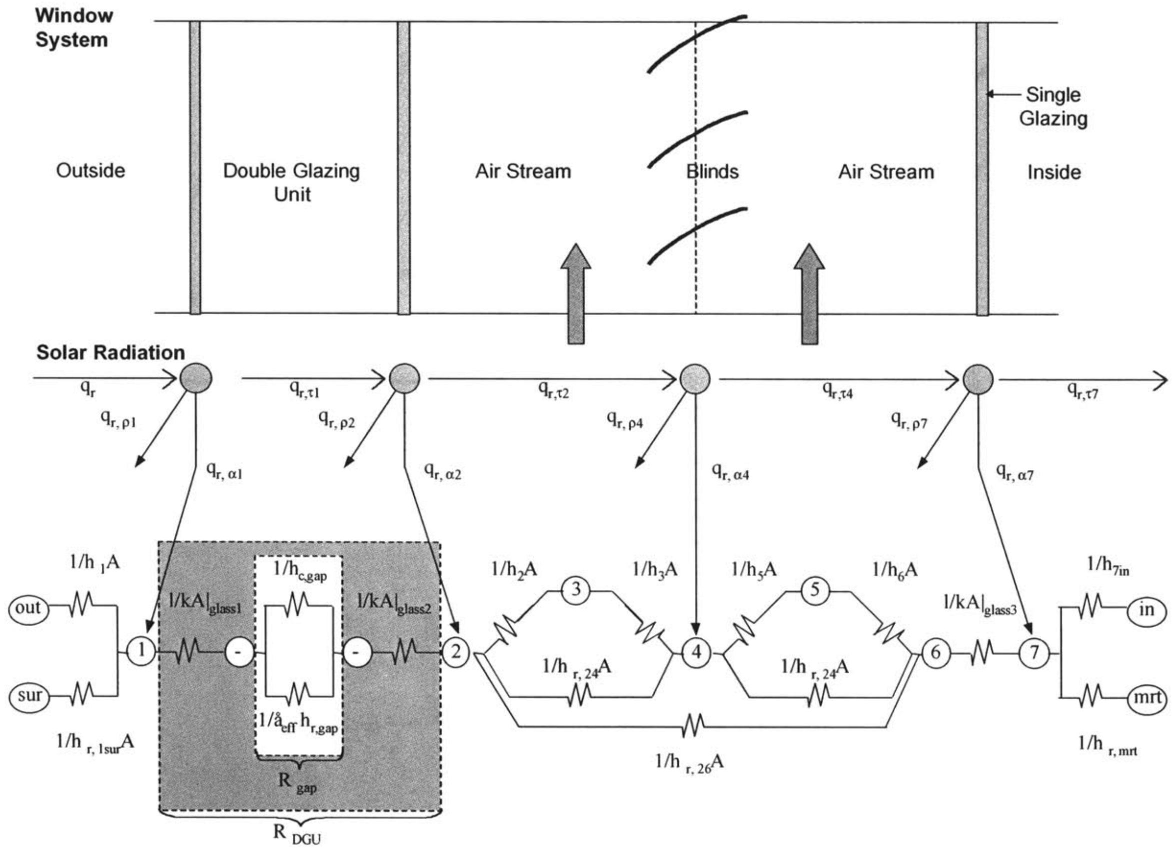


Figure 29: Model convection, conduction and infrared radiation

4.2.4 Energy Balances for Horizontal Stations

It is assumed for simplicity that each node in the window is in steady state; the energy flow into and out of each node is equal and opposite. Under this condition, the temperature of each node is unchanging:

$$Q_{Net} = \sum UA\Delta T + Q_{Solar}A = 0 \quad \text{or} \quad Q_{Net} = \sum \frac{A\Delta T}{R} + Q_{Solar}A = 0$$

Balances are for a given horizontal section through the system. The secondary equations, (1a), (2a), (3a) etc incorporate coefficients Ai, Bi, Ci, Di and Ei as resistance coefficients. These are defined below. The units of each expression are [W].

For T_1:

(1) $$\frac{T_{sur}-T_1}{\frac{1}{h_{r_{1,sur}}A_{dy}}}+\frac{T_{out}-T_1}{\frac{1}{h_1A_{dy}}}+\frac{T_2-T_1}{R_{DGU}}+q_r\left[\alpha_{11}+\tau_{11}\rho_{21}\alpha_{12}+\tau_{11}\tau_{21}\rho_{4,tot-out}(1-F_{sol})\tau_{22}\alpha_{12}+\tau_{11}\tau_{21}F_{sol}^{\ 2}\rho_{31}\tau_{22}\alpha_{12}\right]A_{dy}=0$$

(1a) $$A_1(T_{sur}-T_1)+A_2(T_{out}-T_1)+A_3(T_2-T_1)+Q_{\alpha_1}=0$$

For T_2:

(2) $$\frac{T_1-T_2}{R_{DGU}}+\frac{T_3-T_2}{\frac{1}{h_2A_{dy}}}-Q_{IR_{2,others}}+q_r\tau_{11}\left[\alpha_{21}+\tau_{21}\rho_{4,tot-out}(1-Fsol)\alpha_{22}+\tau_{21}F_{sol}^2\rho_{31}\alpha_{22}\right]A_{dy}=0$$

(2a) $$A_3(T_1-T_2)+B_1(T_3-T_2)-Q_{IR_{2-others}}+Q_{\alpha_2}=0$$

For T_3:

(3) $$\frac{T_2-T_3}{\frac{1}{h_2A_{dy}}}+\frac{T_4-T_3}{\frac{1}{h_3A_{dy,blind}}}=\dot{m}_3c_p\frac{dT_3}{dy}\Delta y$$

(3a) $$B_1(T_2-T_3)+C_2(T_4-T_3)=\dot{m}_3c_p\frac{dT_3}{dy}\Delta y$$

For T_4:

(4) $$\frac{T_3-T_4}{\frac{1}{h_3A_{dy,blind}}}+\frac{T_5-T_4}{\frac{1}{h_5A_{dy,blind}}}-Q_{IR_{4-others}}+q_r\tau_{11}\tau_{21}\left[\alpha_{4,tot}(1-F_{sol})+\alpha_4F_{sol}(1-F_{sol})\rho_{31}\right]A_{dy}=0$$

(4a) $$C_2(T_3 - T_4) + C_3(T_5 - T_4) - Q_{IR_{4-others}} + Q_{\alpha_4} = 0$$

For T_5:

(5) $$\frac{T_4 - T_5}{\dfrac{1}{h_5 A_{dy,blind}}} + \frac{T_6 - T_5}{\dfrac{1}{h_6 A_{dy}}} = \dot{m}_5 c_p \frac{dT_5}{dy} \Delta y$$

(5a) $$C_3(T_4 - T_5) + D_1(T_6 - T_5) = \dot{m}_5 c_p \frac{dT_5}{dy} \Delta y$$

For T_6:

(6) $$\frac{T_5 - T_6}{\dfrac{1}{h_6 A_{dy}}} + \frac{T_7 - T_6}{\dfrac{l}{kA_{dy}\Big|_{glass3}}} - Q_{IR_{6-others}} = 0$$

(6a) $$D_1(T_5 - T_6) + D_2(T_7 - T) - Q_{IR_{6-others}} = 0$$

For T_7:

(7) $$\frac{T_{mrt} - T_7}{\dfrac{1}{h_{r_{7in}} A_{dy}}} + \frac{T_6 - T_7}{\dfrac{l}{kA_{dy}\Big|_{glass3}}} + \frac{T_{in,air} - T_7}{\dfrac{1}{h_7 A_{dy}}} + q_r \tau_{11} \tau_{21} \alpha_{31} \left[F_{sol} + (1 - F_{sol})(\rho_{4,tot-in})\right] A_{dy} = 0$$

(7a) $$E_1(T_{mrt} - T_7) + D_2(T_6 - T_7) + E_2(T_{in,air} - T_7) + Q_{\alpha_3} = 0$$

Solving for the temperatures at the indicated locations gives T in [°C]:

(8) $$T_1 = \frac{A_1 T_{sur} + A_2 T_{out} + A_3 T_2 + Q_{\alpha_1}}{A_1 + A_2 + A_3}$$ [°C]

(9) $$T_2 = \frac{A_3 T_1 + B_1 T_3 - Q_{IR_{2-others}} + Q_{\alpha_2}}{A_3 + B_1}$$

(10) $$T_4 = \frac{C_2 T_3 + C_3 T_5 - Q_{IR_{4-others}} + Q_{\alpha_4}}{C_2 + C_3}$$

(11) $$T_6 = \frac{D_1 T_5 + D_2 T_7 \ - Q_{IR_{6-others}}}{D_1 + D_2}$$

(12) $$T_7 = \frac{D_2 T_6 + E_1 T_{mrt} + E_2 T_{in} + Q_{\alpha_7}}{D_2 + E_1 + E_2}$$

The coefficients are defined in the following manner. For definitions of Q_{α_i}, see "Solar Radiation Calculations" below:

$A_1 = h_{r_{1sur}} A_{dy}$

$A_2 = h_1 A_{dy}$

$A_3 = 1/R_{DGU}$ [w/K]

$B_1 = h_2 A_{dy}$

$B_2 = unused$

$B_3 = unused$

$C_1 = unused$

$C_2 = h_3 A_{dy,blind}$

$C_3 = h_5 \ A_{dy,blind}$

$D_1 = h_6 A_{dy}$

$D_2 = \left.\frac{kA_{dy}}{l}\right|_{glass3}$

$E_1 = h_{r_{7in}} A_{dy}$

$E_2 = h_7 A_{dy}$

We may assume that the total mass flow through the window system is equal to the sum of the flow through the channel on each side of the blind. $\dot{m}_{Total} = \dot{m}_3 + \dot{m}_5$ (The flows are $p\dot{m}_3$ and $(1-p)\dot{m}_5$ where $0 \le p \le 1$). This model assumes that there is no mass transfer between the channels. This is probably not actually the case, but the generalization holds for cases where the temperature difference between the channels is relatively small: $\frac{\dot{m}_3}{\dot{m}_5} \approx 1$

To understand how the temperature of the air changes as it rises (falls) through the channel, let Δy be the step-size of vertical increments (horizontal slices) through the window. The model will divide the height of the window into 10 equal slices. Then the energy balance indicated in equation (3) above may be solved for $\frac{dT_3}{dy}$.

(13) $$\frac{dT_3}{dy} = \left(\frac{T_2 - T_3}{\frac{1}{h_2 A_{dy}}} + \frac{T_4 - T_3}{\frac{1}{h_3 A_{dy}}} \right) \frac{1}{\dot{m}_3 c_p \Delta y}$$ or from (3a), [°C/m]

(13a) $$\frac{dT_3}{dy} = \frac{B_1(T_1 - T_3) \_ C_2(T_4 - T_3)}{\dot{m}_3 c_p \Delta y}$$

Similarly, solve equation (5) for $\frac{dT_3}{dy}$.

(14) $$\frac{dT_5}{dy} = \left(\frac{T_4 - T_5}{\frac{1}{h_5 A_{dy}}} + \frac{T_6 - T_5}{\frac{1}{h_6 A_{dy}}} \right) \frac{1}{\dot{m}_5 c_p \Delta y}$$

(14a) $$\frac{dT_5}{dy} = \frac{C_3(T_4 - T_5) + D_1(T_6 - T_5)}{\dot{m}_5 c_p \Delta y}$$

This will give the change per incremental vertical step as the air moves up through the cavity. The solution for $\frac{dT_{3,5}}{dy}$ will give the temperatures at locations 3 and 5 at elevation $y+\Delta y$.

(15) $$T_3\big|_{y+\Delta y} = T_3\big|_y + \frac{dT_3}{dy}\bigg|_y \Delta y \text{ and } T_5\big|_{y+\Delta y} = T_5\big|_y + \frac{dT_5}{dy}\bigg|_y \Delta y$$ [°C]

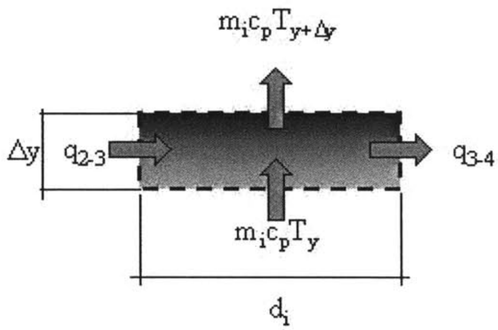


Figure 30 Energy balance for cavity airflow

Equations (6), (7) and (8) can then be used to find temperatures at locations 2, 4 and 6 at $y+\Delta y$.

Special low or no flow condition:

In order to evaluate steady state conditions when the mass flow, $\dot{m}$ is very low, the mass flow must drop out of the balance. In this case equation (3) becomes:

For T_3:

(16) $$\frac{T_2 - T_3}{\frac{1}{h_2 A_{dy}}} + \frac{T_4 - T_3}{\frac{1}{h_3 A_{dy,blind}}} = 0 \Rightarrow T_3 = \frac{B_1 T_2 + C_2 T_4}{B_1 + C_2}$$

and equation (5) becomes

For T_5:

(17) $$\frac{T_4 - T_5}{\dfrac{1}{h_5 A_{dy,blind}}} + \frac{T_6 - T_5}{\dfrac{1}{h_6 A_{dy}}} = 0 \Rightarrow T_5 = \frac{D_1 T_6 + C_3 T_4}{D_1 + C_3}$$

The area of the blind per horizontal section, $A_{dy,blind}$ is defined as:

$$A_{dy,blind} = (l_{blind} w)\frac{dy}{H}\frac{H}{S_{blind}} = (l_{blind} w)\frac{dy}{S_{blind}}$$

The area per horizontal section is:

$$A_{dy} = wdy$$

The area of the window is simply:

$$A = wH$$

The terms for this equation are defined in the glossary of terms.

4.2.5 Exterior and Interior Convection and Radiation

Heat transfer coefficients can be calculated. Calculation of the exterior heat from Newton's Law of Cooling :

$\dot{q}_c = h_{1out}(T_{out,air} - T_1)$ for the convection and

$q_{rad} = h_{r_{1sur}}(T_s - T_{sur})$ for the radiation, with

T_s = Temperature of the surface. In this case T_1.

$$h = h_{eff} = \frac{1}{\dfrac{1}{h_{1out}} + \dfrac{1}{h_{r1sur}}}$$

where h_{1out} must be assumed from a wide range of possible values dependant on air speed. ASHRAE F27.3 and F2.3 give convective s at standard temperature and air velocity conditions. The standard value of 29 W/(m^2 K) corresponding to a 24 km/h [6.67m/s]wind speed for *winter* conditions and 22.7 W/(m^2 K) corresponding to a 12 km/h [3.4m/s] wind speed for *summer* conditions. See Figure 31 below from ASHRAE F22 for a range of conditions and surface conductance.

$h_r = \varepsilon\sigma(T_s + T_{sur})(T_s^2 + T_{sur}^2)$ gives the radiative heat transfer coefficient where,

$\varepsilon =$ the emissivity of the surface. For glass, use 0.90.

$\sigma =$ the Stefan-Boltzmann constant, 0.1713x10^{-8} Btu/(hr ft^2 R^4) or 5.673x10^{-8} W/(m^2 K^4)

$T_{sur} =$ the temperature of the surroundings is assumed to be the outside temperature

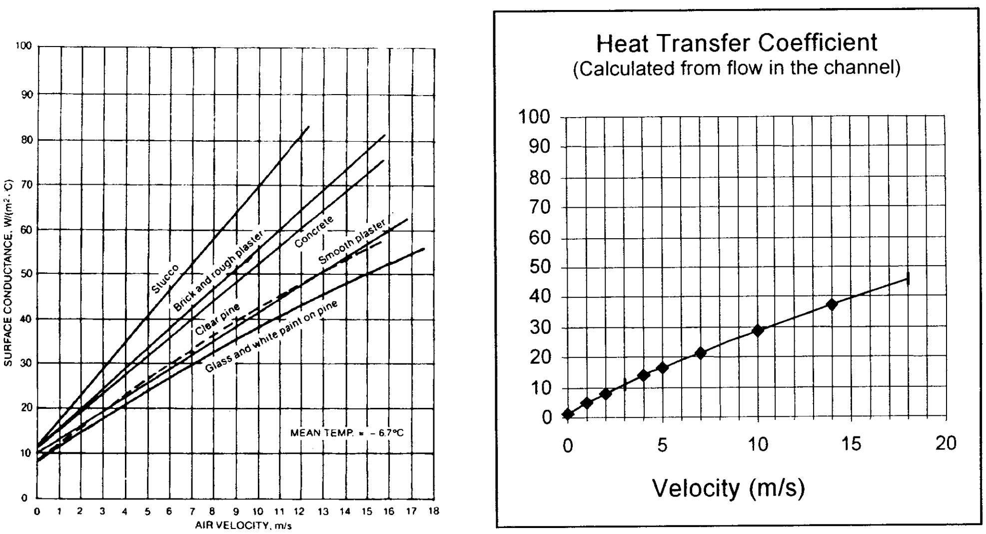


Figure 31 Surface conductance for surfaces with air movement

4.2.6 Heat Transfer within the Double Glazing

The calculation of convective, conductive and radiative properties of the cavity within the double glazing unit, can be simplified by using ASHRAE F22.2, table 2, "Thermal Resistances of Plane Air Spaces" for large air spaces greater than 13 mm in width, or by using the following equation for thinner spaces.

R_{gap}=1/C and $C = h_c\big|_{gap} + \varepsilon_{eff} h_r\big|_{gap}$

$\varepsilon_{eff} h_r \big|_{gap} \cong 0.227\varepsilon_{eff}[(T_{m_{12}} + 273)/100]^3$ For y=0 use $T_{m_{out3}}$ where $T_{m_{12}} = \frac{T_1 + T_2}{2}$

$h_c \big|_{gap} = 21.8(1 + 0.00274 T_{m_{12}})/d_0$ where

$h_c \big|_{gap} =$ heat transfer through the air space only (excluding glass) [W/(m^2 K)]

$t_m =$ mean temperature of the air space

$d_0 =$ air space thickness [mm] in the 'x' direction.

$$1/\varepsilon_{eff} = 1/\varepsilon_{12} + 1/\varepsilon_{21} - 1$$

$\varepsilon_{12}, \varepsilon_{22} =$ emittances of the surfaces of the air spaces (in this case, the inner and outer panes of glass).

For the inner pane of glass, $h_6 = h_{in}$ the inside heat transfer coefficient. This is given in ASHRAE F22.1 Table 1 as $h_i = 8.29 W/(m^2 K)$ for a vertical plane with horizontal heat flow and "non-reflective" surface of $\varepsilon = 0.90$.

The total resistance from the outside to the inside of the double glazing unit is given by (see Figure 29 above for the electrical circuit analogy):

$$R_{DGU} = \sum R_{12} = \left(\frac{l}{kA_{dy}}\right)_{glass1} + R_{gap} + \left(\frac{l}{kA_{dy}}\right)_{glass2}$$

4.2.7 Convective Heat Transfer within the Airflow Cavity

Consider the sides of the cavity as internal flow in a duct. The correlations for h_2 and h_6, the convective heat transfer coefficients on the cavity side of the inner and outer glazing and the blinds are based on $\dot{m}$, the mass flow rate [kg/s-meter of length] and hence the velocity along the surfaces. This method uses the correlation for forced internal flow with uniform heat flux and infinite length. Additional models for h_c are considered in the following section. The model currently assumes that buoyancy effects are , and could benefit from checking the heat transfer coefficient of natural convction to evaluate it's relative effect.Mo calculations for buoyance are shown in Section 4.2.12 below.

$\upsilon_i = \dot{m}_i / (\rho_{air} \cdot d_i)$ or with $\dot{m}_3 = \dot{m}_5$, $\upsilon = \dot{m}_{3+5} / [\rho_{air} \cdot (d_1 + d_2)]$ with

$\upsilon_i =$ air velocity [m/s].

$\rho =$ air density [kg/m^3].

$d_i =$ width of the given cavity[m] (assume 1m of depth along the cavity).

Transition to turbulence occurs at

$$\mathrm{Re}_x = u_e x / v \approx 2{,}800$$

$$\mathrm{Re}_{D_H} = \frac{u_e D_H}{\upsilon}$$

$$u_e = \frac{\dot{m}}{\rho d_i w} = \frac{\dot{m}}{\rho A_{cs}}$$

$u_e =$ free-stream velocity

$v =$ viscosity

$x =$ distance along the plate

$A_{cs} = d_i w$ area in cross section to flow

$D_H = 4\frac{A_{cs}}{P}$ hydraulic diameter with perimeter, $P = 2w$ for cavity flow.

$\mathrm{Pr} = \frac{c_p \mu}{k} = \frac{v}{\alpha} \approx 0.69$ This could be a table lookup value, but assuming constant Prandtl number will not lead to significant error.

For laminar flow:

(18) $$\overline{Nu}_{D_h} = 8.235 + \frac{0.03(D_h/L)\mathrm{Re}_{D_h}\mathrm{Pr}}{1+0.016\left[(D_h/L)\mathrm{Re}_{D_h}\mathrm{Pr}\right]^{2/3}}$$; Pr > 0.5 Mills (4.51) [Mills 1995 p.240]

For turbulent flow:

(19) $$f = \left(0.790\ln\mathrm{Re}_{D_h} - 1.64\right)^{-2} \qquad 10^4 < \mathrm{Re}_{D_h} < 5x10^6$$

(20) $$\overline{Nu}_{D_h} = \frac{(f/8)\left(\mathrm{Re}_{D_h} - 1000\right)\mathrm{Pr}}{1+12.7(f/8)^{1/2}\left(\mathrm{Pr}^{2/3}-1\right)};$$ $3000 < \mathrm{Re}_{D_h} < 10^6$ [Mills 4.45]

(21) $$\overline{Nu}_{D_h} = \frac{hD_h}{k} \Rightarrow h = \frac{k\overline{Nu}_{D_h}}{D_h}$$ [Mills 4.83]

This version of the model does not include effects of entry length on the heat transfer coefficients within the cavity.

4.2.7a ALTERNATE HEAT TRANSFER MODELS

Flow over a flat plate

Rather than modeling the flow as a long smooth duct, the flow along the blinds may be considered as external flow over a flat plate. This model implies that the boundary along the blinds is restarted at the leading edge of each blind. When the blinds are closed, but are loose fitting, they will tend to fit this model.

It is assumed that the length of the blinds is relatively short, and that due to their high conductivity they are nominally isothermal. Mills gives the correlation for the average Nusselt number as

(22) $$\overline{Nu} = \frac{\overline{h_c}L_{blind}}{k_{air}} = 0.664\,\mathrm{Re}_L^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}}$$ Pr>0.5 [Mills 4.57]

(23) Solving for $\overline{h_c}$:

(24) $$\overline{h_c} = \frac{k}{L_{blind}} 0.664 \mathrm{Re}_L^{\frac{1}{2}} \mathrm{Pr}^{\frac{1}{3}} = \frac{k}{L_{blind}} 0.664 \left(\frac{vL_{blind}}{\upsilon} \right)^{\frac{1}{2}} \mathrm{Pr}^{\frac{1}{3}}$$ Re<5x10^5

Flow perpendicular to an object

Another model that may apply to the flow in the cavity is external flow perpendicular to an object. The blinds can be considered as a cylinder lying along the length of the façade (perpendicular to the typical wall section). By considering the length of the blind as the diameter of the cylinder, the model may be approximated. This is most applicable when the blinds are horizontal ($\Sigma = 0$). Mills provides the following correlations for the Nusselt number:

(25) $$\overline{Nu_D} = \frac{\overline{h_c} L_{blind}}{k_{air}} = 0.3 + \frac{0.62 \mathrm{Re}_L^{\frac{1}{2}} \mathrm{Pr}^{\frac{1}{3}}}{\left[1 + \left(0.4/\mathrm{Pr}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}}$$ Re<10^4 [Mills 4.71a]

(26) $$\overline{Nu_D} = \frac{\overline{h_c} L_{blind}}{k_{air}} = 0.3 + \frac{0.62 \mathrm{Re}_L^{\frac{1}{2}} \mathrm{Pr}^{\frac{1}{3}}}{\left[1 + \left(0.4/\mathrm{Pr}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}} \left[1 + \left(\frac{\mathrm{Re}_L}{282{,}000}\right)^{\frac{1}{2}}\right]$$ 2x10^4<Re<4x10^5 [Mills 4.71b]

(27) $$\overline{Nu_D} = \frac{\overline{h_c} L_{blind}}{k_{air}} = 0.3 + \frac{0.62 \mathrm{Re}_L^{\frac{1}{2}} \mathrm{Pr}^{\frac{1}{3}}}{\left[1 + \left(0.4/\mathrm{Pr}\right)^{\frac{2}{3}}\right]^{\frac{1}{4}}} \left[1 + \left(\frac{\mathrm{Re}_L}{282{,}000}\right)^{\frac{5}{8}}\right]^{4/5}$$ 4x10^5<Re<5x10^6 [Mills 4.71b]

The heat transfer coefficients for each of these may be found: $\overline{Nu_{D_h}} = \frac{hD_h}{k} \Rightarrow \overline{h} = \frac{k\overline{Nu_L}}{L_h}$.

Comparison of cavity heat transfer coefficients

The actual heat transfer coefficient along blinds has not been determined experimentally. However the impact of the alternative cavity flow models may be examined to determine the potential variation in window performance.

Four heat transfer models are considered:

- Flow through a *cavity* with smooth sides: $h = \frac{k}{NuD_h}$
- Flow over a *flat plate* with the length of plate equal to the width of a single blind: $$h = \frac{k}{L_{blind}} 0.644 \left(\frac{L_{blind} v}{\nu} \right)^{1/2} \Pr^{1/3}$$
- Flow over a *cylinder* lying perpendicular to the direction of flow: $$h = 0.3 + 0.62 \frac{\left(\frac{L_{blind} v}{\nu} \right)^{1/2} \Pr^{1/3}}{\left[1 + \left(\frac{0.4}{\Pr} \right)^{2/3} \right]^{1/4}}$$
- *Hens'* heat transfer coefficient: $h = 5.8 + 4v$

The following figure shows the variation of the heat transfer coefficient with velocity. The differences are not as dramatic with low velocities as they are with high velocities. Volumetric flow rates advertised by manufacturers are in the range of 20 ~ 40 m^2/hm and due to geometry relates to the range of 0.02 ~ 0.2 m/s. In practice these differences may be quite significant. On-site measurements [Arons 1999] indicate that actual face velocities at the inlet to DSF forced convection cavities may be in the range of 1~1.5 m/s. At this velocity, the difference in heat transfer coefficients covers a range with 500% variance between the lowest and highest model predictions.

The effect of the heat transfer coefficient on U-Value and SHGC may be seen in the comparisons below (A typical window with one low-E coating, blinds closed and winter conditions for the night time U-Value and summer conditions with 500 W/ m^2 solar radiation for the SHGC calculation is used in the model). Most notable is the under prediction of values by the cavity flow method. The other three models are reasonably close in the low velocity range.

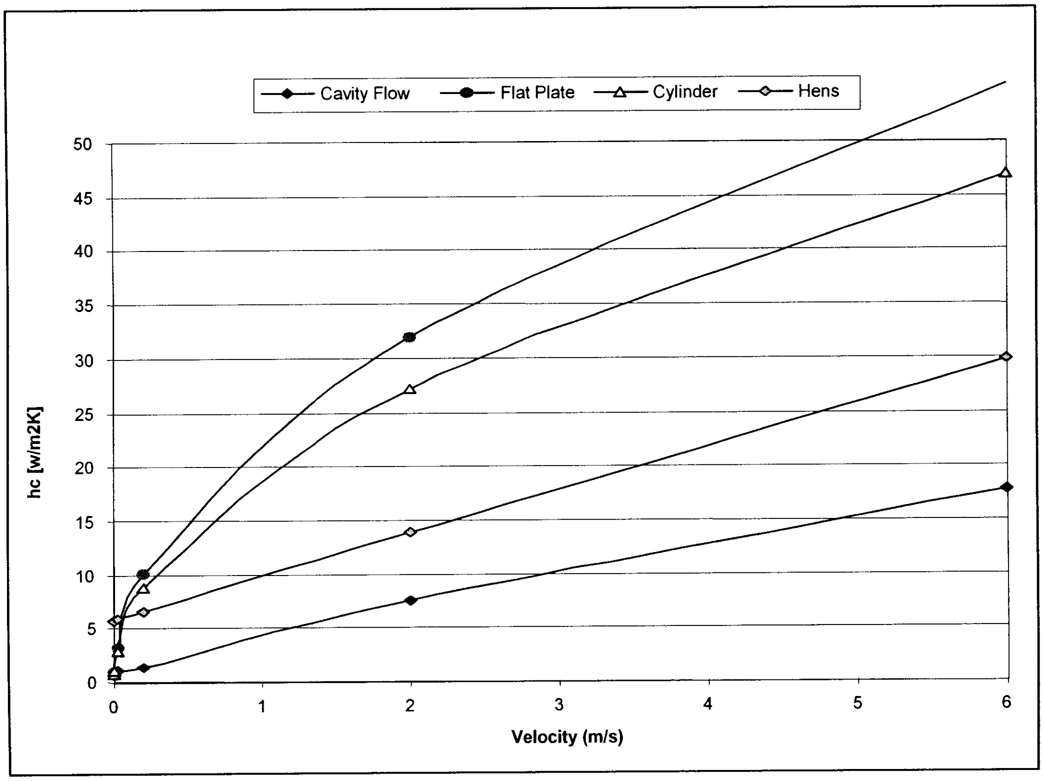


Figure 32 Comparison of Heat Transfer Models Airflow over Blinds

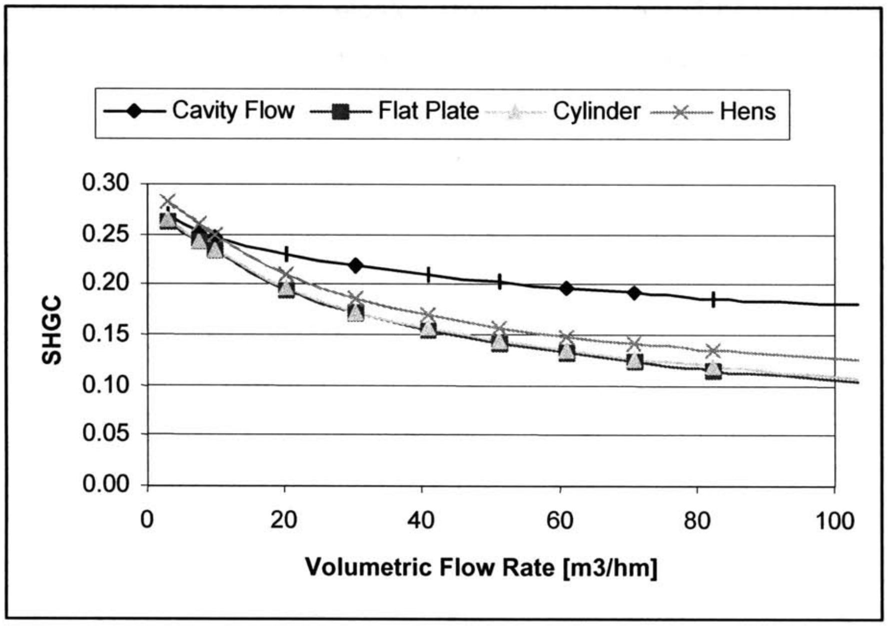


Figure 33 Heat transfer coefficient model effects on SHGC

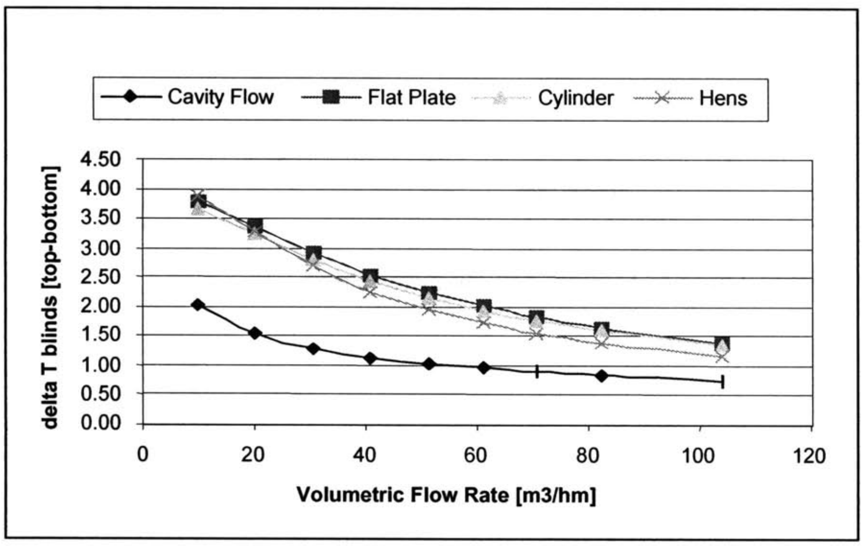


Figure 34 Heat transfer coefficient models and blind temperature

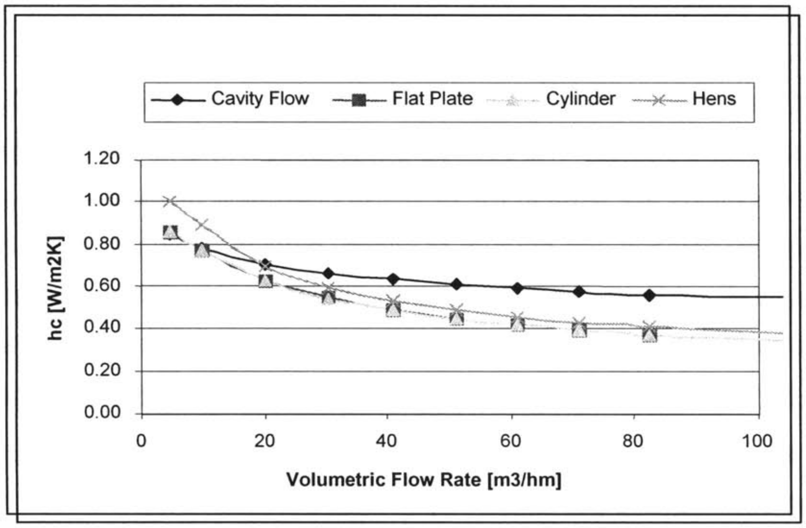


Figure 35 Heat transfer coefficient models and U-value

4.2.8 Solar Radiation Calculations

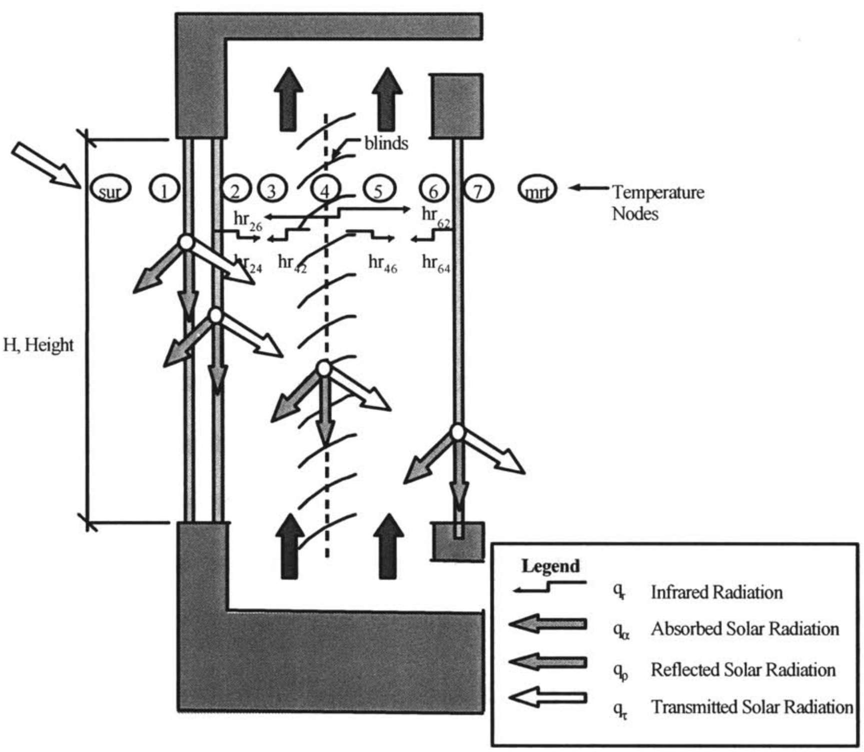


Figure 36 Solar and infrared radiation models

Solar and infrared radiations are considered separately. The solar radiation is addressed in this section, and infrared is considered below. The transparency, reflectivity and absorptivity of each layer of glazing and the blinds are used in the model to determine three properties of the window system; the energy balance, the amount of energy evacuated by the air as it moves through the cavities, and, perhaps most importantly, the amount of energy that passes through the inner pane of glass and into the occupied space. The solar radiation coefficients, Q_i, that appear in the energy balances for horizontal stations utilize the material properties to determine the distribution of energy at each layer. The coefficient represents the solar energy absorbed on each surface per unit area per vertical section (dy).

Assuming one bounce from adjacent surfaces, the solar radiation coefficients are defined:

(28) $$Q_{\alpha_1} = q_r\left[\alpha_{11} + \tau_{11}\rho_{21}\alpha_{12} + \tau_{11}\tau_{21}\rho_{4,tot-out}(1-F_{sol})\tau_{22}\alpha_{12} + \tau_{11}\tau_{21}F_{sol}{}^2\rho_{31}\tau_{22}\alpha_{12}\right]A_{dy}$$

(29) $$Q_{\alpha_2} = q_r\tau_{11}\left[\alpha_{21} + \tau_{21}\rho_{4,tot-out}(1-F_{sol})\alpha_{22} + \tau_{21}F_{sol}{}^2\rho_{31}\alpha_{22}\right]A_{dy}$$

(30) $$Q_{\alpha_4} = q_r\tau_{11}\tau_{21}\left[\alpha_{4,tot}(1-F_{sol}) + \alpha_4 F_{sol}(1-F_{sol})\rho_{31}\right]A_{dy}$$

(31) $$Q_{\alpha_7} = q_r\tau_{11}\tau_{21}\alpha_{31}\left[F_{sol} + (1-F_{sol})(\rho_{4,tot-in})\right]A_{dy}$$

where,

F_{sol} = the geometry factor for the blind that expresses the openness of the blinds relative to the sun angle. It is a number between 0 and 1. $F_{sol}=1$ implies that the blinds are completely transparent (open) to the sun, and $F_{sol}=0$ implies that the blinds are opaque (closed) to the sun's rays. The calculation of this geometry factor is explained below in Section 4.2.8b below

$(1-F_{sol})$ = is the geometry factor for the blind that expresses the fraction of the blinds that is struck by incoming sun light directly.

τ_{ij} = transmissivity of glass i through surface j where j is 1 is the front (outside) and j=2 is the back (inside)

α_{ij} = absorptivity of glass i through surface j where j is 1 is the front (outside) and j=2 is the back (inside)

ρ_{ij} = reflectivity of glass i through surface j where j=1 is the front (outside) and j=2 is the back (inside)

$\rho_{4,tot-out}$ = the fraction of energy that bounces off the blinds and is reflected back towards Glass 2 /surface 2(towards the outside).

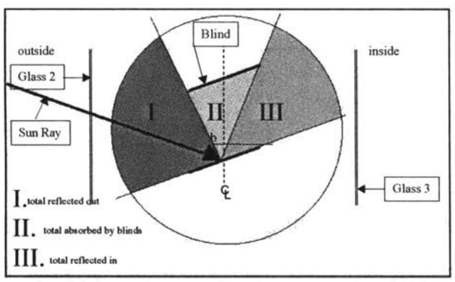


Figure 37 Reflection of sunrays between blinds

$\alpha_{4,tot}$ = the fraction of energy that initially strikes the blinds (in the area defined by $(1-F_{sol})$ and is either absorbed when it first strikes the blinds or is absorbed after bouncing off a blind and later absorbed by the neighboring blind.

$\rho_{4,tot-in}$ = the fraction of energy that bounces off the blinds and is reflected towards Glass 3 / surface 6 (towards the inside).

$\rho_{4,tot-out}$, $\alpha_{4,tot}$ and $\rho_{4,tot-in}$ are derived in the following section.

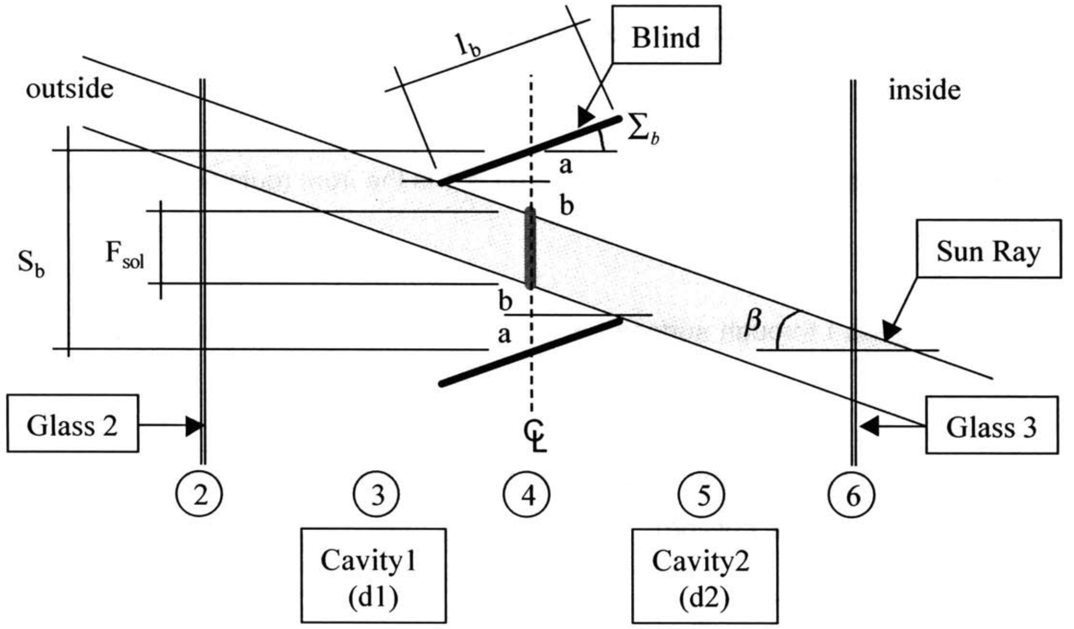


Figure 38 Direct solar radiation: Fsol Definition

4.2.8a Blind Geometry and Reflections

In the simplified model, there are four possible outcomes for the sunlight that hits the blinds. It may be reflected back out of the system, it may be reflected into the occupied space, it may be reflected onto another blind or the blinds may absorb it. The reflected portion is divided into specular reflections and diffuse reflections. The total reflectivity of the blind material ρ_4 may be assigned a certain percentage of specular ρ_s versus diffuse ρ_d components, such that $\rho_4 = \rho_{4s} + \rho_{4d}$.

The total energy reflected off the blinds in the outward direction is then the sum of the specular and diffuse portions:

(32) $$\rho_{4,tot-out} = \rho_{4s,tot-out} + \rho_{4d,tot-out} \Rightarrow$$

(33) $$\rho_{4,tot-out} = \rho_{4s} \sum_{R1}^{R4} \tfrac{1}{4}[lit,out] + \left[\rho_{4d}\left(F_{4_L 2}\right) + \rho_{4d}\left(F_{44}\right)\rho_4\left(F_{4_U 2}\right)\right]$$

For the specular condition, sunlight is considered in four rays landing at the center of four segments of the blind if it is divided from front to back.

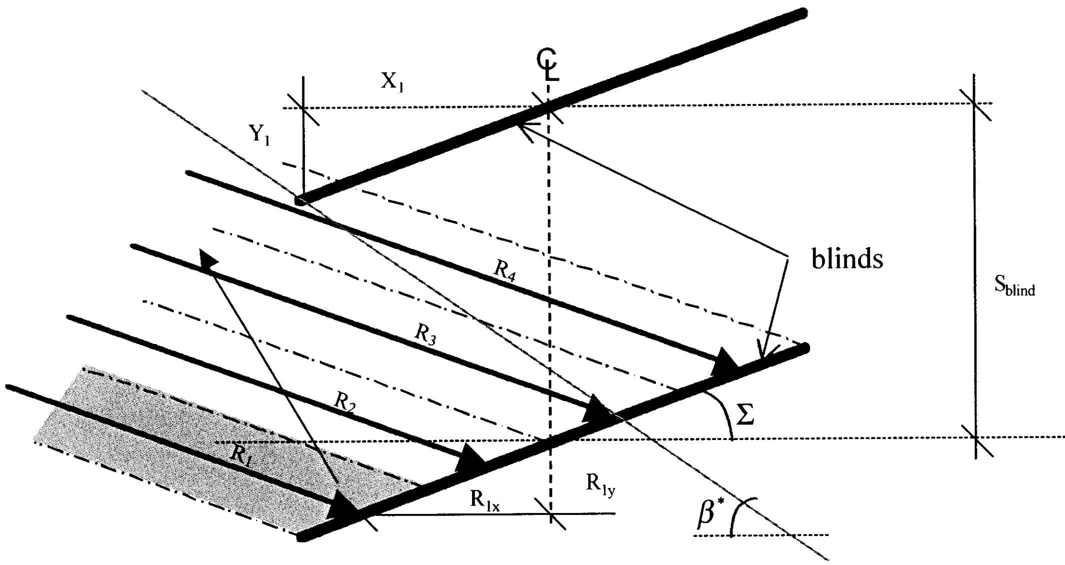


Figure 39 Division of blind into 4 "rays"

The disposition of this ray is then assigned as the average result for that quarter of the blind. The total factor of rays meeting given criteria (indicated in the summation in the equation above) will be rounded to 0, 0.25, 0.50, 0.75 or 1.00 -- see Figure 39 above. Two criteria must be met for the sunlight to impact the portion of the light that is reflected out from the blind. First, it must be lit by the sun (not shaded by a neighboring blind) and second, it must reflect the light in the outwards (-x) direction. If it meets both of these criteria, then the associated 25% of the light hitting the blind is added to the outward reflected energy. The four rays, R1 through R4 are indicated. The shaded area around R1 relates to the blind area that is assigned with the same outcome as the point at the end of ray R1. In the diagram β^* is the critical solar azimuth angle for which Ray 3 (R3) would be "lit". If the actual solar azimuth, β, is less than or equal to β^*, then point R3 will be "lit", but at greater angles, R3 will be shaded, or "unlit".

The total solar energy absorbed by the blinds is a combination of that energy absorbed when sunlight initially hits the blinds, and the light that is absorbed from diffuse or specular reflection from neighboring blinds. Additional energy is absorbed from reflections from other surfaces (glass).

(34) $\alpha_{4,tot} = \alpha_{4s} + \alpha_{4d} + \alpha_4 \Rightarrow$

$$(35)\quad \alpha_{4,tot} = \left[\rho_{4s} \sum_{R1}^{R4} \tfrac{1}{4} [lit, hit] \left(\alpha_4 + \rho_4 \sum \tfrac{1}{4} [hit_{hit}] (\alpha_4 + \tfrac{1}{2} \rho_4) \right) \right] + [\rho_{4d} (F_{44}) (\alpha_4 + \rho_4 (F_{44}) \alpha_4)] + \alpha_4$$

The total solar energy that passes through the blinds is a combination of the energy that passes directly through and that energy that bounces through the blinds, either by diffuse or specular reflections. The direct solar portion that doesn't bounce through is simply associated with F_{sol}, and the bounced portion is associated with $1 - F_{sol}$. For the bounced portion, a factor is defined as

$$(36)\quad \rho_{4,tot-in} = \rho_{4s,tot-in} + \rho_{4d,tot-in} \Rightarrow$$

$$(37)\quad \rho_{4,tot-in} = \rho_{4s} \left[\sum_{R1}^{R4} \tfrac{1}{4} [lit, in] + \sum_{R1}^{R4} \tfrac{1}{4} [lit, hit] \rho_4 \sum_{R1}^{R4} \tfrac{1}{4} [hit_{in}] \right] + \rho_{4d} \left[F_{4_L 3} + F_{44} \rho_4 F_{4_U 3} + F_{44} \rho_4 F_{4_L 6} \right]$$

The simplifications in this model include:

- The second bounce of light (that which reflects off the blind and "hits" the neighboring blind) is assumed to travel either to the inside or back to the first blind. Beyond the second "bounce", reflected light is not accounted for in this model. This may have significant impact on the results only when the incident angle of the sun and the blinds is slightly greater than 90 degrees.

- Diffuse reflections that "hit" the second blind are either absorbed or reflected in. This indicates a limitation that the blind angle is between 0 and 90, and the solar angle must also be between 0 and 90. They are not re-reflected to the originating blind.

- For surfaces 1 and 2 (glass), only two segments of reflected light are considered: light which bounces off the blinds directly, and light which passes through the blinds in both directions without hitting any blind. Light that bounces off the blinds once or more times before striking the glass and being reflected back through the blinds (possibly bouncing again) is not considered. Given the small percentage of light that is reflected off the third layer of glass, this will not cause problems unless the inner glass is highly reflective.

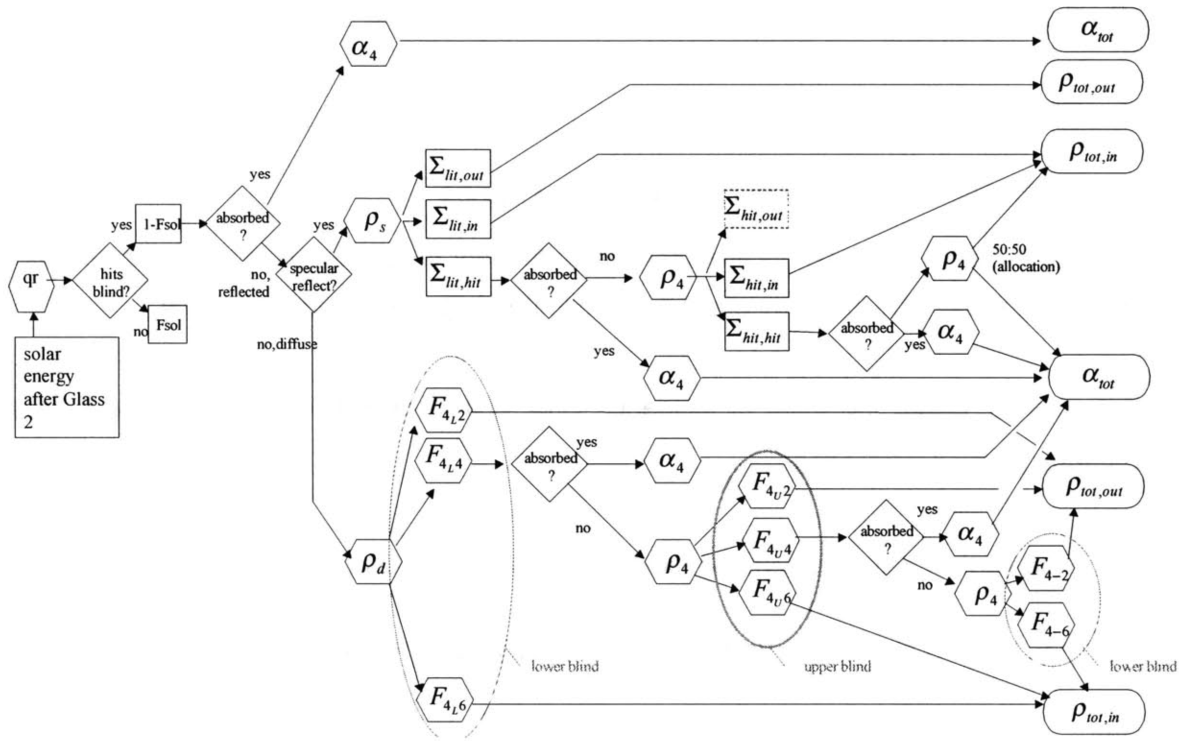


Figure 40 Direct solar radiation distribution

4.2.8b SOLAR RADIATION VIEW FACTOR, F_{SOL}

F_{sol} is a dimensionless number representing the open-ness of the blind to solar radiation based on geometry. No intra-blind reflections are thus far considered. As stated above, F_{sol}=1 indicates that the blinds are transparent to solar energy, F_{sol}=0 indicates that the blinds are opaque to solar radiation

(38) $F_{sol} = \dfrac{S_b - 2(a+b)}{S_b}$ given from the geometry that

$a = \dfrac{l_b}{2}\sin\Sigma_b$ $\qquad b = c\tan\beta$ $\qquad c = \dfrac{l_b}{2}\cos\Sigma_b$

with Σ_b = the angle of rotation of the blind, and

β = the solar azimuth, and

S_b = spacing between blinds in meters.

4.2.8c SPECULAR SOLAR REFLECTIONS FROM BLINDS

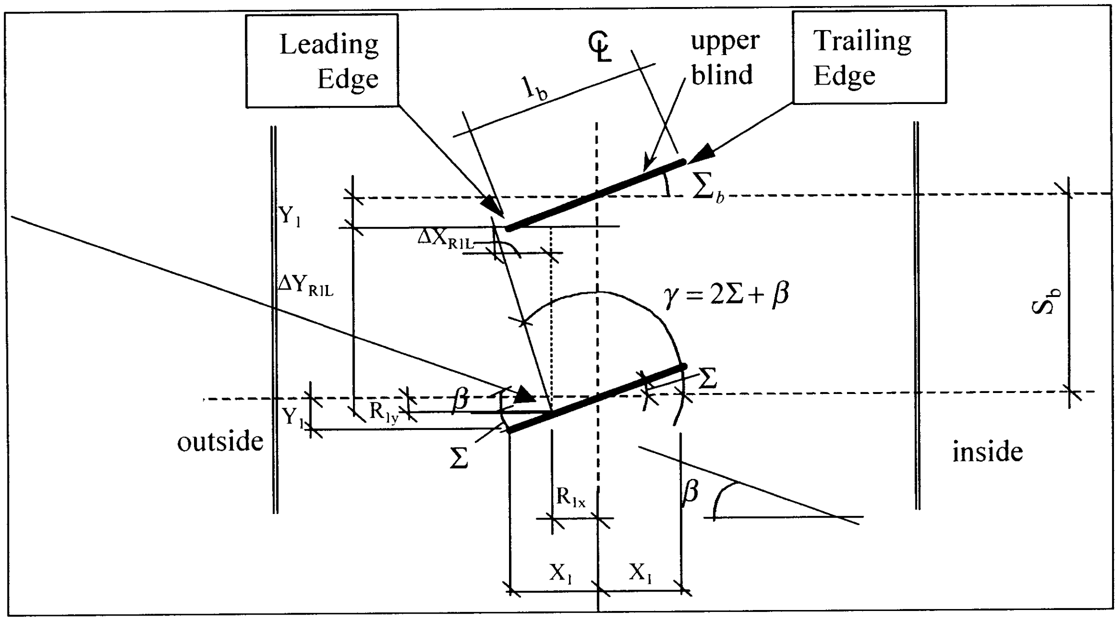
Some geometric relationships are useful in sorting out the pathways of specular reflections from the blinds. The following are illustrated in the diagram (Figure 41) below.

R_{1y} and R_{1x} locate the point of incidence ("ray point") by x and y coordinates from the centroid of the (lower) blind.

R_{1y} = the vertical distance from the blind centerline to the Ray1 intercept. R_{iy} are similar.

R_{1x} = the horizontal distance from the blind centerline and the Ray1 intercept. R_{ix} are similar.

(39) $R_{1y} = R_{4y} = \frac{3}{8} l_b \sin \Sigma$ and $R_{2y} = R_{3y} = \frac{1}{8} l_b \sin \Sigma$



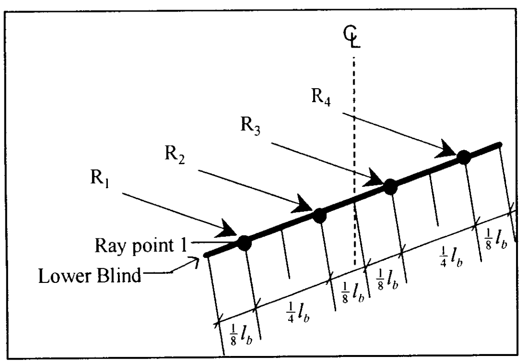


Figure 41 Blind geometry for direct solar "rays"

(40) $R_{1x} = R_{4x} = \frac{3}{8} l_b \cos\Sigma$ and $R_{2y} = R_{3y} = \frac{1}{8} l_b \cos\Sigma$

$\gamma =$ the angle of the reflection relative to the horizontal. $\gamma = 2\Sigma + \beta$

For the leading edge of the upper blind:

For $180 < \gamma$ all light bounces out.

For $90 < \gamma < 180$, the leading edge of the upper blind must be checked to see to which side the ray bounces. It can either bounce out (toward glass 2 or "hit" the blind).

For $0 < \gamma < 90$ light either hits or bounces in (it can not bounce out if the blind angle and sun azimuth are within the limits of the model).

The coordinates of the travel distance from the ray point to the vertical elevation of the leading edge of the upper blind are:

$\Delta y_{R1,L} =$ the vertical "travel distance" and $\Delta X_{R1,L}$ the horizontal "travel distance".

(41) $\Delta y_{R1,L} = S_b + R_{1y} - y_1$ and $\Delta y_{R2,L} = S_b + R_{2y} - y_1$ while

(42) $\Delta y_{R3,L} = S_b - R_{4y} - y_1$ and $\Delta y_{R4,L} = S_b - R_{4y} - y_1$

(43) $\Delta x_{R1,L} = \Delta y_{R1,L} \tan(\gamma - 90)$ and for the other points, $\Delta x_{Ri,L} = \Delta y_{Ri,L} \tan(\gamma - 90)$

For the trailing edge of the upper blind:

$\Delta y_{R1,T} =$ the vertical "travel distance" and $\Delta X_{R1,T}$ the horizontal "travel distance".

(44) $\Delta y_{R1,T} = S_b + R_{1y} + y_1$ and $\Delta y_{R2,T} = S_b + R_{2y} + y_1$ while

(45) $\Delta y_{R3,T} = S_b - R_{4y} + y_1$ and $\Delta y_{R4,T} = S_b - R_{4y} + y_1$

(46) $\Delta x_{R1,T} = \dfrac{\Delta y_{R1,T}}{\tan \gamma}$ and for the other points, $\Delta x_{Ri,T} = \dfrac{\Delta y_{Ri,T}}{\tan \gamma}$

To determine the direction that each ray bounces:

For $180 < \gamma$, all light bounces out.

For $90 < \gamma < 180$, there are two conditions:

For both R_1 (shown) and R_2 (implied) :

(47) $\Delta X_{R1,L} + R_{1x} > X_1 \Rightarrow "out"$ and $\Delta X_{R1,L} + R_{1x} < X_1 \Rightarrow "hit"$

(48) For both R_3 and R_4 $\Delta X_{R3,L} - R_{3x} > X_1 \Rightarrow "out"$ and $\Delta X_{R3,L} - R_{3x} > X_1 \Rightarrow "hit"$

For $0 < \gamma < 90$, there are also two conditions:

For both R_1 and R_2

(49) $\Delta X_{R1,T} > R_{1x} + X_1 \Rightarrow "in"$ and $\Delta X_{R1,T} < R_{1x} + X_1 \Rightarrow "hit"$

(50) For both R_3 and R_4 $\Delta X_{R3,T} > X_1 - R_{3x} \Rightarrow "in"$ and $\Delta X_{R3,T} < X_1 - R_{3x} \Rightarrow "hit"$

To determine if light reaches the each ray point:

Each ray point may be shadowed by the blind above. If light reaches the blind, it is considered "lit", otherwise, it is "unlit". The conditions to consider are:

For $0 < \beta < 90$:

(51) $\tan\beta \le \dfrac{\Delta y_{R1,L}}{X_1 - R_{1x}} \Rightarrow "lit"$ and if $\tan\beta > \dfrac{\Delta y_{R1,L}}{X_1 - R_{1x}} \Rightarrow "unlit"$ for R_1 and R_2

(52) $\tan\beta \le \dfrac{\Delta y_{R3,L}}{X_1 + R_{1x}} \Rightarrow "lit"$ and if $\tan\beta > \dfrac{\Delta y_{R3,L}}{X_1 + R_{1x}} \Rightarrow "unlit"$ for R_3 and R_4,

For $90 < \beta \Rightarrow "unlit"$ for all R_i

$\beta < 0$ is not considered by this model.

For secondary reflections off the bottom of the upper blind, consider the following diagram :

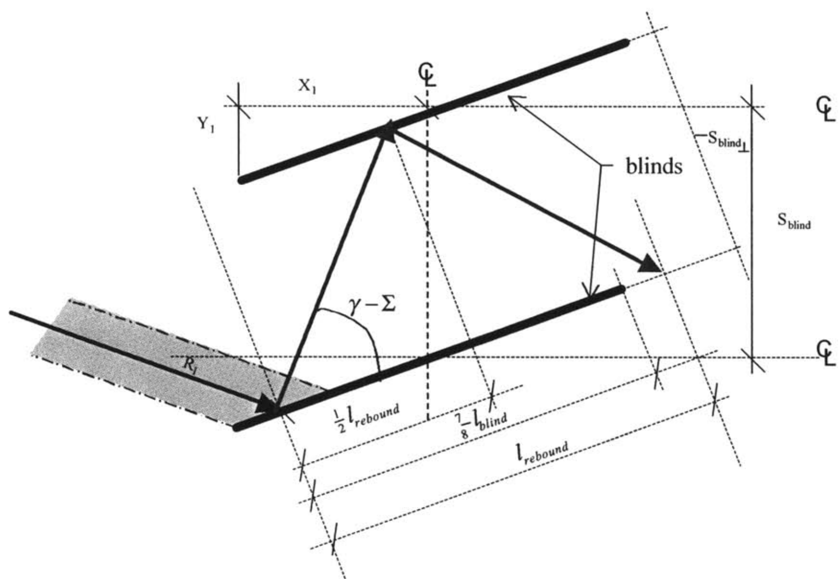


Figure 42 Configuration for "ray" bounces

(53) $$\tan(\gamma-\Sigma)=\frac{S_{blind,\perp}}{\frac{1}{2}l_{rebound}}$$

(54) $$S_{blind,\perp}=S_{blind}\sin(90-\Sigma)$$

If a ray point is lit, (not shaded by the upper blind), then if the specular reflection hits the upper blind (the "lit,hit" condition), it will rebound and again hit the lower blind if for:

Ray1, $l_{rebound}\leq\frac{7}{8}l_{blind}$

Ray2, $l_{rebound}\leq\frac{5}{8}l_{blind}$

Ray3, $l_{rebound}\leq\frac{3}{8}l_{blind}$

Ray4, $l_{rebound}\leq\frac{1}{8}l_{blind}$

If this condition is not met, then the rebound length is greater than the given length of blind, and the ray bounces in, towards glass3.

4.2.9 Infrared Radiation Heat Transfer

Coefficients for infrared radiation are defined for the inside and outside surfaces of the system, in terms of the average temperature of the glass surface and the surface to which it is emitting radiation:

(55) $$h_{r_{7in}} = \frac{4\sigma}{\frac{1}{\varepsilon_{62}} + \frac{1}{\varepsilon_{in}} - 1} T^3_{m_{6,in}}$$ Units are $\lfloor W/m^2K \rfloor$

(56) $$h_{r_{1,sur}} = 4\sigma (T_{m_{1,sur}} + 273)^3 \text{ where } T_{m_{1,sur}} = \frac{T_{sur} + T_1}{2}$$

For the cavity, the radiation circuit between three gray bodies is modeled as shown on the left in (simplified for closed blinds). The circuit for four gray bodies where the emissivity, area and temperature of rU and rL are equal is shown on the right. (used for open blinds):

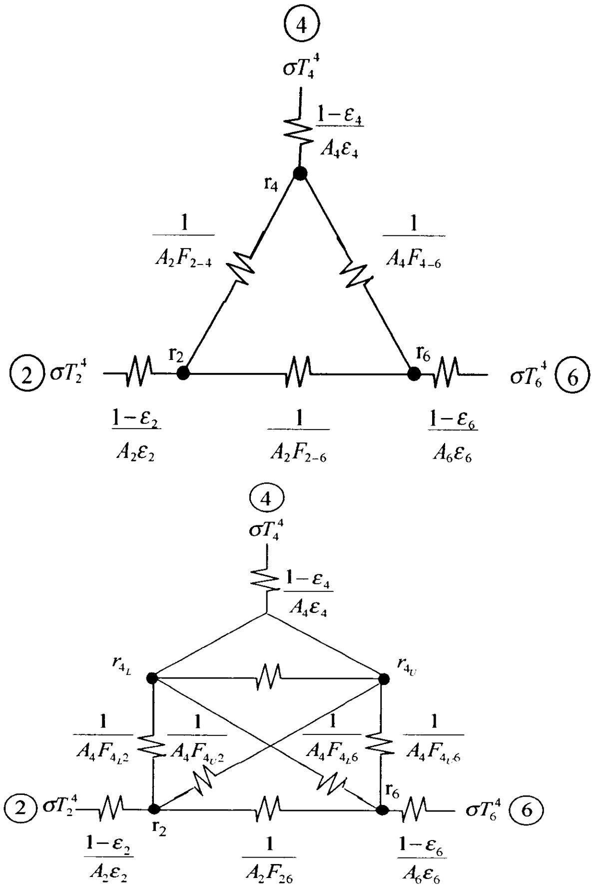


Figure 43 Electrical analogies for infrared radiation

The energy transfer from each of the points is:

(57) $$Q_{IR,2-others} = \frac{\sigma T_2^4 - r_2}{(1-\varepsilon_2)/A_2\varepsilon_2}$$ (simplified for closed blinds, otherwise)

$$Q_{IR,2-others} = \frac{\sigma\left(4T_m^3T_2 - 3T_m^3\right) - r_2}{(1-\varepsilon_2)/A_2\varepsilon_2} = 4A_2\varepsilon_2\sigma T_m^3 T_2 - 3A_2\varepsilon_2\sigma T_m^3 - A_2\varepsilon_2\left[r_{4_L}F_{24_L} + r_{4_U}F_{24_U} + r_6F_{26}\right]\text{[W]}$$

(58) $$Q_{IR,4-others} = \frac{\sigma T_4^4 - r_4}{(1-\varepsilon_4)/A_4\varepsilon_4}$$ (simplified for closed blinds, otherwise for the lower blind per blind pairing)

$$Q_{IR,4_L-others} = \frac{\sigma\left(4T_m^3 T_4 - 3T_m^3\right) - r_{4_L}}{(1-\varepsilon_4) / A_{dy,blind}\varepsilon_4} = 4A_{dy,blind}\varepsilon_4\sigma T_m^3 T_4 - 3A_{dy,blind}\varepsilon_4\sigma T_m^3 - A_{dy,blind}\varepsilon_4\left[r_2 F_{4_L 2} + r_{4_U} F_{4_L 4_U} + r_6 F_{4_L 6}\right]$$

and for the upper blind per blind pairing)

$$Q_{IR,4_U-others} = \frac{\sigma\left(4T_m^3 T_4 - 3T_m^3\right) - r_{4_U}}{(1-\varepsilon_4) / A_{dy,blind}\varepsilon_4} = 4A_{dy,blind}\varepsilon_4\sigma T_m^3 T_4 - 3A_{dy,blind}\varepsilon_4\sigma T_m^3 - A_{dy,blind}\varepsilon_4\left[r_2 F_{4_U 2} + r_{4_L} F_{4_U 4_L} + r_6 F_{4_U 6}\right]$$

and for the combination of upper and lower blind,

$$Q_{IR,4-others} = Q_{IR,4_L-others} Q_{IR,4_U-others}$$

(59) $$Q_{IR,6-others} = \frac{\sigma T_6^4 - r_6}{(1-\varepsilon_6) / A_6\varepsilon_6}$$ (simplified for closed blinds, otherwise)

$$Q_{IR,6-others} = \frac{\sigma\left(4T_m^3 T_6 - 3T_m^3\right) - r_6}{(1-\varepsilon_6) / A_2\varepsilon_6} = 4A_2\varepsilon_6\sigma T_m^3 T_6 - 3A_2\varepsilon_6\sigma T_m^3 - \left[r_{4_L} F_{64_L} + r_{4_U} F_{64_U} + r_2 F_{62}\right]$$

The radiosity for each node is:

(60) $r_2 = \varepsilon_2\sigma T_2^4 + (1-\varepsilon_2)\left[r_4 F_{24} + r_6 F_{26}\right]$ (simplified for closed blinds, otherwise)

$$r_2 = \varepsilon_2\sigma\left(4T_m^3 T_2 - 3T_m^3\right) + (1-\varepsilon_2)\left[r_{4_L} F_{24_L} + r_{4_U} F_{24_U} + r_6 F_{26}\right]$$

(61) $r_4 = \varepsilon_4\sigma T_4^4 + (1-\varepsilon_4)\left[r_2 F_{4-2} + r_6 F_{4-6}\right]$ (simplified for closed blinds, otherwise)

$r_{4_L} = \varepsilon_4\sigma\left(4T_m^3 T_4 - 3T_m^3\right) + (1-\varepsilon_4)\left[r_2 F_{4_L 2} + r_{4_U} F_{4_L 4_U} + r_6 F_{4_L 6}\right]$ for the lower blind per pair

$r_{4_U} = \varepsilon_4\sigma\left(4T_m^3T_4 - 3T_m^3\right) + (1-\varepsilon_4)\left[r_2F_{4_U2} + r_{4_L}F_{4_U4_L} + r_6F_{4_U6}\right]$ for the upper blind per pair

$$r_4 = \varepsilon_4\sigma\left(4T_m^3T_4 - 3T_m^3\right) + (1-\varepsilon_4)\left[r_2\left(F_{4_U2} + F_{4_L2}\right) + r_{4_L}F_{4_U4_L} + r_6\left(F_{4_U6} + F_{4_L6}\right)\right]$$

(62) $r_6 = \varepsilon_6\sigma T_6^4 + (1-\varepsilon_6)\left[r_2F_{6-2} + r_4F_{6-4}\right]$ (simplified for closed blinds, otherwise)

$$r_6 = \varepsilon_6\sigma\left(4T_m^3T_6 - 3T_m^3\right) + (1-\varepsilon_6)\left[r_{4_L}F_{64_L} + r_{4_U}F_{64_U} + r_2F_{62}\right]$$

4.2.10 View Factors for Glass 2 and Glass 3, FIR

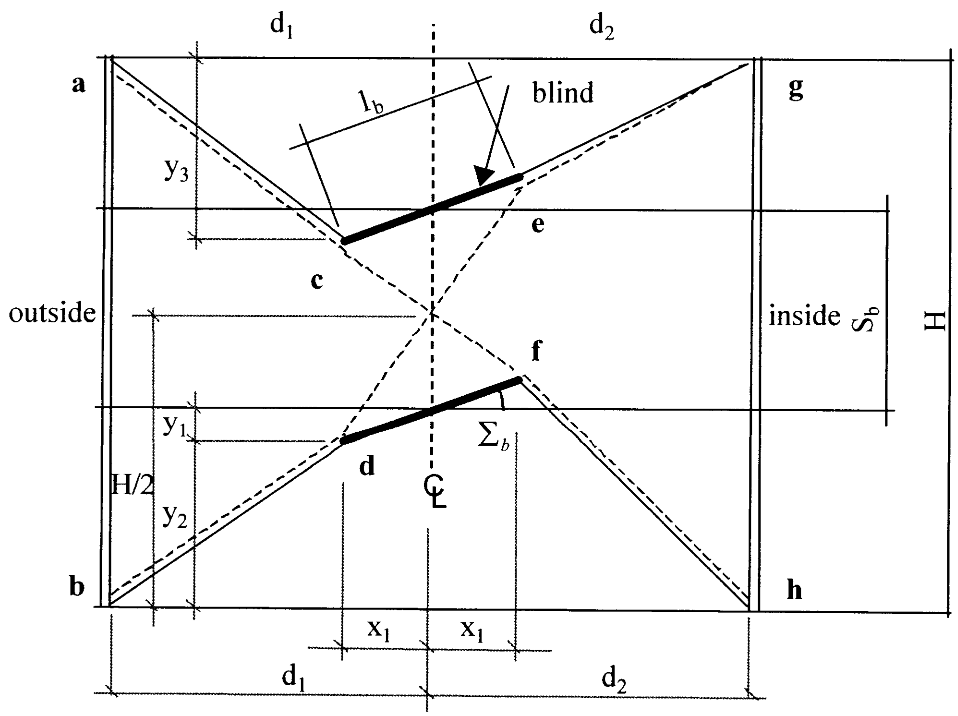


Figure 44 Geometries for blind view factors

$x_1 = \frac{l}{2}\cos\Sigma$ $\qquad$ $y_1 = \frac{l}{2}\sin\Sigma$

$$y_2 = \frac{H}{2} - \left(\frac{S_b}{2} + y_1\right)$$

$$y_3 = \frac{H}{2} - \left(\frac{S_b}{2} - y_1\right)$$

$$\overline{bd} = \left[(d_1 - x_1)^2 + y_2^2\right]^{\frac{1}{2}}$$

$$\overline{fh} = \left[(d_2 - x_1)^2 + y_3^2\right]^{\frac{1}{2}}$$

$$\overline{ac} = \left[(d_1 - x_1)^2 + y_3^2\right]^{\frac{1}{2}}$$

$$\overline{eg} = \left[(d_2 - x_1)^2 + y_2^2\right]^{\frac{1}{2}}$$

$$\overline{de} = 2\left[\left(\frac{S_b}{2} + y_1\right)^2 + x_1^2\right]^{\frac{1}{2}}$$

$$\overline{cf} = 2\left[\left(\frac{S_b}{2} - y_1\right)^2 + x_1^2\right]^{\frac{1}{2}}$$

$$\overline{fg} = \left[(d_2 - x_1)^2 + \left(\tfrac{H}{2} + \tfrac{S_b}{2} - y_1\right)^2\right]^{\frac{1}{2}}$$

$$\overline{dg} = \left[(d_2 + x_1)^2 + \left(\tfrac{H}{2} + \tfrac{S_b}{2} + y_1\right)^2\right]^{\frac{1}{2}}$$

$$\overline{da} = \left[(d_1 - x_1)^2 + \left(\tfrac{H}{2} + \tfrac{S_b}{2} + y_1\right)^2\right]^{\frac{1}{2}}$$

$$\overline{fh} = \left[(d_2 - x_1)^2 + (y_3)^2\right]^{\frac{1}{2}}$$

These geometries can be used with the following relationships to find the view factor for one blind-to-blind space:

$$A_2 F_{2-bdfh} = \frac{A_2 + A_{bdfh} + A_{acfh}}{2}$$

$$A_2 F_{2-aceg} = \frac{A_2 + A_{aceg} + A_{b\deg}}{2}$$

$F_{2-bdfh} + F_{2-6} + F_{2-aceg} = 1$, and combining this with the previous equations gives,

(63) $F_{2-6}\big|_{\sin gle} = \dfrac{A_{acfh} + A_{b\deg} - A_{bdfh} - A_{aceg}}{2A_2}$ for one intra-blind slot, S_{blind} high or

(64) $F_{2-6} = Numberofspaces \times F_{2-6}|_{\sin gle}$ for the entire window.

(65) Note that $A_{ab} = A_2 = A_6 = Hx1m$ and that $l_b = \overline{ce} = \overline{df}$. Also note the relationship that $F_{2-6} + F_{2-4} = 1$ such that $F_{2-4} = 1 - F_{2-6}$.

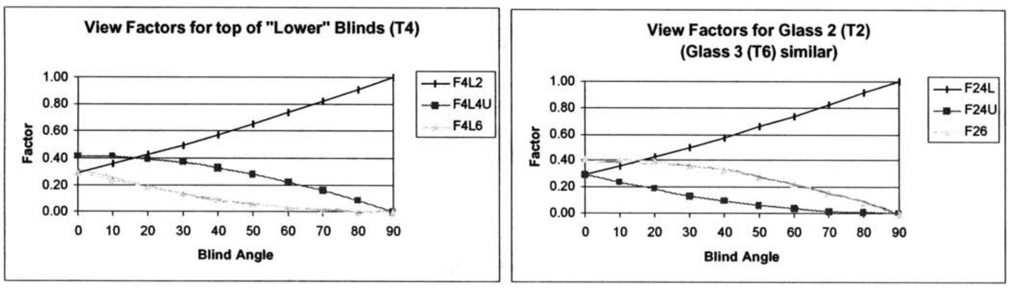


Figure 45 View factors for glass and blinds

4.2.11 View Factors for Blinds

Radiation view factors for diffuse reflections and infrared transmissions are determined using Hottel's crossed string method [Sielgal 1981 p.203]. The diagram for "Infrared Radiation View Factor" below shows the geometric relationship. The results of this method give:

(66) $$F_{blind-blind} = F_{44} = F_{df-ce} = \frac{A_{cf} + A_{de} - A_{cd} - A_{ef}}{2A_{df}}$$

(67) $$F_{lower.blind-glass3} = F_{4_L6} = F_{df-gh} = \frac{A_{dfh} + A_{\deg} - A_{\deg} - A_{fh}}{2A_{df}}$$

(68) $$F_{lower.blind-glass2} = F_{4_L2} = F_{df-ab} = \frac{A_{ad} + A_{fdb} - A_{db} - A_{fca}}{2A_{df}}$$

(69) $$F_{upper.blind-glass3} = F_{4_U6} = F_{4_L2} = F_{lower.blind-glass2}$$

(70) $$A_{4total}F_{4_{total}} = A_{4_U}F_{4_U6} + A_{4_L}F_{4_L6} \Rightarrow F_{4_{total}6} = \tfrac{1}{2}\left[F_{4_L6} + F_{4_U6}\right] = \tfrac{1}{2}\left[F_{4_L6} + F_{4_L2}\right]$$

(71) $F_{4_{total}6} = \frac{1}{2}\left[F_{4_L6} + F_{4_U6}\right] = \frac{1}{2}\left[F_{4_L6} + F_{4_L2}\right]$

(72) $F_{4_{total}4} = 1 - F_{4_{tot}6} - F_{4_{tot}2}$

4.2.12 Natural Convection: Buoyancy

The net force due to buoyancy created when there is a difference in temperature between the top and bottom of the cavity is defined by the difference in density of air and by the pressure loss due to friction at the ends and along the length of the cavity.

(73) $F_{Net} = (P + \rho_{\infty} gH)A_{cs} - PA_{cs} - \rho_{ave} gHA_{cs}$

(74) $F_{Net} = (\rho_{\infty} - \rho_{ave})gHA_{cs} = \Delta P_{Net} A_{cs} = \Delta P_{cavity} A_{cs}$

(75) $F_{Net} = \Delta P_{cavity} A_{surf} + \left(\Delta P_{entrance} + \Delta P_{exit}\right)A_{cs}$ including entrance and exit effects.

First, we assume that the average temperature along the height of the cavity can be assumed, then the pressure difference can be found:

(76) $T_{ave} \to \rho_{ave} : P_{atm} = \rho_{ave} RT_{ave} \Rightarrow \rho_{ave} = \dfrac{P_{atm}}{RT_{ave}}$

(77) $T_{\infty} \to \rho_{\infty} : P_{atm} = \rho_{\infty} RT_{\infty} \Rightarrow \rho_{\infty} = \dfrac{P_{atm}}{RT_{\infty}}$

(78) $\Delta P_{Net} = \left(\rho_{\infty} - \rho_{ave}\right)gH$

Assuming laminar flow within the cavity, the following relates flow in the cavity to viscosity and pressure:

(79) $\frac{Q}{w} = -\frac{1}{12\mu}\left(-\frac{\Delta P_{Net}}{H}\right)d_i^3 = \frac{d_i^3 \Delta P_{Net}}{12\mu H} \Rightarrow Q = \frac{wd_i^3 \Delta P_{Net}}{12\mu H}$ and the velocity is then:

(80) $$\bar{v}_{ave} = \frac{Q}{A_{cs}} = \frac{d_i^2 \Delta P_{Net}}{12\mu_{ave} H} \qquad \left[\frac{m}{s}\right]$$

where the properties of air are based on the average temperature as calculated by:

(81) $$T_{ave} = \frac{\sum_{i=1}^{N} T_i}{N}$$

The velocity found in equation (80) above can be plugged into the heat balance equations to find the resultant temperatures for the related mass flow.

The velocity is given by:

(82) $$v = \frac{\dot{m}}{\rho A_{cs}} = [{}^{m}/_{s}]$$

In many studies on the subject of airflow windows, the flow rate is given in ${}^{m^3}/_{h \cdot m}$ meaning that it is a flow rate per meter of façade length along the building. This quantity can be calculated in the following manner:

(83) $$\dot{V}/_{m} = \frac{\dot{m}}{\rho \cdot m}\frac{3600s}{h} = \left[\frac{kg \cdot s}{s \cdot {}^{kg}/_{m^3} \cdot h \cdot m}\right] = \left[\frac{m^3}{h \cdot m}\right]$$

The assumption that the velocity produces laminar flows must be checked against

(84) $\mathrm{Re}_{\substack{trans \\ lam \to turb}} = 10^5$ (Fox and McDonald p. 360)LRG Please Check this assumption.

If the Reynolds number indicates turbulent flow, then the cavity can be modeled as a flow through a smooth pipe with a hydraulic diameter and friction factor (the Blasius correlation):

(85) $f = \dfrac{0.316}{\mathrm{Re}^{0.25}}$ smooth pipe assumes that $\dfrac{e}{D} \approx 0.000{,}001$

Major head loss due to static pressure and shear is calculated as (from McQuiston and Parker):

(86) $l_f = f \dfrac{L}{D_H}\dfrac{\bar{v}^2}{2g} = f \dfrac{H}{8d_i}\dfrac{\bar{v}^2}{g}$ where $D_H = \dfrac{4Acs}{w}$ and LRG Please check, if this is 4Acs or 2 Acs

(87) $f = \dfrac{0.316}{\mathrm{Re}^{0.25}}$ (Equation 8.38 from Fox and McDonald)

(88) $\mathrm{Re} = \dfrac{\rho \bar{v} D_H}{\mu} = \dfrac{\bar{v} D_H}{\upsilon}$

(89) $\Delta P = \rho g l_f$

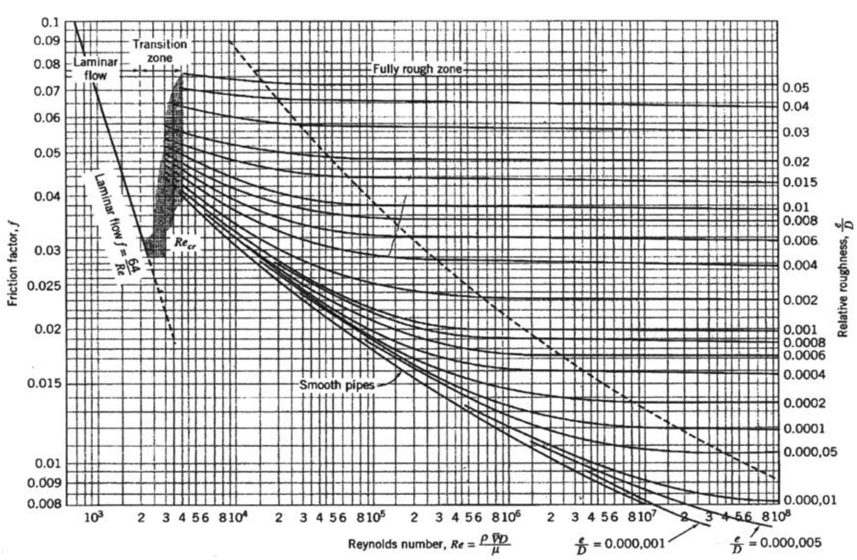


Figure 46: Moody Chart from Fox and McDonald

4.3 Desired Output

4.3.1a Room Impacts

(90) $$Q_{cavity-room} = qA = \int_{y=0}^{y=H} \frac{T_7 - T_{in}}{\frac{1}{h_7} + \frac{1}{h_{r_{7in}}}} dy + \int_{y=0}^{y=H} q_\tau A_{dy} dy = \sum_0^H \frac{(T_7 - T_{in})}{\frac{1}{h_7} + \frac{1}{h_{r_{7in}}}} \Delta y(1m) + \sum_0^H q_r \tau_1 \tau_2 F_{sol} \tau_3 A_{dy}$$

$$[W] = \left[\frac{W}{m^2} \cdot m^2\right] = \left[\frac{{}^\circ K}{\frac{1}{W/m^2 \cdot {}^\circ K}} m(1m) + \frac{W}{m^2} m^2\right]$$

4.3.1b HVAC Impacts

The amount of energy exhausted from the window (to the duct, or outside) is:

(91) $$Q_{Duct} = \sum \dot{m}_i c_p \left(T_{y=h} - T_{y=0}\right) = (\dot{m}_3 + \dot{m}_5) c_{pi} \left(T_{y=h} - T_{y=0}\right)$$

4.3.1c Effective U-Value

An effective U-value may be defined that represents the U-value that is experienced by the occupied side of the façade, disregarding the heat flow to the duct. The overall heat flow at steady state is:

(92) $Q_{cavity-outside} + Q_{cavity-room} + Q_{Duct} = 0$ and the effective U-value can be defined as:

(93) $$Q_{cavity-room} = U_{eff} A_{window} \left(T_{out} - T_{in}\right) \Rightarrow U_{eff} = \frac{Q_{cavity-room}}{A_{window}\left(T_{out} - T_{in}\right)}$$

4.3.1d Solar Heat Gain Coefficient

(94) $$SHGC = \frac{q_{room}}{q_{incident}} = \frac{q_{whole-window} / A_{window}}{q_{solar-incident}} \left[\frac{W/m^2}{W/m^2}\right]$$

4.3.2 Glossary of Terms

Term	Description	Units
T_{sur}	Temperature of surrounding surfaces including the sky.	°C
T_{out}	Temperature of outdoor air.	°C
T_i	Temperature of surface or location *i* (T_3 and T_5 are air temperatures)	°C
T_{in}	Temperature of indoor air.	°C
h_i	Convective heat transfer coefficient.	$W/(m^2K)$
$h_{r_{ab}}$	Coefficient of radiation heat transfer from *a* to *b*	$W/(m^2K)$
R_{DGU}	Resistance of double glass unit.	K/W
R_{gap}	Resistance of air gap (including radiation and convection) within double glass unit.	K/W
Q_{α_i}	Absorbed solar radiation on surface *i*.	W
q_r	Incident solar radiation normal to outside face of building.	W/m^2
α_{ij}	➸Absorptivity of surface i (for each layer of glass in the system) in the direction j where j=1 for front, 2 for back.	Dimensionless
ρ_{ij}	➸Reflectivity of surface i (for each layer of glass in the system) in the direction j where j=1 for front, 2 for back.	Dimensionless
τ_{ij}	➸Transmissivity of surface i i(for each layer of glass in the system) in the direction j where j=1 for front, 2 for back.	Dimensionless
F_{sol}	Configuration Factor of blinds relative to solar radiation	Dimensionless

F_{IR}	Configuration Factor of blinds relative to infrared radiation	Dimensionless
σ	Stefan-Boltzmann constant	$W/(m^2K^4)$
ρ	Density of air	kg/m^3
c_p	Specific heat of air	J/kgK
$\dot{m}_i$	Mass flow rate of channel *i* of air	kg/s
k	➛Conductivity of glass	W/mK
l	➛thickness of glass	m
l_{blind}	➛length of the blind (from front to back)	m
w	➛width of blind or window along façade (z axis)	m
S_{blind}	➛vertical center to center spacing of blinds	m
H	➛vertical extent (unimpeded height) of the window cavity.	m
Δy	height of a control volume for an energy balance	m
A or A_{dy}	Cross-sectional area of vertical segment: Typically $\Delta z = 1$m deep by Δy high	m^2
$A_{dy,blind}$	Area along length of blind per vertical segment Δy high	m^2
d_0	clear space between panes in double glazed unit	mm
d_1	clear space between face of glass 2 (T2) and centerline of blinds	m
d_2	clear space between centerline of blinds and face of glass 3 (T6)	m

ε_4	emissivity of blind material	dimensionless
ρ_4	reflectivity of blind material	dimensionless
α_4	absorptivity of blind material	dimensionless
Σ_4	angle of blinds	degrees
	forced or natural convection	binary
	v_i or V_i velocity or (volumetric flow rate) of airflow in each side of the channel	m/s
	or	(m^3/hr.m)
	vented from inside or outside	binary

4.4 Troubleshooting methodology

The model has been tested extensively element-by-element to verify that it gives logical and reasonable results. Each element has been isolated in turn so that only those attributes of the model that relate to the particular aspect of interest will have a significant impact on the results. Once isolated, the module of interest was then scrutinized and refined. Any required changes were then made to the base model as well.

This troubleshooting methodology served to ensure that the model is working as designed. This *verification* is different from *validating* the model. The goal of validation is to compare the analytical model to the physical world to show that the model is reasonably accurate. The verification process shows that the computational model works as intended, and matches the mathematical relationships outlined in the simplified model (as described above in this chapter). Verification includes the understanding that assumptions are made in the definition of the mathematical model that will be inherent in the tool results.

4.4.1 Temperature Difference Verification

To evaluate the U-value of the system, solar radiation is eliminated and mass flow is minimized. The driving force for the energy is then the difference in temperature between the inside and outside of the window. To test that the model handles this heat transfer effectively, we compare the temperature distribution in the window given by the worksheet model to a simplified calculation. The inlet temperature is set to 19.3 as per the model of Saelens and Hens [Saelens and Hens 1998]. The winter condition of outside temperature, Tout is 0 degrees Celsius, and indoor temperature Tin is 20 degrees Celsius. To focus on the driving force of this temperature differential, the airflow is set as low as possible. The airflow is mixed so that 90 % of the mass flow is to the outside cavity, (T3) and 10% is to the inner cavity (T5). The blind angle is 90 degrees (closed). The mass flow rate is 0.0009 kg/s per meter of façade. The resultant velocities are v3=0.0135 m/s and v5=0.0035 m/s for the outer and inner cavities respectively.

The model runs into difficulty with evaluating very low mass flow rates (in the order of 0.0005~ 0.0008 kg/s) because the delta T in the channel is defined relative to the inverse of the mass flow rate (equations 13a and 15a):

$$\frac{dT_3}{dy} = \frac{B_1(T_1 - T_3) \_ C_2(T_4 - T_3)}{\dot{m}_3 c_p \Delta y}$$

To look at the low mass flow rate condition, $\frac{dT_3}{dy}$ must be abandoned, and the temperature of the cavity must be found in terms of the temperature of the surrounding surfaces and this was indicated previously.

For T_3: $\frac{T_2 - T_3}{\frac{1}{h_2 A_{dy}}} + \frac{T_4 - T_3}{\frac{1}{h_3 A_{dy,blind}}} = 0 \Rightarrow T_3 = \frac{B_1 T_2 + C_2 T_4}{B_1 + C_2}$

For this reason, the flow rate of 0.0009 was chosen to be just above the 0.0008 kg/s per meter cut-off. The R-value of the double-glazing unit (T1 to T2) is set to 0.001 so that the cavity temperatures can be focused on. The emissivities of glazing and blinds are set to 1.0 so that infra red effects are also minimized.

A simplified routine was set up to evaluate the heat flow and resultant temperature gradients across the idealized system. Heat transfer coefficients were input to this routine from the model. The results show that the model is highly accurate. The greatest error in temperatures for a given node was 0.01 degrees Celsius. (0.14% error)

SUMMARY: U-Value Verification

Simplified calculations compared to DSF Calculator (worksheet)

	T2,glass	T3	T4,blinds	T5	T6,glass	
Simplified Calcs	0.09	5.03	9.97	14.94	19.92	
Worksheet (Model)	0.09	5.03	9.98	14.95	19.92	
	0.00%	0.04%	0.13%	0.14%	0.00%	
	h2	**h3**	**h5**	**h6**	**Ady**	**Ady blind**
	5.85	5.85	5.81	5.81	0.12	0.12

Figure 47 Comparison of model and simplified equations for U-value verification

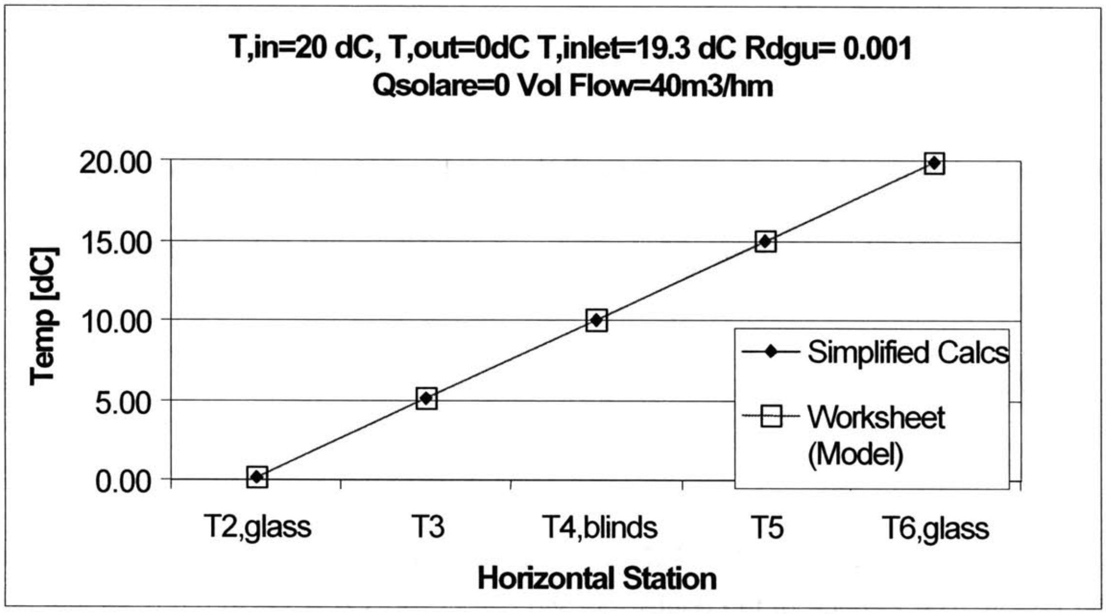


Figure 48 Comparison of simplified calculations and worksheet model for temp. distribution.

The plots for the simplified routine and the model ("worksheet") are nearly identical. Currently there are twenty divisions allowed in the model. Adding more divisions would improve the results. Also, programming in a language that would allow more sophisticated iteration (rather than a spread sheet) would help.

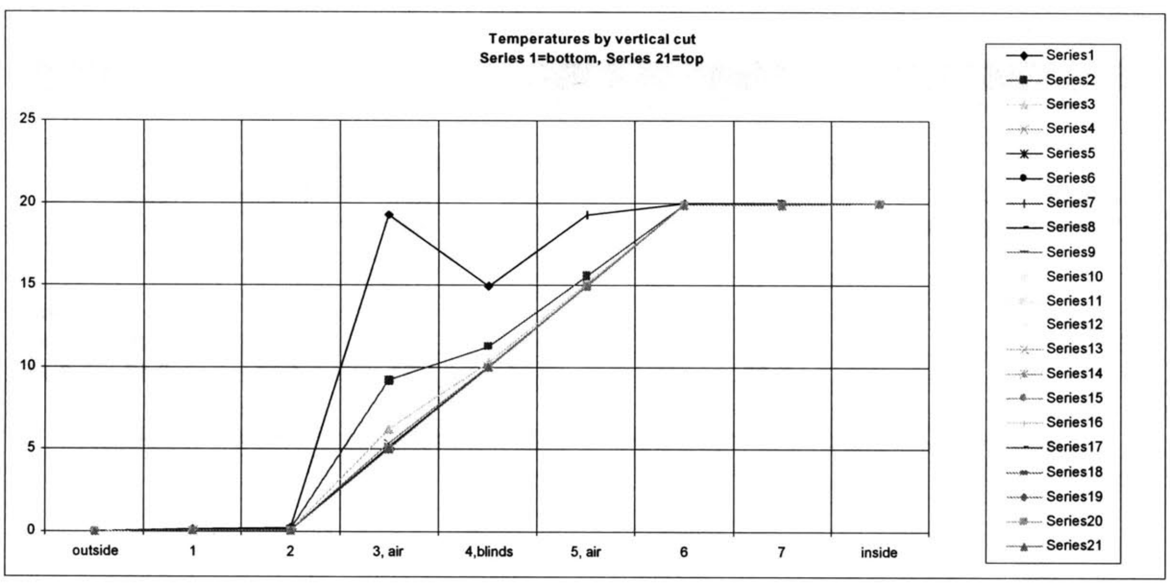


Figure 49 Temperature distribution for temperature distribution verification (Tin=20dC, Tout=0dC)

A region of dramatic variation occurs at the bottom of the window. Series 1 in Figure 1 represents the temperature at the bottom 0.12m of the window. Each successive series is another distance, dy (0.12 in this case) above the entrance. Because the air entering the cavities (stations 3 and 5 on the horizontal axis), is close to room temperature, it is far from the equilibrium temperature of that is finally reached in each cavity. Because the volumetric flow rate is low, the heat transfer coefficient in the cavity is also low. However, the result is that the temperature change for each step, dT/dy is large. (dT/dy is inversely proportional to the mass flow rate). The longer the air is in the cavity, the closer each horizontal cut comes to an equilibrium state. By series 4 (0.36m above the inlet) the temperature in each cavity is virtually at the equilibrium point. A detailed report on this verification is included in the appendix.

4.4.2 Verification of Cavity Flow with Forced Convection

In order to assess the cavity flow calculations in the model, it is adjusted to represent a single channel with forced convection. The heat transfer coefficients on the "outside" of the channel (along the glass surfaces at T2 and T6) and the U-value of the double glazing unit (1/Rdgu) are set so high that they offer no resistance to heat flow and create infinitesimal changes in temperature (in the order of 0.01 degrees C). The blinds are given properties so that they also have minimal impact on the temperature gradient across the system. They represent a vertical plane with emissivity .001. Now air is forced through the channel at a flow rate of $40m^3/(hr\text{-}m)$. The entrance temperature is 19.3 degrees Celsius and the channel wall temperatures (T2 and T6 – the channel side of both the double glazing unit and the inner layer of glass) equilibrate at about 30 degrees Celsius.

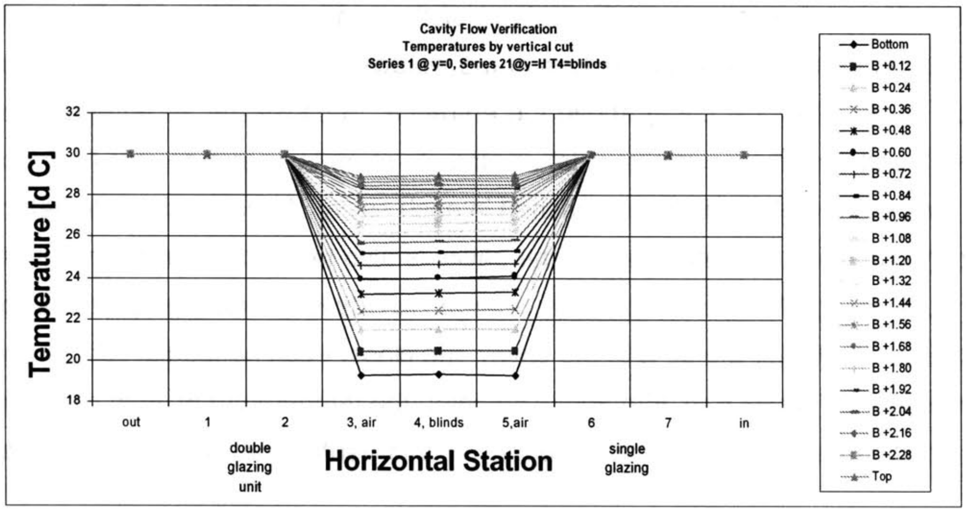


Figure 50 Cavity flow verification: temperature distribution

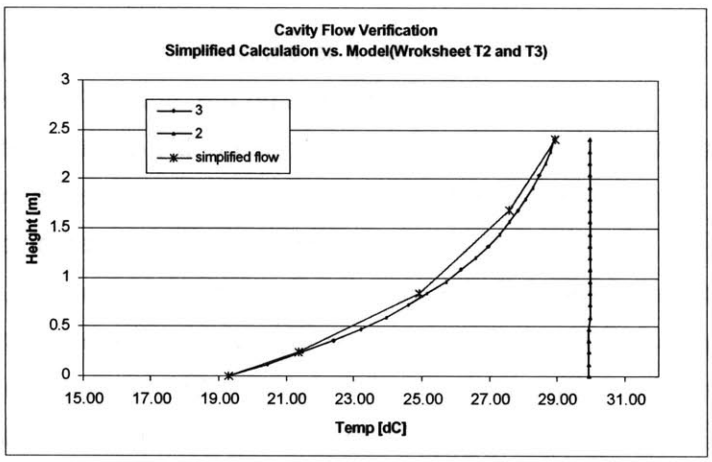


Figure 51 Cavity flow verification: Air and blind temperatures

As seen in the figure, the air entering the cavity warms as it passes along the walls of the channel. The model has been adjusted so that the blinds do not impact the airflow or heat transfer. They represent a plane of high conductivity and low emissivity. The wall temperature is seen to be nearly constant, while the air being forced through the cavity approaches this temperature with inverse exponential degree. This is seen on the right hand side Figure 50 above.

The governing equations for the simplified calculations are as follows:

$$\dot{m}c_p \frac{dT_3}{dy} = -h_3 w(T_{3,f} - T_w)$$

$$\frac{dT_3}{T_{3,f} - T_w} = -\frac{h_3 w}{\dot{m}c_p} dy$$

$$\ln(T_{3,f} - T_w) = -\frac{h_3 wy}{\dot{m}c_p}$$

$$T_{3,f} - T_w = (T_{3,i} - T_w)e^{-\frac{hwy}{\dot{m}c_p}}$$

$$T_{3,f} = (T_{3,i} - T_4)e^{-\frac{hwy}{\dot{m}c_p}} + T_w$$

This final equation explains the exponential decline that is observed in the temperature of the air stream. This method for finding the final temperature of the cavity flow may be compared to the temperature as determined by the model:

The error is found to be –2.23% and is given by:

$$error\% = \frac{T_{3,f} - T_{3,i}}{\Pr ogram - T_{3,i}}$$

Simplified Model: Validation set 2							
			T3, .3H	21.349156	Tw,.3H		29.94
			T3, .3H	24.939115	Tw,.3H		29.97
variable	**value**		T3, .6H	27.593477	Tw,.6H		29.99
T3,i	19.30		**T3,f**	28.724088			
Tw	29.97		**program**	28.9387			
hc	6.02		**error**	-2.23%			
w	2	this is the perimeter: (2 sides)					
y	2.4					height	Temp
m	0.0134	This is mass flow for 2 cavities				0	19.3
cp	1005.00					0.24	21.3492
						0.84	24.9391
						1.68	27.5935
						2.4	28.9387

4.4.3 Verification of Cavity Flow with Buoyant Forces

To solve for the steady state condition in a window dominated by buoyant forces an iterative process has been investigated. This method uses an assumed forced convection volumetric flow (or mass flow), which gives a resultant temperature matrix. The temperatures inside and outside the cavity can then be used to determine a resultant buoyant force.

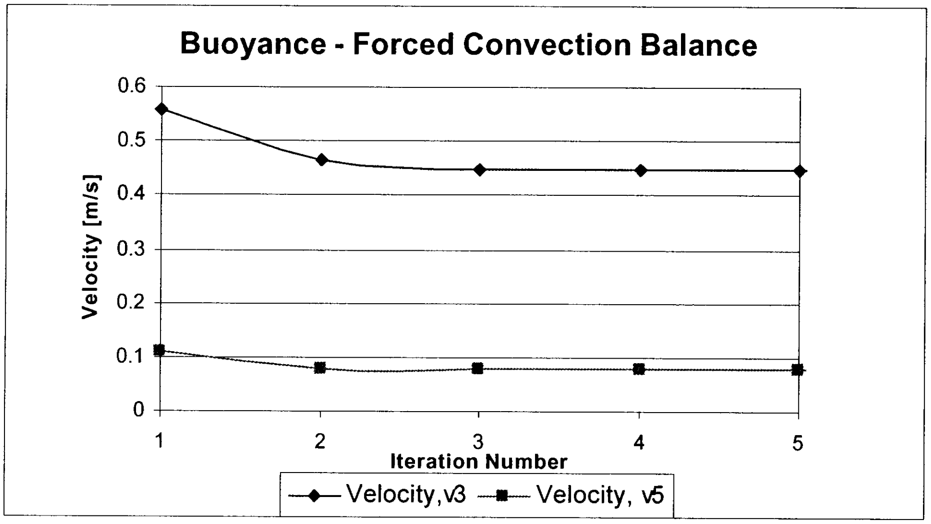


Figure 52 Velocities in air cavities by iteration. Convergence is to buoyant velocity.

The buoyant force can be used to determine a resultant velocity or mass flow that can be fed back into the forced convection model, giving a new temperature matrix and new buoyant forces. The process is repeated until it converges to a velocity and temperature profile that satisfies both models. This is the steady state buoyant condition. This process is seen Figure 52 above. After just three iterations, constant conditions are experienced in cavities d1 and d2.

It is possible to get divergent conditions when air velocities are extremely low. In that case, no solution will be found with this process. The reason for this is that with very small mass flow rates, a large delta T will result. A large delta T will indicate a large mass flow rate, which will then give a low delta T as illustrated below in Figure 53.

A different approach to buoyancy is taken to avoid this pitfall. The feasible range of temperature differences is solved for in both the forced and natural convection models. Both ranges are plotted and their solution is the intersection of the curves.

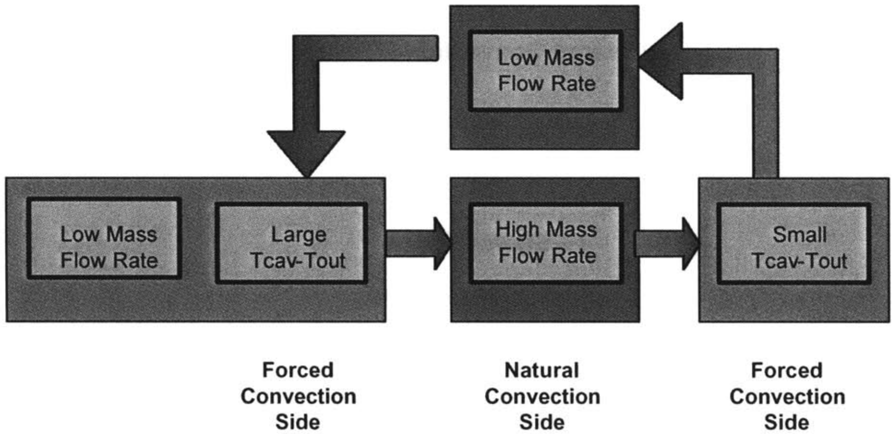


Figure 53 the iterative process in low mass flow conditions

Another method for determining the stable buoyancy case is to plot the difference in temperature between the cavity and the supply air side (typically the outside) versus the volumetric flow rate for both buoyancy and forced convection as shown in Figure 54. At the intersection of the curves can be found the equilibrium point for buoyancy. If the volumetric flow rate were increased from the intersection, the additional flow would decrease the temperature delta such that the air flow rate would be reduced. If the volumetric flow rate were decreased from the intersection, the temperature delta would increase thus increasing the volumetric flow rate.

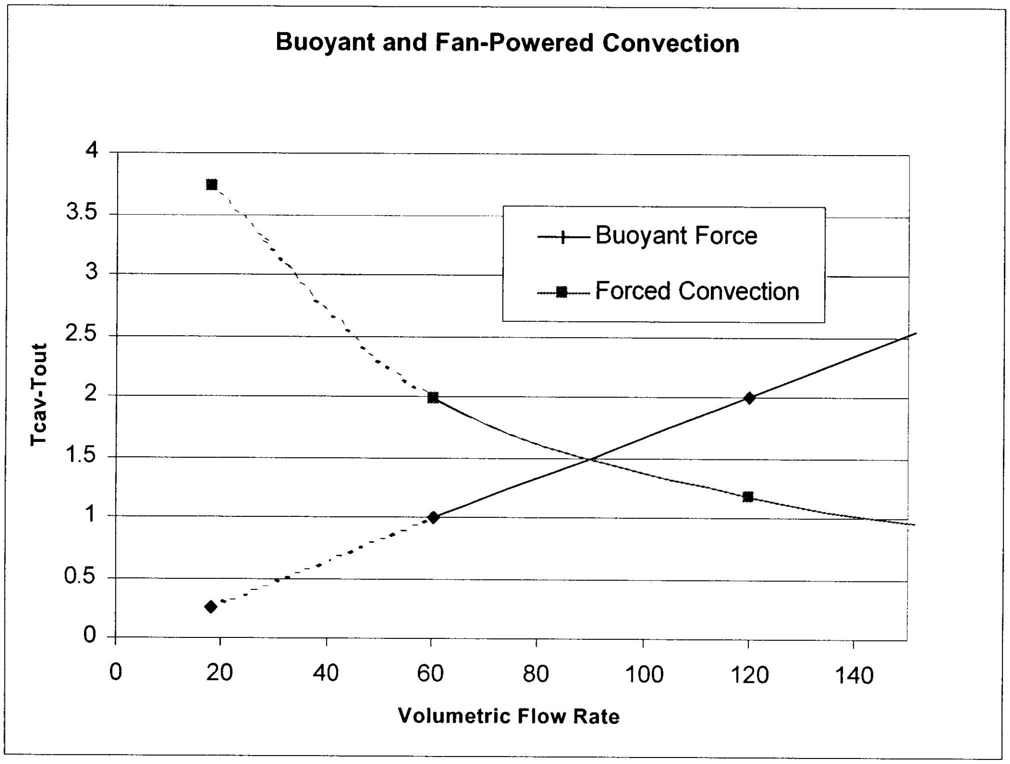


Figure 54 Relationship of buoyancy and forced convection flow rates and temperatures

Verification of Model by Mirroring Hens and Saelens' Model

The model has been compared to the results given by Hens and Saelens. A comparison of the U-values and solar heat gain coefficients are shown in figures Figure 55 andFigure 56. All possible parameters were "mirrored" in the spreadsheet to achieve quite similar results. One parameter not specified by Hens was the blind position for assessing the SHGC. Based on implications in the documentation and the results, it is assumed that the blinds were in the closed position (labeled "90" in Figure 56) for Hens' evaluations.

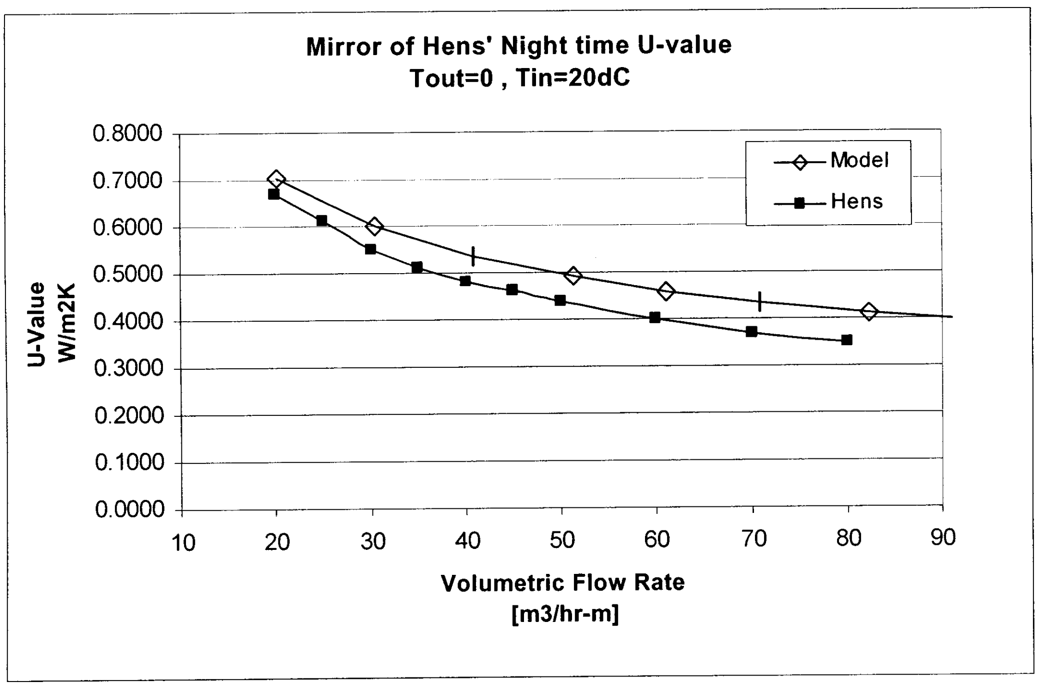


Figure 55 comparison of Hens and MIT nighttime U-values

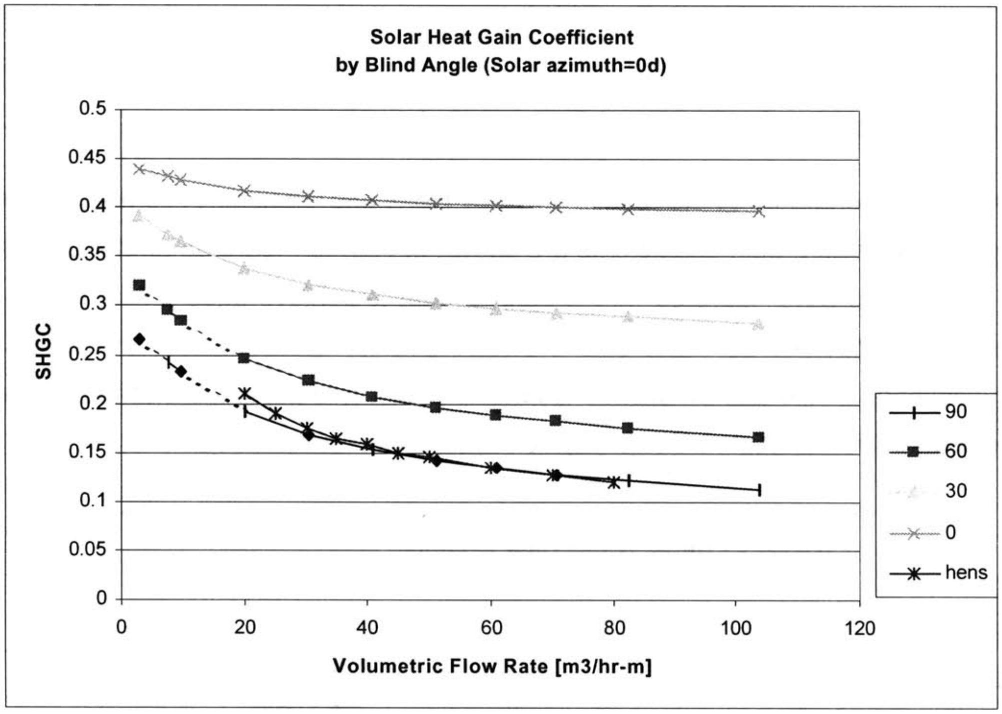


Figure 56 Hens and MIT solar heat gain coefficients

4.5 Implications and Analysis of Design Parameters

For building designers to select a façade or mechanical system for a given practice they must understand the functionality of the various systems available to them. The gap in knowledge between typical consulting architects and mechanical engineers and system researchers and developers is great. The consulting professional is responsible for the ultimate performance of the systems but have little budget or time to fully understand the elements that they bring together into their designs. The complexity and uniqueness of buildings as compared to many manufactured products is often beyond the comprehension of the professionals that are in the role of "expert". For this reason, the complexity of new systems such as double-skin facades must be distilled for those that would like to utilize them so that informed decisions may be made. Otherwise the designers have two choices: to avoid their use or to use them with limited understanding (or misunderstanding).

4.5.1 Parameters and Properties

The full complexity of the system is summarized so that it can then be distilled into something useful. The simplified numerical model is useful in understanding that there are many parameters for the design of double-skin façade. A multitude of parameters must be input in order to get results for the energy flows through the façade. These include the following:

- Spatial aspects
  - The depth of the cavity
  - The height of the window
- Glazing properties
  - The emissivity, trans-missivity, reflectivity and absorptivity of each pane.
- Thermal and structural qualities of frames (not included in the model)
- The location of mullions
- Blind properties
  - Location dimensions and spacing.
  - Emissivity, absorptivity and reflectivity of the material
- Air movement path
  - Inlet to the inside or outside
  - Forced or natural convection.
- Controls
  - Individual control of blinds and operable windows.
  - Building control of blinds, windows and fans.
- Interaction with other systems such as mass storage and air supply/exhaust (not included in the model)
- The configuration and inter-relationship of other mechanical components -- ducts, fans and controls
- The overall color and visual reflectivity of the system (not included in the model)

The model is meant to be a preliminary aid in designing buildings with airflow facades. As the list of parameters suggests, there is a large number of them to consider when setting out to design such a system to respond to energy concerns. Additional parameters are required if one is to investigate impacts of thermal mass and other building-side impacts on energy consumption. Still more variables exist if one is to consider thermal comfort or daylight distribution within the space.

The number and interdependency of the parameters can create the perception of an insurmountable obstacle if the relative role of each parameter is not understood. It is therefore important to determine which are the most important variables. It is also important to understand the range for which each parameter is active and what trends can be understood.

A distinction may be made between the parameters of the window and its properties. The parameters are measures of the physical makeup of the window and may have little *direct* effect on the outcome for the designer (architect *or* engineer). The properties of the window are, in essence, the combined effect that these parameters have in defining the performance of the system.

To illustrate this point, if a designer is trying to design an energy efficient façade, he or she may choose glazing with a particular parameter, say, a visible light transmissivity of 60%. This may be important to know, but a more useful *property* of the window is the overall Solar Heat Gain Coefficient SHGC. This designer would like to know, what are the effects of changing the parameter (transmissivity) on the window property of interest (SHGC). The behavior of the façade is determined by key properties including the U-Value (conductance) and Solar Heat Gain Coefficient (coefficient of solar energy transmission).

The SHGC is measured when the blinds are closed, and there is no difference in temperature between inside and outside but there is incident solar radiation. The U-value is also measured when the blinds are closed, and when there is a difference in temperature between inside and outside by no solar radiation. The importance of the variables is sensitive to the design intent for each building. While the model developed and described above focuses on energy, this approach may at times conflict with other goals such as day lighting, ventilation and even aesthetics. Optimizing only energy may be detrimental to of other goals of the design.

To see the effect of changing the infrared emissivity of the glazing, low–E glazing was applied to the double-skin façade on surface 2, the inside face of the outermost glazing layer. Figure 57 shows that reducing the infrared emissivity will actually increase the SHGC -- the amount of solar energy reaching the occupied space as a fraction of total incident radiation. Note that a reduction to 0.10 emissivity glazing would increase the SHGC by just about 3%. Such a change would only be significant in spectacularly sunny locations. The effect of emissivity on U-value is shown in the next Figure 58. It shows that the U-value may be reduced by nearly 50% by using low-E glazing, a significant change particularly for cold climates where the driving force for energy transfer through the window, a difference in temperature, is large.

Adjusting the blinds will effect the nighttime U-value of the system as shown in Figure 59, but modulating the angle of incidence of solar radiation (reflected in "solar altitude") for a window with fixed (45d) blinds is by far the most dramatic variation as seen in Figure 60. Comparing the double-skin to conventional (not low-e) glazing systems without blinds shows that the SHGC of the double-skin is similar to triple glazing for more transparent positions of the blinds (azimuth of the sun is equal to the tilt of the blinds).

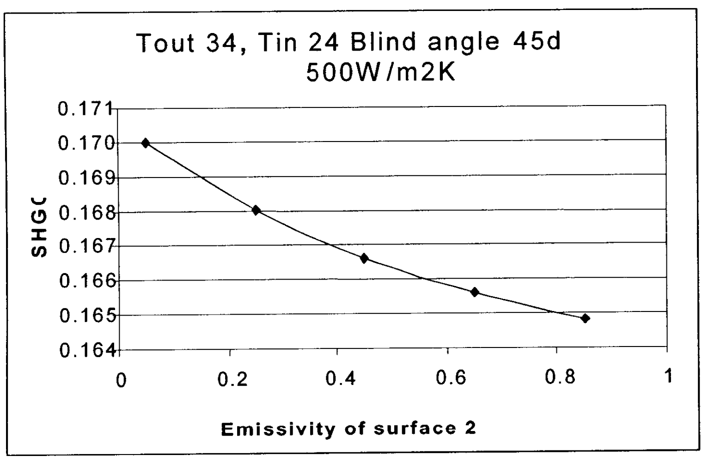


Figure 57 Parametrics: Glass emissivity and SHGC

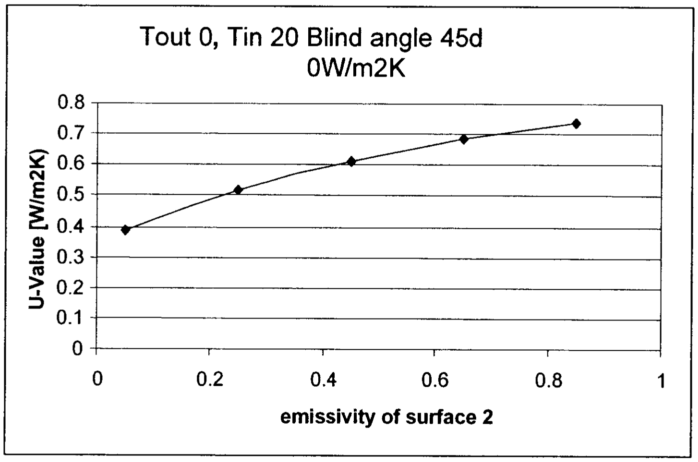


Figure 58 Parametrics: glass emissivity and U-Value

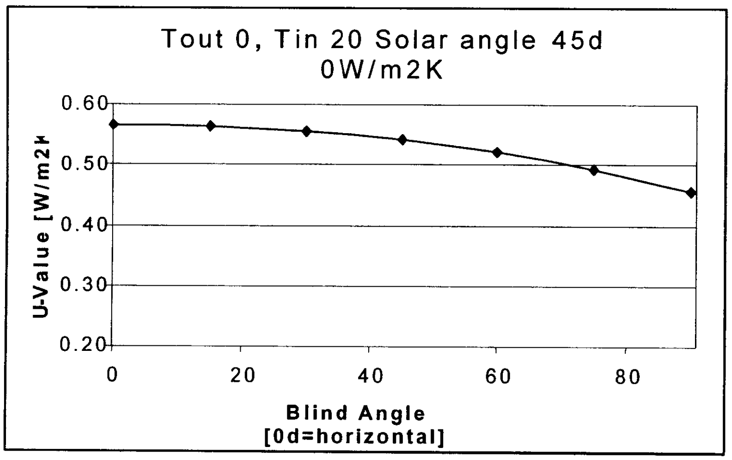


Figure 59 Parametrics: Blind angle and U-Value

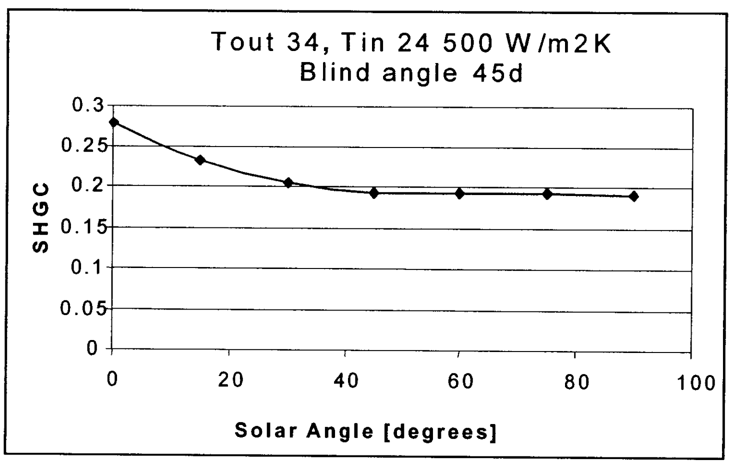


Figure 60 Parametrics: Solar angle and SHGC

The type of blind used is of great importance. Most blinds have been made of aluminum finish. This shiny material reflects a great deal of solar energy (as well as infrared radiation). The model has been used to observe the effects of these parameters independently and together. Figure 61 shows that varying solar absorptivity while maintaining infrared emissivity constant (E=0.85) will increase the SHGC from 0.07 ~ 0.19 as the absorptivity ranges from 0.2 ~ 0.9. Similarly, by varying infrared emissivity while maintaining absorptivity constant (a=0.75) will increase the SHGC from 0.13~0.17 over the same range.

The solar heat gain coefficient is generally defined when the blinds are closed. In this condition, the solar absorptivity or reflectivity has a larger influence on the solar heat gain coefficient than does the infrared emissivity. Figure 61 shows that the solar absorptivity has a closer dependence on variations (a steeper slope) than the infrared emissivity. Also notice that the "combined effect" which has both parameters varying, doesn't lower the SHGC much below the level that solar absorptivity alone assumes.

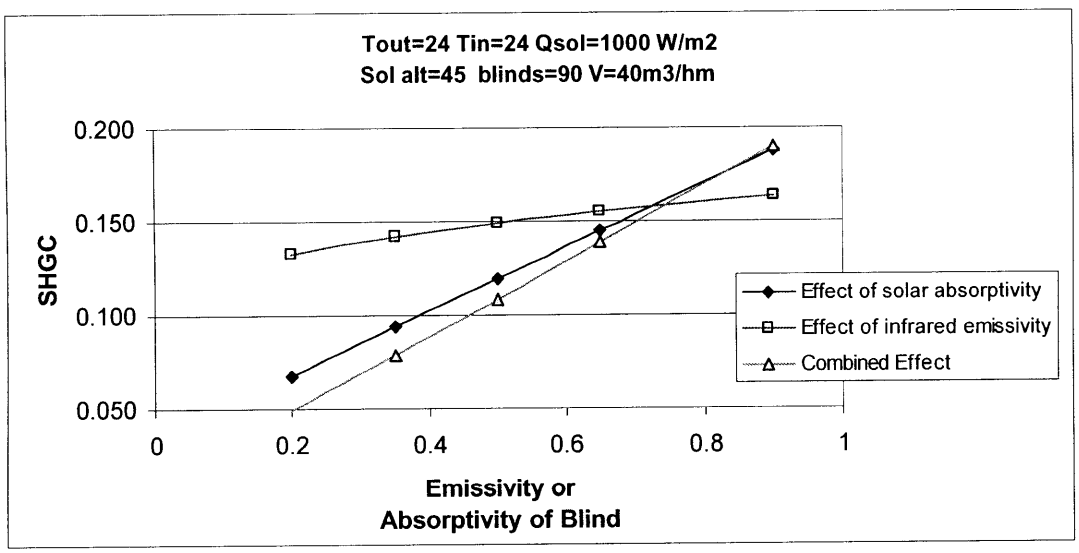


Figure 61 Effect of blind solar absorptivity and infrared emissivity on SHGC

This description of the parameters is still difficult use in practice without the context of "real-life" examples. The examination of specific materials will be made easier by examining a group of typical blind materials by their individual properties. Five blinds are shown in Figure 62.

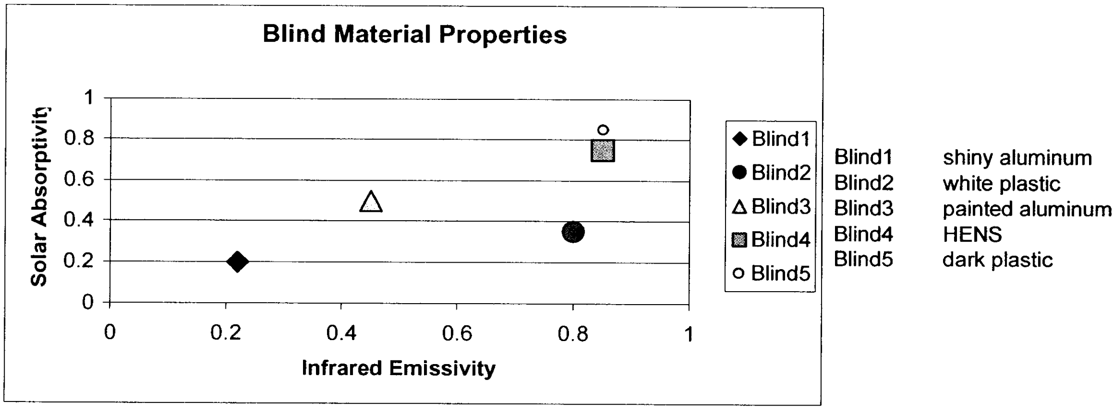


Figure 62 Typical blinds by material properties

The properties have been run through the model to determine their SHGC for a typical window system with 40 m^3/hm volumetric flow and subject to solar radiation by not to a temperature differential. The results are shown in Figure 63; the difference in blind materials results in a 100% increase in solar load on the space behind the window system.

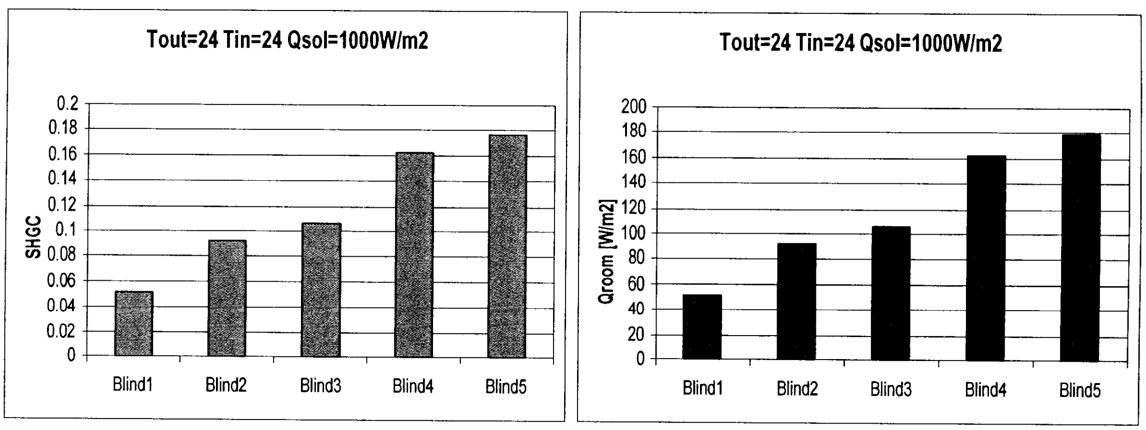


Figure 63 SHGC and related instantaneous heat gain

This type of analysis begins to demonstrate that the simplified modeled described herein may be used as a design tool. Given particular design conditions (indoor and outdoor temperature and radiation) the model may be used to consider a variety of window systems with individual parameters to relate their properties to energy loads for a particular location. Understanding the general trends and relative importance of the parameters helps the designer in refining choices.

4.5.2 Comparison to Other Technologies

The goals of double-skin facades and other façade technologies are generally the same. Like standard static windows and curtain walls, DSF's are mediators of daylight, temperature (energy flux), moisture, precipitation and air exchange pressurized by wind and building mechanical systems. There are human elements to moderate as well, aesthetics and views, comfort and productivity, cost, noise reduction and security. All façade systems address each of these parameters to some degree. The multiple layers and adjustability coupled with airflow give DSF's the potential to adjust their performance to a greater degree and with more flexibility. In order for the design team to assess the value of DSF's it is helpful to consider their place within the context of the systems that they for which they may substitute.

4.5.2a U-VALUE, SHGC, CRF, CONSTRUCTION

A straight comparison of DSF's with their counterparts is a little more complex than comparing, say, double versus triple glazed windows or clear windows with low-E windows. This is because the performance of DSF's is more dynamic than their static counterparts. Opening the inner cavity to air movement, whether by forced or natural convection, means that the thermal performance will vary dramatically with airflow. The U-Values for some static and dynamic systems are compared in the chart below.(window system props.xls). The windows included are double glazed (DG), triple glazed (TG), clear and low-E (LoE). For the low-E glazing, ASHRAE provides numbers for emissivities 0.4 and 0.2 [ASHRAE Fundamentals]. One can clearly see that based on optimizing for minimum U-value alone, the DSF would be preferable to any existing system. The fact is that because the DSF is a dynamic system, its performance is variable. For what Permasteelisa calls the "Active Façade", the interior ventilated, forced convection façade, it is possible to get such a U-Value, or even a lower U-Value by increasing the airflow rate. It should be understood, however that lower flow rates will decrease this performance dramatically. Saelens and Hens [Saelens 1997] show that halving the airflow rate from 40 to 20 m^3/hm will increase the U-Value from 0.5 to about 0.7. Still this is lower than most of the static options, but the difference between this and triple glazed argon windows with two low-E coatings is relatively minor.

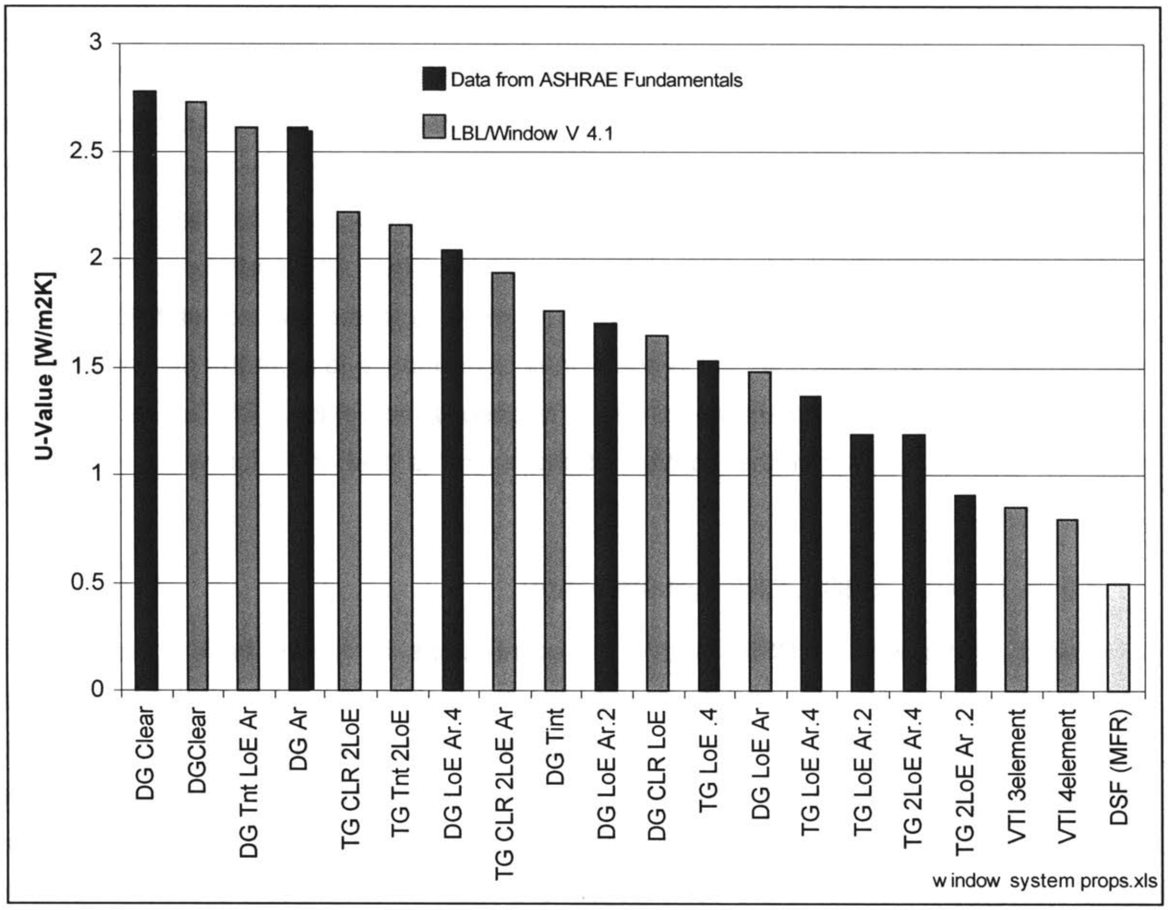


Figure 64 U-value comparisons of standard systems versus DSF at 40 m^3/hm See system definitions in

Table 1: Key for window comparisons

The solar heat gain coefficient measures the amount of energy that enters a space through the glazing as compared to the incident radiant energy. The chart below shows two data sets,

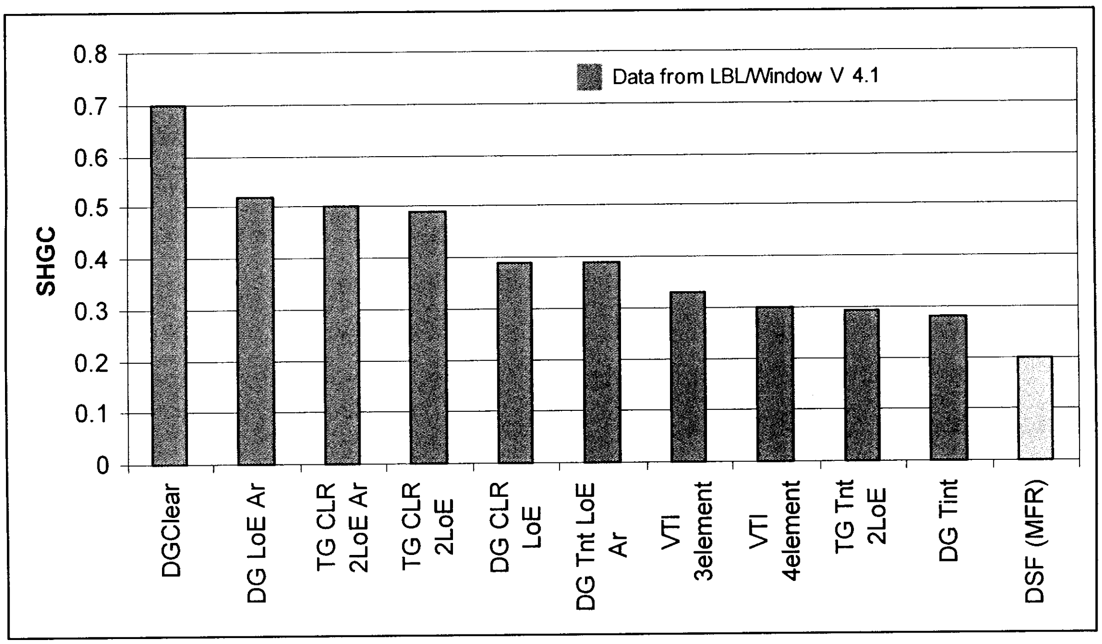


Figure 65 SHGC comparisons of standard systems versus DSF at 40 m^3/hm. See

Table 1: Key for window comparisons

below for description of systems

the standard static systems and the range of SHGC's expected for DSF's for a volumetric flow rate of 40 m^3/hm (by Permasteelisa). At the given rate of 40 m^3/hm, many of the window systems may be reasonably close to the DSF's, but none would be competitive in a critical application. However, these SHGC's are for windows without blinds. The model developed for this thesis can be used to examine what happens if shading is put in the systems. The values taken are for the low end of the volumetric flow rate (about 3 m^3/hm). In this range, the natural buoyancy is assuredly going to be as important as the forced convection, but the model will give an idea of the trend. Figure 66 gives an example of a DSF with low-E 0.15 coating on "surface 4" which is the inner side of the double glazing unit facing the cavity. The equivalent static window system has a SHGC of approximately 0.3. The difference between the static and dynamic systems, which is predicted to be 0.15 (measured at 40 m^3/hm), is about 50% of the static version. [This model is from "shgc for static systems.xls:case 7"].

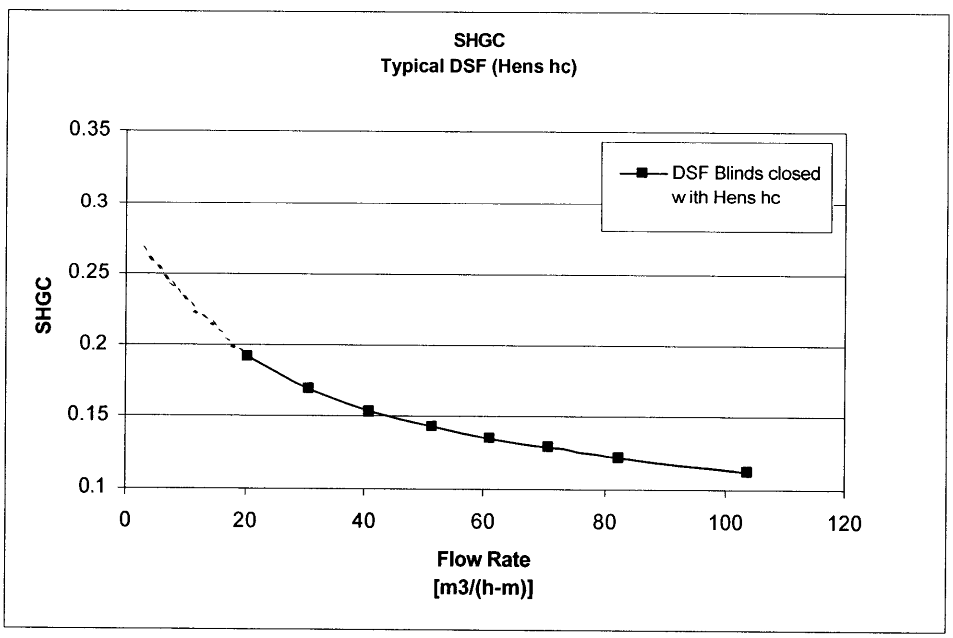


Figure 66 SHGC of typical double-skin façade with low-E coating

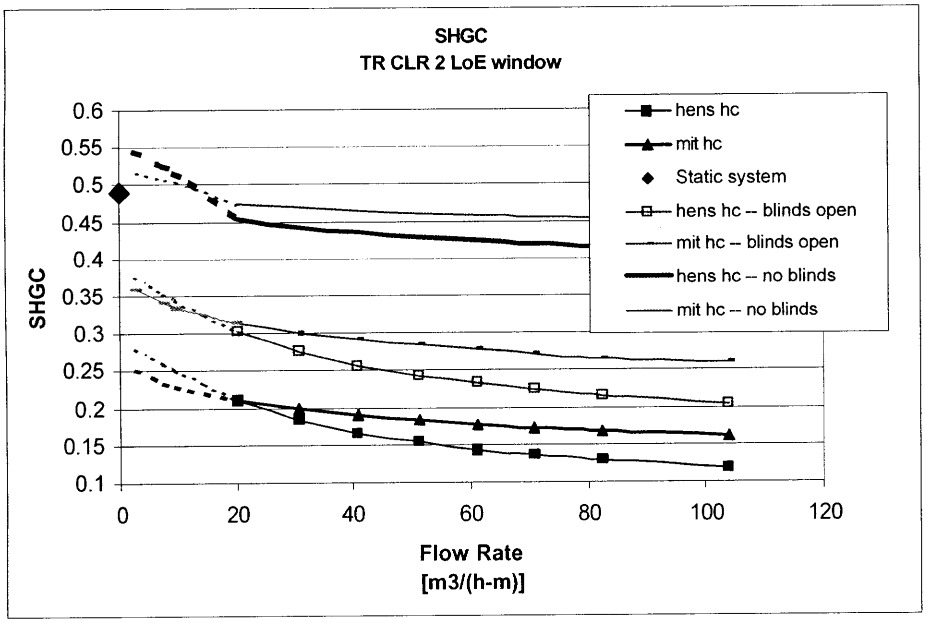


Figure 67 Comparison of systems with cavity flow model and Hens' model

Figure 67 above examines the effect of airflow on the window system labeled TR CLR 2 LoE a triple glazed unit with two low-E coatings. The predictive values for SHGC as given by the mathematical model developed for this paper can be seen varying as a function of volumetric flow. The uppermost curves are for a window with no shade and generally point to a value in the range of 0.5. This is more or less the value given by the Window 4.1 program. One can see that a volumetric flow rate of 40 m^3/hm will reduce this SHGC from 0.5 to approximately 0.25 ~ 0.30. (Depending on the heat transfer coefficient used in the cavity. When the blinds are closed (the default position) the value is further reduced to 0.16 ~ 0.18 for the same flow rate of 40 m^3/hm. Two curves are shown for each condition, the Hens heat transfer coefficient model and the "MIT" model, which in this case is actually the cavity flow model. More on the heat transfer coefficients is discussed in section "4.2.7a Alternate heat transfer models".

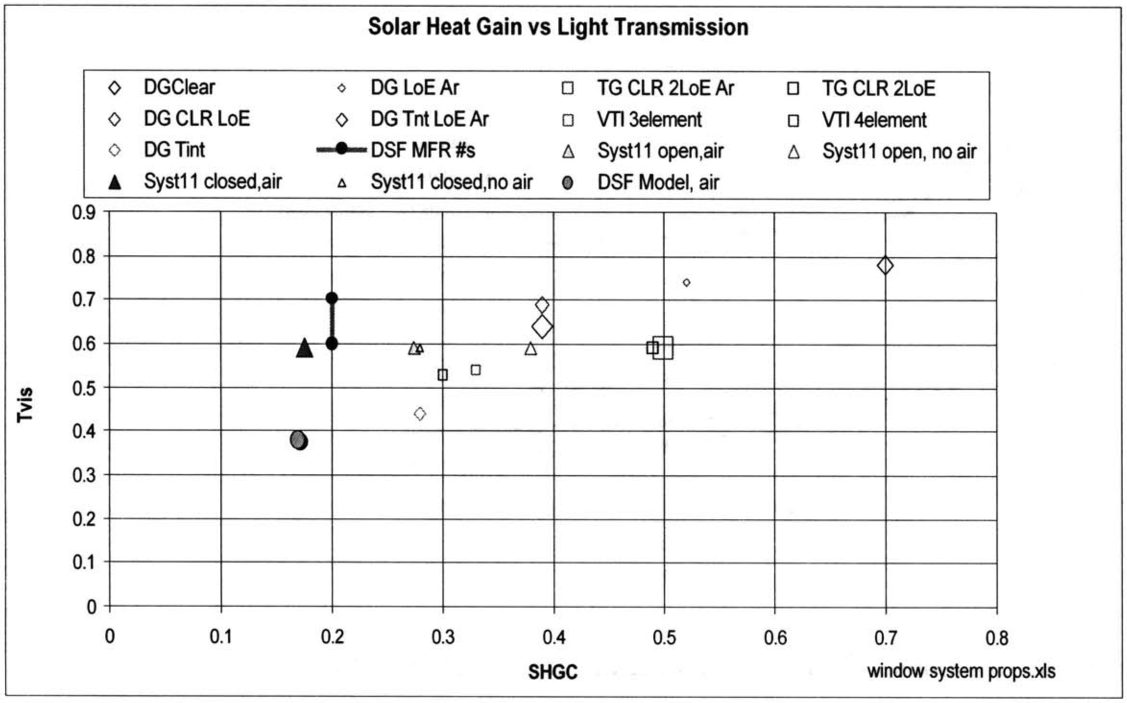


Figure 68 SHGC and Tvis for standard and DSF systems

Table 1: Key for window comparisons

Abbreviation	Description of system	Tvis	SHGC
Double Glazed			
DGClear	Double glazed clear glass	.78	.70
DG CLR LoE	Double glazed clear glass with 1 low-e coating	.69	.39
DG Tint	Double glazed tinted glass	.44	.28
DG LoE Ar	Double glazed low-e glass, argon filled	.74	.52
DG Tnt LoE Ar	Double glazed tinted glass with low-e coating and argon filled	.64	.39
Triple Glazed			
TG CLR 2LoE	Tripled glazed clear glass with 2 low-e coatings	.59	.49
TG CLR 2LoE Ar	Tripled glazed clear glass with 2 low-e coatings and argon fill	.59	.50
VTI 3element	Double glazed system with film between by Visionwall Technologies	.54	.33
Quad Glazing			
VTI 4element	Double glazed system with 2 films between by Visionwall Technologies	.53	.30
Model Variations			

Syst11 open, no air	Tripled glazed clear glass with 2 low-e coatings as modeled in spreadsheet (similar to TR CLR 2LoE above) Blind spacing is 2 meters.	.59	.38
Syst11 closed, no air	Syst11 with blinds closed.	.59	.28
Syst11 open, air	Syst11 with blind spacing 2 meters with 40 m^3/hm airflow through cavity	.59	.275
Syst11 closed, air	Syst11 with blinds closed and with 40 m^3/hm airflow through cavity	.59	.175
Double-skin Facade			
DSF Model, air	Double-skin façade properties given by manufacturer Permasteelisa.	.60 ~ .70	.20

By plotting SHGC's against visible light transmission we can see principle properties of the fenestration that are particularly important to study in large perimeter to floor area commercial/office buildings. An ideal façade would maximize visible light (top) and minimize shgc (left). The chart appears to reveal that the DSF is exemplary, breaking from the trend that the static windows set.

One must always consider the optimum energy strategy more holistically. The Stata Center at MIT is designed as a computer-intensive classroom and laboratory building. A study by the author of showed that load balances and local weather conditions indicated that a conventional curtain wall with a U-value of 2.6 (compared to 0.55 for a DSF) would out perform the double-skin façade. While this is an unusual programmatic building use, it points up the importance of considering envelope strategies carefully.

4.5.2b Solar Architecture Typologies and Design Approach

> *Passive systems are fundamentally different from active space-heating systems in that most passive system components are part of the building itself. Therefore the design of passive systems takes place earlier in the architectural design process than does the design of active systems. [Kreider and Keith 1982 p. 151]*

Solar architecture is typified by the need for a holistic approach to design and the design process that supports it. The importance of recognizing system interconnections is paramount. A prime example is the consideration of thermal mass and adjustable systems. The design of buildings with double-skin facades should be informed by this concept. The use of the model should be taken within the context of broader goals than just energy.

4.5.3 Defining Value for Individual Properties

Value implies a human aspect to evaluating materials. We may value energy, daylight, individual environmental control, global and local ecology, initial or maintenance costs. So far we do not have a model that quantities value for architectural decisions. LEEDS is a system that is under development that assigns value to issues of sustainability. It claims to evaluate environmental impacts of building on a "whole building" perspective over the life of a building, and to provide a "definitive standard for what constitutes a 'green building'" [US Green Building Council 1999]. Unfortunately there is a long way to go in properly assigning value to different attributes of a building. The system is meant to be a national (U.S) system, but doesn't address the variety of building types and climatic zones, or the regional differences in product availability. Can the utility that various properties of a building be assigned in a rational manner? This is doubtful. LEEDS version 1.0 assumes implicitly that environmental, energy and indoor air quality issues are independent of human occupancy. Version 2.0 recognizes that human impacts of controlling lighting and ventilation are valuable. This is a step in the right direction, but becomes less rational because the actual performance of the building will no longer be certain; it will be subject to human whim. And so it should be. While it is important for designers to be cognizant of the properties of window systems, value judgments will eventually need to be made. The more data that is on the table the better will be the quality of the decision, so designers should be comfortable with the trends in parameters and their effects on achieving the goals of the design.

5.0 Design Implications and Technology Transfer

Designers face many challenges in adapting DSF technology to other contexts. Some work has been carried out for projects outside Western Europe including a completed building for NEC in Japan, a design for skyscraper by IOKP architects for Hong Kong, and two U.S. buildings. But what must be considered in order to transfer this technology? There is a range of issues that is important to the success of any DSF project.

It is also important to understand that there is a limited understanding of existing projects in their initial context. While there has been some analytical work done in recent years, it has come late in the adaptation of DSF's to commercial buildings. In an article that was published after the Commerzbank and RWE towers were both completed, one author lamented that, "although extensive computer studies have been carried out, no-one knows quite how the whole thing will work...The whole building will be extensively monitored in use... it should also have many lessons to give to future buildings"[Davey 1997a p. 38]. Yet, dissemination of information is not efficient, and many hold their knowledge as proprietary.

Among the considerations that must be addressed are aesthetics, day lighting, interaction with mechanical systems and loading, control systems, local climate, culture and economy, and lifecycle impacts. Additionally, the project team structure plays a role in the potential success of implementing new technological solutions.

5.1 Aesthetics and day lighting

5.1.1 Aesthetics

A leading architectural reason for using DSF's is to capitalize on their high-tech image of transparency. The Helicon and RWE are two buildings whose partís are based on maximizing transparency. The Helicon is meant to be sleek and to allow visual connection between the city street and retail space within. RWE is meant to be an elegant cylinder-within-a-cylinder. Neither is as successful as they might first seem. Transparency through multiple layers of glass is highly dependent on the angle of light falling on the surface and the relative brightness on either side of the façade. Some of the projects, including RWE, have low-iron glass that doesn't have the same familiar green tint that most commercial buildings have. This is particularly the case with low-E coated glass. At RWE, the clear glass is made viable because of the shading capacity of the DSF.

Based on Norman Foster's other architectural masterpieces, it can be imagined that the Commerzbank building is meant to be very light and transparent. It has, however been criticized as being to the contrary [Davey 1997a]. Perhaps, this is because of the enormous clear spans that allow the winter gardens to be very open and airy spaces that necessitate deep spandrel panels and make floor-to-ceiling glass impossible. On the whole, this author believes that the building succeeds at being light, if not airy. It doesn't however compete with RWE in being transparent. Further, the DSF does not aid in the transparency. In fact, the blinds tend to have the opposite effect.

One advantage of having the fixed-glass exterior of the DSF is architectural; the outside of the building tends to look uniform even when air and light control mechanisms are in a variety of configurations exist just behind the outer layer. This is particularly successful at the Commerzbank because of its large scale, degree of opacity (about 40% of the wall is opaque spandrel glass), and distance of observation (the tower is not only high, but also shielded from close observation by the location of neighboring buildings). But this is not always the case. Adjustable blinds that are close to the outer skin will be quite visible, particularly when illuminated by the sun. If the control regimen for a given façade is not centrally handled (rather than by users), then the look of the façade will be varied rather than uniform. The desirability of uniformity versus organicism in the façade is subjective, but the designer must be aware that the DSF alone does not guarantee either trait. Kohlbecker proposes a countervailing argument to the sleekness of RWE with the example of Renzo Piano's Daimler Benz tower in Potsdamer Platz, Berlin. The outer skin of this building consists of small-scale glass panes on horizontal pivots. This louvered skin opens and closes automatically, creating a "delicate and subtle" façade that offsets the inner and outer facades against each other, rather than trying to make the whole assembly transparent [Kohlbecker 1998 p. 40].

5.1.2 Day Light

Access to daylight is a critical element in holistic design. As previously mentioned, in Germany it is mandated that workers be within seven meters of a window. The result is buildings that take the form of cylinders (RWE and Commerzbank) or narrow slivers with double-loaded corridors (Debis building by Renzo Figure 69) [Evans 1997b p. 47].

Figure 69 Debis Building site plan

The outer glazing is intended to protect the sun control blinds that minimize glare and redistribute daylight throughout the room [Buchanan 1998 p. 36]. However, this proves not to be the most effective way to accomplish this task. The blinds are infrequently in the ideal location because building management systems are not sophisticated enough, or are not programmed carefully enough. People are probably the best mechanism for optimized daylight control, but they are not likely to adjust the sunscreens frequently enough to co-optimize glare control and electric light usage. Often overlooked, blinds have some severe limitations with glare control. Because they are generally opaque, they set up a condition that is prone to high contrast between the shaded back side of the blind and the bright exterior (especially when direct solar illumination is present). Some systems are better than others. At the Helicon, the blinds are perforated so that a percentage of the blind also admits light penetration. This is minimally detrimental to the energy regimen, but beneficial to visual comfort. Some systems are also worse than average. Those with dark blinds, as at the New Parliament Building, exacerbate the situation.

There is a cultural aspect to daylight and transparency. The architectural profession is generally prejudiced to appreciate maximizing both of these. This near-obsession should be questioned. The balance of solidity and lightness or opacity and transparency can offer a complexity of visual and thermal interests that may be valuable not only to architectural design but to the human psyche as well. There is a cultural aspect of light that is not addressed in all-glass facades that should be considered in transferring DSF's from Northern Europe to other locations; In sunnier climates, there may be a desire not only to be cool indoors, but also to be visually separated from sunlight. While DSF's may be adjusted to obscure vision, the designer should examine their potential use for new cultures.

Part of the appeal of transparent buildings may be in their novelty, as well as their aesthetic quality. The first glass towers in a city may be welcome forerunners of a sophisticated future in which the advancement of society is portrayed through ephemeral edifices. It is also possible that they will be the harbinger of a world of hard surfaces, reflecting noise and visually confusing light in an environment that has lost the tactile and grounding quality of stone and brick. Designers should consider the use of double-skin facades judiciously.

Daylight should be used to offset the use of electric lighting. Dimmable fluorescent fixtures should be used only to the extent that they are needed because sufficient daylight doesn't exist. Sophisticated building management systems can be designed to compare the energy benefits of admitting solar radiation and associated heat gain with using electrical lighting with *its* internal heat gain. Otherwise, decisions will be made solely on intuition.

5.2 The Effect of DSF and MEP system interdependency on loads

Unlike typical static systems, double-skin facades tend to force designers to consider the interaction of traditional architectural elements of the façade with traditional mechanical requirements of space conditioning and human comfort. Many of the European models take a step away from designing mechanical systems to condition space and toward the goal of conditioning people. The difference is in considering comfort conditions and occupied times rather than conditioning all of the air in a building all of the time. A good example of capitalizing on the interdependency of high tech facades and HVAC systems is the Commerzbank. The load reduction of the facades is coupled with natural ventilation, nighttime "free cooling", and the moderating effects of the (enormous and costly) winter gardens. The chilled ceilings are made possible due to these reduced loads. The cooling capacity of the hydronic ceilings is marginal unless solar loads are minimized. The combination of cold ceilings and natural ventilation means that the temperature of the ceiling is not as low as it would be if the building were sealed so the risk of condensation of hot moist exterior air entering the operable windows and coming in contact with the ceilings is reduced. The externally ventilated facades at Commerzbank, RWE and Victoria Insurance are not physically tied to the mechanical system with ducts as are ABN-Amro and others yet their impacts on the design process is significant. The architectural design is dependant on the functionality of the envelope system for its success. The entire space is formed by the mechanical system: windows are load filters, ceilings are cooling elements, floors in other buildings are ventilation channels, and structure is a thermal storage device. Each member of the project team must consider its role as influencing each of the other members. Communication between each entity and efficient sharing of information is essential

One of the primary goals of DSF's is to reduce impacts of solar radiation on building climate control and comfort. The relative importance of solar loads varies from building to building and location to location. The relative importance of solar load to internal loads such as those from equipment, computers and people should be understood for most commercial and institutional buildings. For buildings with demanding air quality constraints (health care facilities and laboratories), the importance of envelope loads may be less significant than airside loads. The thoughtful designer will compare impacts of solar radiation on overall building loads. The impact will vary based on latitude and façade orientation.

The relative importance of the envelope to building loads will also be different in a typical U.S. building compared to the European model. U.S. buildings tend to be significantly deeper, meaning that there is more internal occupied space that is not influenced by the façade as compared with their thinner European counterparts.

Even with the smaller floor plate at the Commerzbank, one must be certain to consider overall energy savings as the result of the building design and its systems, *not* solely as a result of the envelope. It has been suggested that in Foster's building, the greatest savings may well come from the naturally ventilated atrium and gardens [Buchanan 1998]. While the windows are an important aspect of the natural ventilation, there are other means that the ventilation might have been accomplished such as with operable louvers or other vents.

5.2.1 Load Shifting

When architecture and engineering systems are designed together, it is possible to consider diurnal weather cycles and to use passive cooling strategies. Many northern European regions are perfect for implementing strategies of night cooling. Such a strategy combined with the load offsetting of DSF's lead to the installation of different mechanical systems of a reduction in the design size of the systems. This is highly dependent on local climate, internal loads and occupancy factors, and must be considered anew if DSF technology is to be transferred to new climes. The diurnal swing must provide a reasonable average temperature for most of the summer months so that enough "coolth" may be collected during the nighttime to balance the load reduction necessary during the daytime to keep spaces comfortable.

5.2.2 *Impact of Floor Plate Depth on Load*

Load proportions vary dramatically by window area to floor area ratio. This means that overall building layouts will effect the successful implementation and cost benefit of double-skin facades and windows. A common European office building has a narrow perimeter office depth of about 7 meters. Common U.S. buildings have deeper perimeter depths of 15 to 20 meters. Below, in Figure 70 and Figure 71, is a comparison of the two for windows that are half the height of the space. They consider the impacts of energy loads as affected also by switching between System 11—the triple glazed window with two low-E coatings—and a double-skin façade – with one low-E coating. In Figure 72Figure 73 the same comparisons are made for a full height façade.

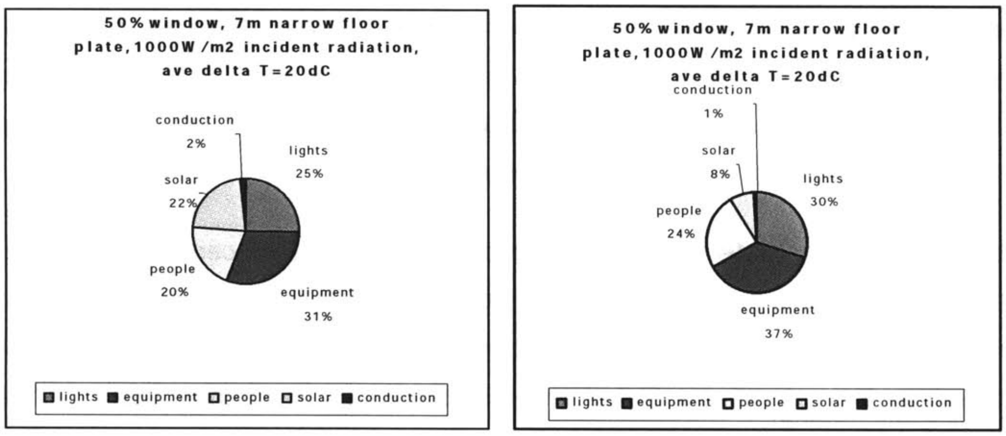


Figure 70 Loads for narrow floor plate building: Triple low-E glass (left) and DSF (right) windows

Figure 71 Loads for deep floor plate: Triple low-e glass (left) and DSF (right) windows

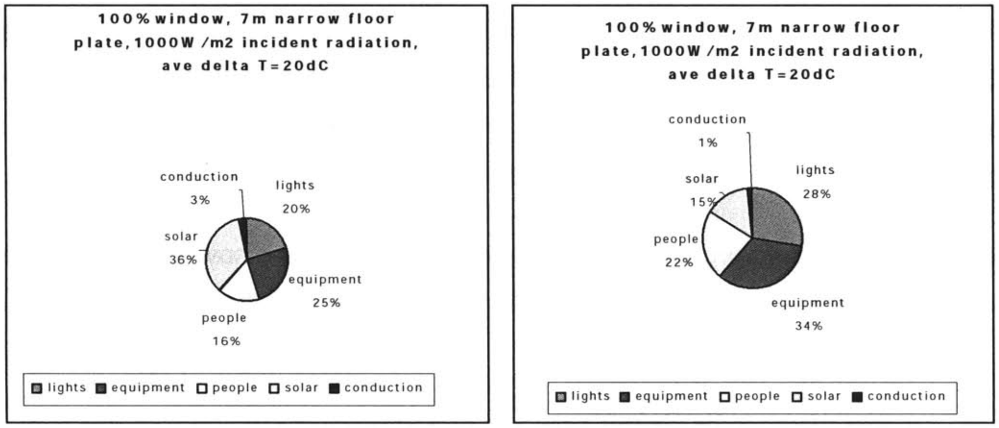


Figure 72 Loads for narrow floor plate: Triple low-E glass (left) and DSF (right) facades.

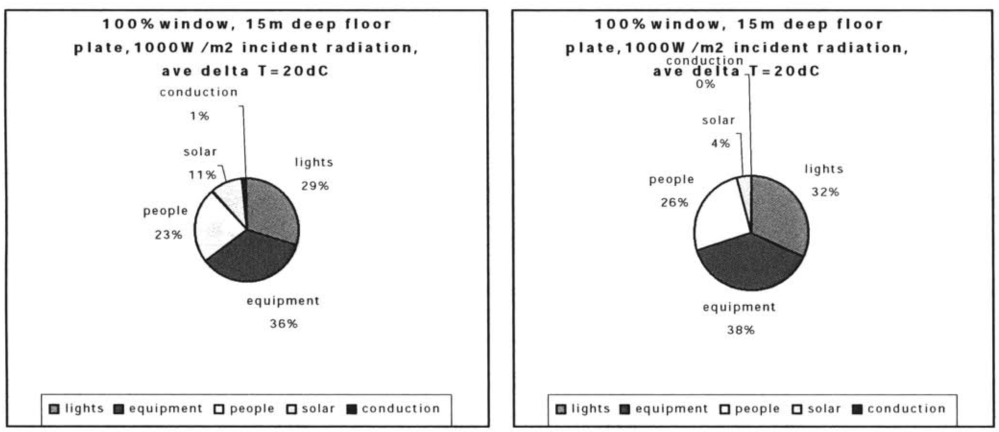


Figure 73 Loads for deep floor plate: Triple low-E glass (left) and DSF (right) facades.

5.2.3 Volumetric Flow Rate and Fan Power

The relationship between ventilation or heating and cooling air supply to a room and the volumetric airflow rate desired for the window system is important to understand. If the flow through the window is equal to or less than the rate that is required for the room then there is no penalty for fan power to move the air through the window, and no additional ductwork required. If the flow rate desired for the windows is greater than the room flow rate, then there will be additional fan power required to run the window system.

Figure 74 shows iso-air-change lines indicating the distance from the façade at which the requirements for the room at a given air change rate and the window flow rate are in balance. For the most common volumetric flow rate of 40 m^3/hm the typical 7m deep European office balances with approximately 2 air changes per hour. The 15m deep US model balances at about 1 air change per hour (ACH). This means that additional exhaust would be required to provide more than 1 ACH. The good news is that additional fan power would probably not be required in US buildings. However, depending on the system this may be perceived as a parallel or additional system to be coordinated and constructed.

Figure 75 shows the same data organized by fixed flow rates. It shows how a fixed flow rate through the window provides diminishing air exchange for the room as the depth of the room contributing to the window flow increases.

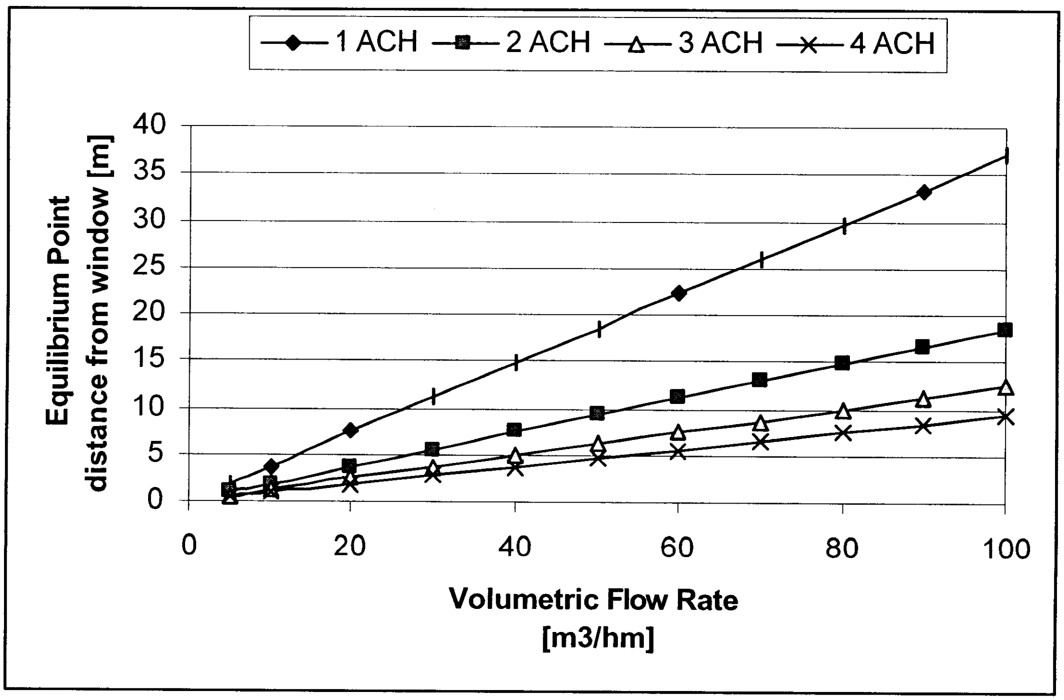


Figure 74 Equilibrium distance for room and window ventilation by air changes per hour

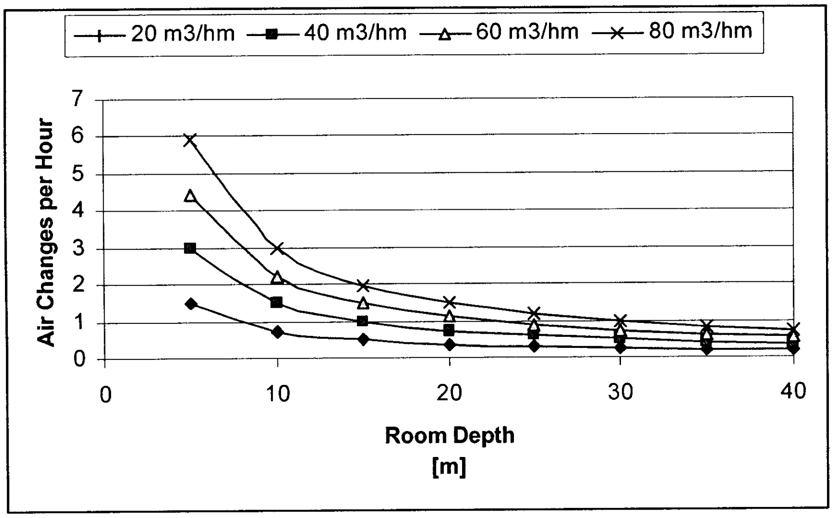


Figure 75 Air change rates based on fixed volumetric flow through facade.

5.2.4 Potential for Load Reduction and Capital Cost Avoidance

One reason to minimize extraneous loads on the building is to reduce the design peak loads so that capital equipment may be of minimal required size. Oversized equipment tends to be both more expensive initially but also tends to be less efficient in operation. A significant side benefit of smaller equipment is that it requires less housing. The smaller it is, the less constructed building volume must be allotted to housing equipment. In turn, the space may be given over to human occupancy or it may not need to be built at all.

There is also the potential to eliminate systems from designs in their entirety. Often perimeter heating is provided to warm windows in order to avoid condensation and to increase the mean radiant temperature of that part of the room. However, if the thermal properties of windows are good enough, then the windows take care of themselves, and perimeter radiation need not be included. Heating of the room may be achieved with systems that are already in place to either cool or ventilate the room. This strategy has *not* been actively pursued in many buildings. Commerzbank, Victoria Insurance, RWE and others still use the perimeter approach in addition to radiant ceilings.

Architects and engineers must understand their buildings not only in terms of appearance, spatial qualities and functionality, but also in terms of energy performance. It is the role of architects to integrate performance criteria with traditional architectural criteria. This is particularly important in transferring technologies from a particular context, and others.

Architects must understand the basic relationships, of loads, building form and use, as outlined in this section.

5.3 Policy, operating and life-cycle costs

The accounting and evaluation of building costs are slowly evolving to include operational and maintenance costs of the building in addition to initial capital costs. As the construction industry adopts this approach, credit will be given to upfront costs that lead to cost savings over the life and use of buildings. For building systems, the envelope is second only to the structure in longevity. Facades therefore have the potential of providing reasonable a financial payback over their life span. There appears to be an incentive to ask design professionals to study such options for the benefit of project owners.

In public forum, Alex Krieger, head of Harvard University School of Graduate Design, said that architects should not be told to design "green buildings", that they should be enticed by the "fashion" of the day. He believes that such design will not happen in the U.S. until "energy costs are as high as they are in Europe" [Green Building Conference 2000].

Still, there is a significant up-front cost at present. "The cost of innovative curtain walls, with their controls and motors, can't yet be justified – even in high-energy-cost Europe – without a design that optimizes thermal performance, lighting and [HVAC performance]" [Pepchinski 1995]. Pepchinski writes that in Europe in general and in Germany particularly, the role of government in encouraging environmental design is significant. In that country, energy use standards were reduced by 30% in 1995 and were slated to be a total of 50% by the year 2000. In addition to this stick, grants and subsidies are available for the use of many environmentally sensitive technologies.

Facades should be designed to last a long time, by minimizing internal condensation and by shedding rain so as to minimize water infiltration. Durable materials should be used that minimize internal degradation. Glazing and spandrel panels should be easily replaced if new glass or photovoltaic technologies are developed during their useful life.

At the end of their life, they should be demountable. This means that they can be easily taken down and separated into constituent parts that can be reused or recycled. The modular design of some of the tall buildings was done for ease and speed in on-site assembly. The same design may facilitate disassembly or changes, but that is not necessarily the case. The design of the Commerzbank modules is for sequential assembly from bottom to top. The panels are interconnected in a fashion that will make replacement of a single panel in a field of panels exceptionally difficult [Colin and Lambot 1997].

Ospelt has outlined an approach to life cycle assessment (LCA) for buildings. LCA considers the entire impact of buildings from resource procurement through the life of the building and decommissioning. He suggests that once a building is planned, and its location set, designers have many considerations left to make. "A long-term perspective and assumptions about the future of the building are necessary...the lifetime of different systems has to correspond to the long-term scenario for the building [Ospelt 1999]. The use of aluminum for curtain walls is clearly a high-embodied energy choice. However, it may make sense in the context of commercial, and particularly high-rise commercial structures that have difficult and costly maintenance concerns. The Stadttor is a remarkable exception to this rule. The DSF is comprised of an outer layer of glass, and an inner layer of wood frames. Wood is renewable and if it is provided from sustainably managed forests, can encapsulate CO_2 for a period. Because it is protected from the weather, its maintenance is less. A meter-plus wide cavity allows ready access to all surfaces for care over the life of the building. Using an exterior skin of bolted glass rather than continuous frames will dramatically reduce material consumption.

The use of glass is difficult to minimize, but should be considered as well. Suspended film technologies may replace interstitial glass and provide comparable performance.

Local production and access to technologies and materials must be considered in light of life cycle analysis. Rather than importing the actual materials to Tokyo, for instance, it may be best to consider local or regional alternatives. Importing knowledge and applying it to construction with local materials may be the best solution of all.

5.4 Control systems

Beyond the selection of systems, they must also be incorporated into the building as part of an organism. Carefully designing the control system does this. This must be tested during design, implemented during building commissioning, and refined and verified during operations.

Static windows in U.S. commercial buildings are usually only controlled for glare and privacy by adjusting interior blinds or shades. Some windows in passive solar buildings are considered part of an overall strategy and have movable insulation or are operated more actively. There is a history of interacting with windows more in residential buildings than in commercial buildings. People will adjust their windows to block summer heat and open them to allow cool night air to enter. This is a practice that is arguably waning as homes are becoming increasingly air-conditioned. Other cultures, and other times, there has been great interaction with and control of blinds. Exterior blinds, shutters and roll-screens are still popular in most hot locations, whereas the American southwest has grown up with air conditioning at the ready.

The incorporation of double-skin facades has the potential to reinvigorate the commercial sector in its acceptance of a varied envelope that requires attention so that it remains tuned to the cycles of weather, sunshine and noise. Two types of controls will need to be married to achieve the greatest success: user (occupant) control and centralized (building management system) control.

5.4.1 User Control

Double-skin facades are equipped with options for the building occupant. They typically contain Venetian-style blinds that may be adjust by rotating the angle of the blind or by raising and lowering the blind. This control strategy is useful for controlling solar heat gain, view and privacy. The down side is that when the sun shines on blinds that are partially closed, glare conditions may be created due to the vast difference between the brightness of daylight and the shaded back side of the blinds.

Translucent fabric shades are sometimes provided in addition to blinds. These roll down devices provide uniform light conditions that do not have the same glare side effects. However, they are a binary response that is either in place or not. This is typically an add-on system. Some buildings use this blind in place of the inner layer of glass and instead of the Venetian blinds. The space between the outer glass and the roll down shade create a cavity through which air is forced as part of an interior ventilated façade. This system is more economical than the typical system described in this paper, but will likely be less efficient because of the proximity of the shade to the occupied space.

Windows have a host of operation options from windows that tilt and turn to doors that pivot or slide. These windows will have varying degrees of success at creating conditions for ventilating the occupied space. Design consideration must be given to facilitate either through or one-sided ventilation. The criteria for systems in hot climates will be more demanding than in the moderate German climate, for example. The efficiency of tilt-turn windows such as the ones in Commerzbank may not be appropriate where large volumes of air movement are required. Either full-height openings or top and bottom opening windows may be more appropriate.

Occupants control window elements as they see fit: to adjust lighting, view or perceived thermal comfort. However, at times, these actions may be in direct contradiction of what is best for energy performance or thermal conditions. For example, warm weather may entice an occupant to open the window. This can provide psychological comfort by admitting a breeze at the expense of letting hot air into the room that will add to the cooling load of air conditioning. In high-rise buildings, opening windows can also create pressure differentials that make opening doors or simply securing paperwork difficult.

Educating and informing occupants is valuable. Implementing a building-wide protocol for window operation can help to guide window control toward sensible and beneficial results in terms of the multi-faceted goals of building management. Sophisticated building management sensors and controls are often worthwhile.

5.4.2 Building Management Systems and Interfaces

Commerzbank and other buildings have weather stations that detect outdoor conditions and relay them to a central building management station. Digital connections to all motors and pumps in the building allow the system or system operators to adjust blind and window positions as well as ventilation, radiative cooling and heating, and lighting. Zones are uniquely small; each room may be controlled individually.

A sophisticated algorithm is required to manage this system.

The building management system at Commerzbank is designed to continuously adjust the Venetian blind blades via motor so that they will protect the building against solar penetrations during the heat of summer and so that they will serve as light shelves during the winter. It is not clear that the system is actually working in this manner. Rather it appears that blinds have closed and open positions and that they are only readjusted about 3 times per day (morning noon and night). This is indicative of the sensitivity of users to working in an automated buildings; it can be distracting or even unnerving to work in a place that is animated remotely by motors. This system might be improved by being able to provide quiet motors capable of micro adjustments rather than the loud and gross adjustments that are (apparently) available with the current technology.

SOME QUESTIONS FOR THE BMS TO ANSWER

- Is the space occupied now, or when is it scheduled to be occupied?
- What are the exterior temperature, wind speed and velocity, and humidity?
- What is the incident solar radiation, intensity, altitude and azimuth?
- What is the prediction for temperatures over the next 24 hours?
- Is daylight desirable? Is solar radiation gain useful? Compare to electrical load.
- If the space is occupied, is electrical lighting required?
- Is room conditioning required?
- Do conditions exist for condensation on cooling panels? On window surfaces?
- Will natural ventilation be beneficial for comfort? Will it be beneficial for energy consumption?
- What recommendations or requirements should be made to building occupants?

5.5 Climate

Humidity is one factor that will be critical to consider for its effects on comfort, need for dehumidification, and condensation control. Condensation control is an issue for passive design strategies (thermal mass) and radiant (hydronic) systems.

Mahadev Raman of Ove Arup and Partners is quoted as saying that, "You don't have the summer humidity in many parts of Europe that is characteristic of much of the American East Midwest and South. You have to look at whether radiant cooling will be able to make enough of a temperature differential to work" [Russell 1995 p. 84]. The potential to use radiant panels has been an important condition in the economic and energy planning of buildings with DSF's. The DSF's can make the difference in reducing energy loads enough to make the radiant panels feasible. Once the panels are feasible, the floor-to-floor height of the buildings may be reduced from what they would need to be for all-air cooling systems.

It may even be a consideration on the more fundamental level of condensation within the double-skin wall. Anecdotal information indicates that this has even been a problem in some European buildings, and would more likely be a problem in US climates that are particularly humid or cold.

Beyond the technical issues of condensation control, a designer must first consider the very potential for using natural ventilation. It is plain to see that the number of hours that the natural ventilation options will be desirable and effective in locations such as Pheonix, Miami, and even Minneapolis may be far fewer than is found in London, Frankfurt and Amsterdam.

5.6 Culture and economy

There is general consensus that European projects are more advanced than American projects in terms of environmental sensitivity. Certainly there is a wider range of exemplary work in Europe. Many ask why this may be.

Occupant requirements that pushed the implementation of DSF's in Germany, and leading to the popularity of the systems do not exist in the US. European workers have demanded access to daylight and outside air at a level not witnessed on this continent. Office workers cannot be located more than 7 meters from a window [Evans 1997b p. 47]. However the trajectories of issues like indoor air quality and human welfare may provide the impetus for US markets to catch up on this issue. However, the dollar may continue to speak louder than the people for some time. Deep-plan buildings will predominate when developers are considering solely cost per square foot. Access to daylight is only beginning to be revived as an important issue for American workers, and management is not yet sold on the economies of worker satisfaction and productivity that is augmented by views, fresh air and comfort.

> *[The deep-plan American-style office building is] efficient only in relation to initial capital costs and net-lettable-to-gross-floor-area ratios. But in terms of the far higher energy costs over the life of the building, and even more so in terms of the health and happiness of the workers inside (whose slaries will account for very many times the capital [and maintenance] costs), such buildings are extremely inefficient [Buchanan 1998 p. 30].*

Further, one of the strengths of DSF's is their ability to be controlled. Operable windows in open office plan are an extreme challenge in trying to provide energy efficient comfort levels, and this is the predominant building typology in the US. "The windowless cubicle landscapes of American office buildings are virtually outlawed in Germany" [Pepchinski 1997 p. 148] The European office tower model has perimeter office cells that can be isolated by control mechanisms. Part of the incentive for and success of the Commerzbank in the eyes of its occupants has been the *perception* of comfort that comes with the greater level of occupant control that comes with operable windows [Buchanan 1998].

As advanced as the European market may seem, "ecologically based briefs [owner's project descriptions] are still the exception. Much depends on the client being able to persuade enough commercial tenants to share in the dream "[Dawson 1997]. "Large buildings that employ environmentally responsible technologies are still the exception in most of the Europe today" [Pepchinski 1995 p. 70]. This trend seems to have reversed itself. A personal communiqué with European researchers indicated that as many as 40% of new buildings in Germany are employing double-skin facades. Pepchinski also describes that German federal guidelines have been increased in the past 5 years for daylight and insulation, while government and utility subsidies are available for "solar" technologies.

While design aspects appear well coordinated in Europe, on large buildings, some construction contracts are on a fixed-price basis. This is similar to the guaranteed maximum price contract used in the US, but in Europe it can give contractors even more power, and render architects and their engineers as consultants to the general contractor. This was the structure for the Commerzbank building. As a result, the original concept of having interior-vented extract air facades with a small single-skin ventilation flap was converted to exterior-vented double-skins without independent flap. The constructed façade was simpler to build and install, but reduced the potential for air intake in summer due to the preheating of air in the ventilation cavity [Swenarton 1997 p. 34]. An overall energy comparison has not been published.

But before writing off the European projects as successful because climate, economics and culture make advanced development far easier than in the US, consider that the standards that have been raised in Germany, for example, are not mutually beneficial. Saving energy and allowing for natural ventilation are often not complimentary objectives. Put another way, the design objective of the towers is to "move conservation and sustainability to a new level without compromising the access to natural ventilation and daylight that German workers regard as a near-birthright" [Pepchinski 1997 p.148]

It might be said that the European market is more flexible in its comfort zone as well. The Richard Rogers building to house Daimler-Benz Offices and Housing in Berlin might be considered to be a high-end building. In the US, this would certainly mean tight tolerances on space conditioning. However, Rogers designed to maximize natural ventilation by using an atrium in a sophisticated manner, but also had the luxury to let comfort standards slide. "With a targeted comfort level of not more than 60 hours annually [0.7%] above 28 [degrees] Celsius [82F]. Above 22 [degrees] -- 73F-- is regarded as comfortable by most office workers" [Russell 1995]. This point alone could be a deal breaker for many US building projects for which such a comfort zone would not be acceptable.

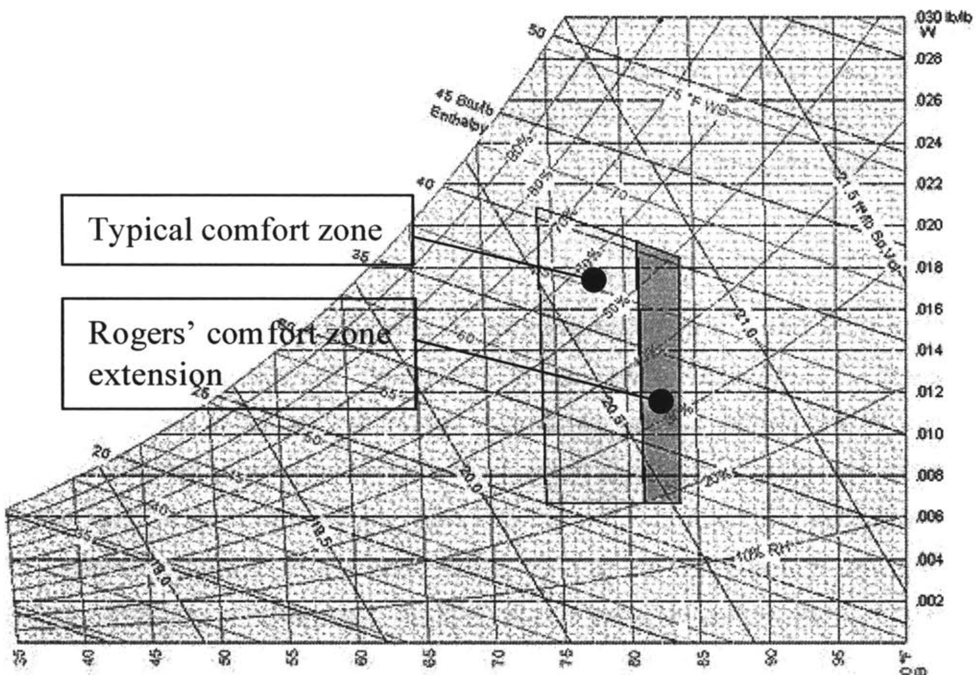


Figure 76 Comfort zone expansion for Rogers' building

5.7 Building forms

5.7.1 Flexibility

One of the growing demands, particularly in the US market, is to provide the building owner with a structure that will work well at the time of occupancy, and that will be flexible enough to accommodate changes to the programmatic requirements of building occupants.

In contrast to the US market, Germany has been characterized by have relatively uniform space requirements with emphasis placed on individual offices or offices shared by two or three individuals rather than open office plans [Evans 1997b p. 47]. This places different requirements on buildings that should be flexible over time.

Commerzbank is designed to be largely free of interior columns. The corners of the buildings have massive columns that hold story-high Vierndeel trusses which span the length from corner to corner of the building. This has dramatic aesthetic impacts including making the building less transparent than it might otherwise have been, but the result is a flexible floor plan. The DSF windows are entirely repetitive and uniform and they are not interconnected in any way. This means that reconfiguring the interior (glass and metal) partitions to make offices larger or smaller or to relocate them is rather easy. The controls for the windows are modular as well, so that there is little impediment to change. The combination of computer floors and modular ceilings and wall systems provides high finishes with minimally intrusive renovation.

5.8 Construction sequences

The DSF designer will need to evaluate impacts on cost and schedule of the project. The long-term benefits of the DSF may be accompanied by reductions in the capital expenditures for HVAC plants, but the installation cost of the façade is certain to be higher than conventional facades. Not only is there more material involved, but there is also an expectation that trades will have to interact. Not only will window manufacturers have to interact with glaziers, but mechanical and electrical subs will be involved as well. HVAC contractors must duct the active windows and specialists must install controls (for all DSF's). The issue of whether to design for site-built or prefabricated will be far more complex than with traditional windows. The designer must consider the relationship between architectural, energy and contractibility aspects in selecting the DSF typology for a given project. The fragmentation of the construction industry in the US, and the segregation of trades and professions means that each party will be looking to either shed risk or be rewarded with profits for taking on risk.

Many designers have developed modular solutions. This is particularly the case in the narrow to mid range windows such as the Commerzbank and RWE. It is also the case in the Daimler Benz building by Piano. There, windows, glass louvers and terracotta cladding articulate the façade. Where possible, the pieces were pre-assembled into story high elements that were shipped to the site as one piece [Kohlbecker 1998 p. 40].

All of this must be done within budgetary frameworks that typically focus on minimizing capital expenditures even at to the detriment of operational and maintenance costs for the lifetime of the building.

5.9 Integrated design

One must have an early start in the design sequence for buildings that will incorporate double-skin facades because it is a serious intervention in the building layout. It is not similar to switching glass type or frame types on a standard window system.

Active versions of DSF's (with forced convection) are different than conventional architectural systems because they are physically and thermally tied to the mechanical systems. Even for the passive systems, it is beneficial to consider these facades as an important part of the mechanical system and overall energy and climate control strategy of the building. Even when they are not physically attached to the HVAC system, attention should be paid to their impacts by the design team. This is contrary to typical design methods in the US that do not have strong interaction between architects and engineers. It is even possible that, without proper study in a collaborative setting, the façade may be a detriment to the design.

In the US there is a preconception that using passive systems, or other non-standard systems to replace now-standard mechanical systems proves "extremely expensive". This was stated by Norman Kurtz, president of one of the most progressive building services engineering firms in the US. [Russell 1995 p. 84]

The degree to which European design can be integrated is exemplified by the degree to which systems are integrated in the RWE Tower. The radiant cooling is used as the finished ceiling. The ceiling also houses a control panel incorporating two types of lights, light sensor, smoke detector, sprinkler head and public address system [Pepchinski 1995 p. 73]. Such well-coordinated services should be considered in contrast to typical US buildings that have different face plates for each electrical service (lights, temp control, etc). Nagel, the architect of RWE stated in a personal conversation that he would like to push this even further, intimating that the façade should incorporate some of these functions as well as power generation and other services.

It is instructive to consider the design and construction of the design offices for Josef Gartner & Company, the renowned curtain wall manufacturer that created the DSF's for Commerzbank RWE and other German buildings [Russell 1995 p. 75]. The building, completed by and published in 1995, (at about the time that the other buildings were being constructed), does not include DSF's. Certainly the company could have chosen any system for this two-story office building in Gundelfingen, Germany. Instead, they opted for thermally broken triple glazed gas-filled windows with external motorized louvers. Internal blinds also aid in glare control. The external location of the louvers may require more maintenance than if they were in the interstitial space, but being just two stories above grade, this is easily and inexpensively accomplished.

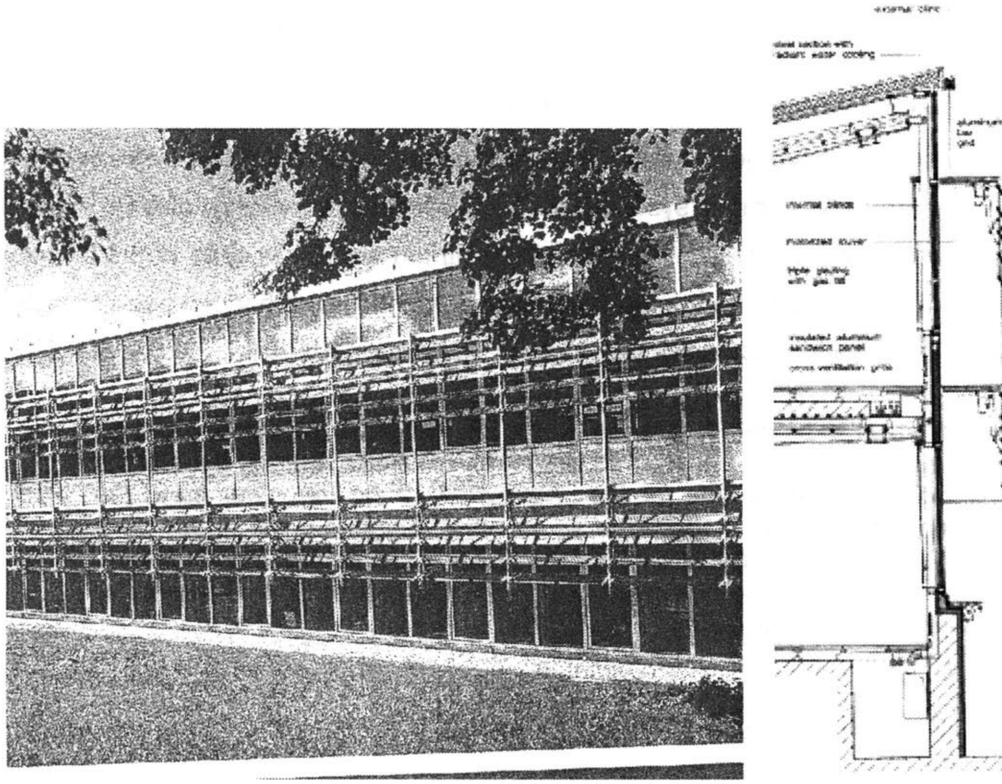


Figure 77 Joseph Gartner & Co. headquarters Gundelfingen, building section at right

The windows are complimented by hydronic cooling and heating within the tubular steel supports for the window frames. Adjacent systems include radiant ceiling panels, raised floors supplying displacement ventilation, light sensors all controlled by a central building management system. Clearly the design and control of this building requires the input of architects and engineers and, like buildings with DSF's, requires sophisticated control systems. The result is a dynamic building with a simple appearance that offers many levels of user control and that will be inexpensive to operate (depending on the reliability of moving parts). It wouldn't have been possible without exemplary communication across disciplines.

5.9.1 Role of the Owner

The importance of a strong project owner's commitment to energy efficiency is critical to the successful implementation of advanced façade systems. The brief for the Commerzbank is an outstanding example of this. Apparently only two architects satisfied the owner's requirements pertaining to their program and the environment. They required that the building use natural day light to minimize consumption of fossil fuel. They suggested that occupants be in contact with plants and that individual control of office windows be provided so that outdoor air would be available "even on the highest floors.[Davey 1997a]"

The role of the owner continues to be important through the life of the building; even after all of the design consultants have gone away. The operation of the building can make or break the success of energy and comfort systems. In the Max Planck building, utilizing natural ventilation on a warm day, the radiant heating of the atrium was on in spite of the already warm conditions. This indicates that the building management system had not been properly commissioned. Regarding the Commerzbank tower, Swenarton notes the following:

> *If the system is exploited to the full, there should be a projected 25-30% savings in energy use compared to standard buildings, plus a substantial improvement in quality of life for the employees. If on the other hand the natural ventilation option is regarded as an inconvenience it will simply be a resource wasted. [The effectiveness of the building systems] depends largely on whether the client's commitment to eco-friendliness is more rhetorical or real. [Swenarton 1997 p. 39]*

Table 2 Benefits and risks in the construction value chain

Participant	Benefits	Risks
Building owner	Leasability, image	Cost, maintenance
Lessee	Productivity, image, space-efficiency at perimeter, operational costs of tuned systems	Maintenance, operational costs of un-tuned systems
Occupant	Comfort, visual and thermal control, daylight and ventilation.	Building management system override of control, Depth of façade may be unpleasant.
Facility Manager	Energy efficiency, potential simplification of other HVAC equipment	Sophisticated control sequences to monitor, maintenance of moving parts, controlling ventilation in humid or windy conditions, interface with user control
Architect	Aesthetic potential, offering high-end product.	Complicated coordination and detailed analysis to ensure success.
Engineer	State of the art technologies, simplification of other HVAC systems	Complicated coordination, new element to discipline
Constructor	Simplification of HVAC systems, often uniform/repetitive system	Complicated coordination, interconnection of trades, knowledge of sophisticated control systems required.
Supplier	New market, high profile jobs	Expensive system with coordination risk, high profile jobs, architects and engineers may not take responsibility for design.

5.10 Applications to Tokyo, Japan

A preliminary investigation has been made to examine the potential transfer of double-skin façade technology to Tokyo. Along with the typical architectural goals – transparency, energy efficiency, comfort, etc. – is the goal of diminishing carbon dioxide emissions. Depending on the primary fuel source for heating and cooling, the environmental impacts will vary. For the purpose of this investigation the reduction of energy consumption is assumed to be analogous with CO2 reductions.

5.10.1 *Energy Calculation Model*

A simple energy model has been developed to complement the double-skin façade calculator that has been extensively described and used in this report. The energy model uses typical hourly weather data for temperature, and radiation. This has been combined with solar altitude and azimuth data based on latitude to provide a reasonable approximation of the energy context of the project. A radiation conversion routine developed by the author translates the solar energy to incident solar energy normal to a given façade orientation. It may be used for non-vertical facades, although the rest of the model would not necessarily support such a condition.

The direct normal radiation, coupled with the solar altitude and outdoor temperature is all that is needed to calculate the external energy transfer through the window. The model does not consider composite walls containing windows within facades because the focus is on the energy impact of the glazing system.

The dynamic nature of double-skin facades should be addressed so that the full advantage of being able to adjust blinds may be realized. While the SHGC is said to be around 0.15 ~ 0.20, this is always evaluated with the blinds closed. This is certainly not the position that the blinds will spend most of their time. Therefore, a reasonable, simplified control sequence is modeled. The blind position is determined as shown in **Table 3**. The nighttime, non-occupied mode defaults the blinds to the closed (90 degree) angle. For daytime, occupied mode, there are two conditions considered – the difference is the weather the incident solar energy (Qsol) is greater or less than a given level (Qsol,critical). Qsol,critical is related to the minimum amount of solar radiation required to have sufficient day light in the occupied space without using electric lighting. Above this level, the blinds may be closed to cut back on extra daylight. This is a simplification because thermal effects of the space should also be considered, as should the energy impact of the lighting itself. Still, the simple control sequence gives an estimate for energy that gives a reasonable comparison.

In a spreadsheet it would be difficult to tie this type of dynamic code for 8760 annual hours to the iterative performance model, a different strategy is used: for each hour of the year, the energy calculation looks up the current solar angle and outdoor temperature given by the weather data and the blind angle given by the control sequence in a table of values previously prepared by with the performance model. Such a table is shown below in Table 4 which gives five blind angle positions that can be used in more complex control sequences than that indicated in the control sequence described.

Condition	**Blind angle**
Nighttime / not work hours	Closed (90 degrees)
Day time and Qsol < Qsol,critical	Open (0 degrees)
Day time and Qsol>Qsol, critical	Semi-open (45 degrees)

Table 3 Basic blind control strategy

Window 1		Blinds closed shgc	Blinds 60 shgc	Blinds 45 shgc	Blinds 30 shgc	Blinds open shgc
solar altitude	0	0.1654	0.2197	0.2675	0.3211	0.4132
	30	0.1654	0.1772	0.1936	0.2091	0.3119
	45	0.1654	0.1772	0.1823	0.1978	0.2331
	60	0.1654	0.1768	0.1819	0.1865	0.2065
	90	0.1640	0.1760	0.1810	0.1857	0.1948

Window 1		Blinds closed U-Value	Blinds 60 U-Value	Blinds 45 U-Value	Blinds 30 U-Value	Blinds open U-Value
Delta T	1	0.75	0.79	0.80	0.80	0.81
	10	0.51	0.58	0.60	0.61	0.62
	20	0.48	0.54	0.56	0.58	0.59
	30	0.45	0.51	0.54	0.55	0.56
	40	0.43	0.49	0.51	0.52	0.53

Table 4 Window properties by blind angle, temperature difference between inside and outside and solar altitude.

These values are then fed into a simple calculation, looking like this:

$$Q = Q_{solar}(SHGC)A + UA(T_{out} - T_{in}) + Q_{internal}$$

where $Q_{internal} = Q_{lights} + Q_{equipment} + Q_{people}$ and is binary; it is on during working hours and off otherwise.

The potential to benefit from natural ventilation is not addressed in these calculations. Neither is energy gained (or lost) due to mechanical ventilation.

5.10.2 Test Case for Tokyo

Energy calculations of this type are run for a standard interior-ventilated double-skin façade. A south-facing space that is 7 meters deep is considered and compared to system 11, a triple glazed window with two low-E coatings called TG CLR 2loE described in on on page 153 above. System 11 has a U-value of 2.21 W/m^2K as given by the Window 4.1 program.

The results are that the double-skin façade will require 10 kWh per square meter of floor area per annum for heating and 226 kWh/m^2 per annum for cooling. System 11, the static system (with no blinds) will require 39 kWh/m^2 per annum for heating and 274 kWh/m^2 per annum for cooling. The overall difference relates to a 27.4% savings for using the DSF in place of the triple glazed window with two low-E coatings. This is summarized in Figure 79. Note that the visible light for the double-skin façade is less than that of system 11 even though there are two coatings on the latter. This deficiency of the DSF can be improved upon without significant energy penalty by more careful glass selection or more sophisticated control sequences and light dimming. In addition, using thermal mass to trim daytime loads when nights are cool will help.

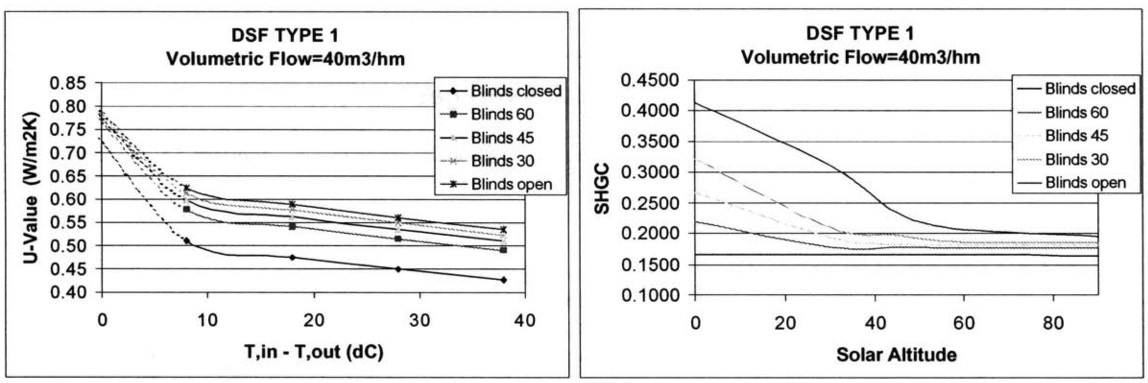


Figure 78 Resultant properties for windows with various blind positions

Determining the value of this energy will vary greatly with exact location and economic variations. The cost of a kilowatt-hour of electricity in New England has been extremely stable, at about $US 0.10. Applying this cost to a savings of 78 kWh/m^2 per annum gives $7.8/$m^2$ per annum. For the 7-meter deep section in question, this is a $55/yr savings. This savings was generated from 2.7 m^2 of window that would carry an additional up-front cost of (roughly) \$300/ m^2 or a total of \$810/m^2. The simple payback period would be just under 15 years. This is approximately ½ to 1/3 the life of the façade.

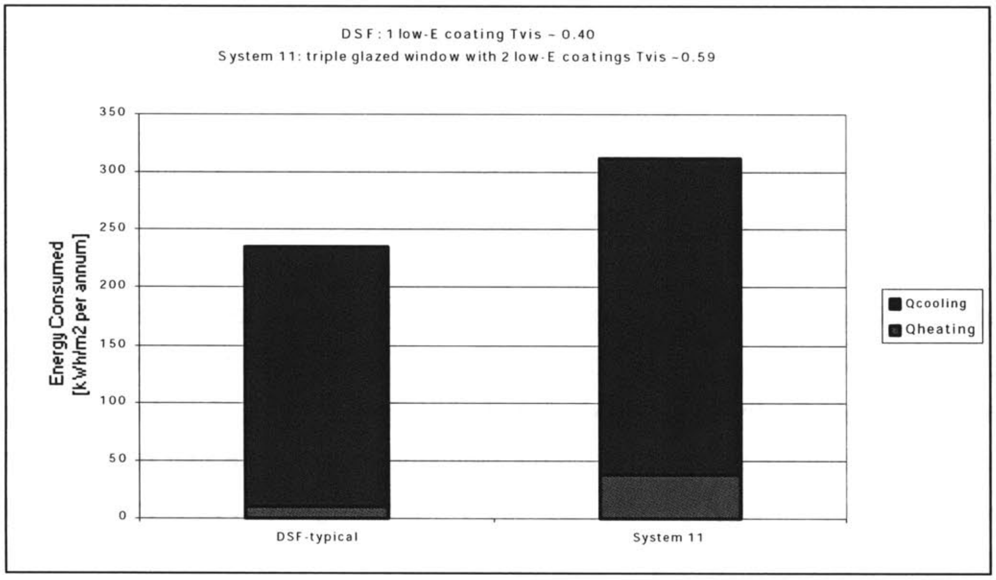


Figure 79 Energy consumption based on hourly weather data

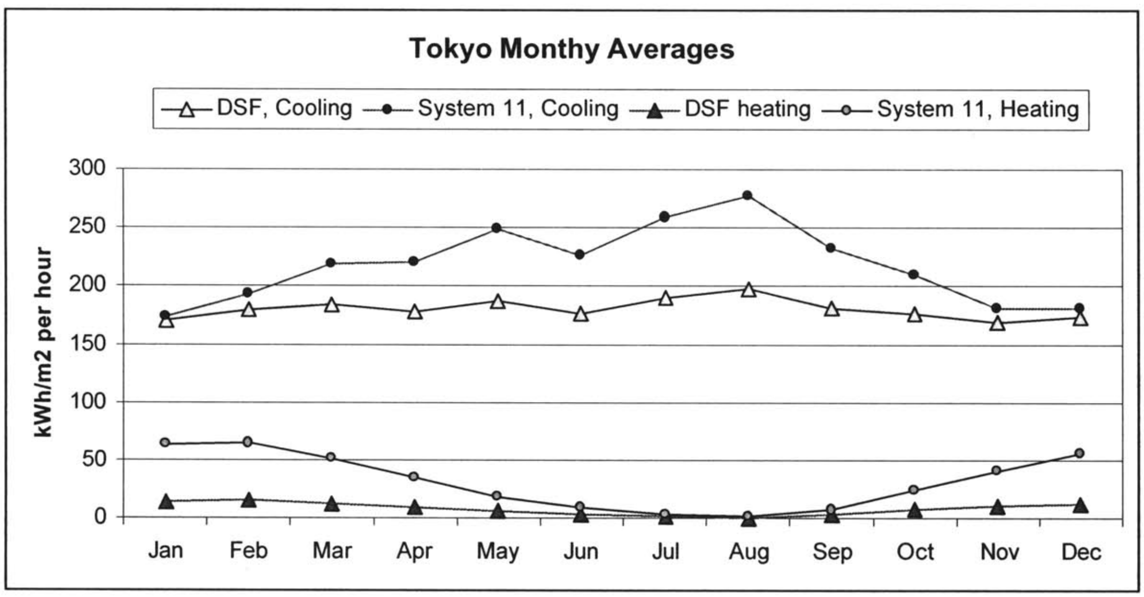


Figure 80 Hourly average energy consumption for typical month: a typical double-skin façade compared to System 11 – triple glazed with two low-E coatings

Condensation

The Tokyo environs are relatively humid compared to Western Europe. The designer will be concerned with the transfer of DSF's to this climate. For interior ventilated windows and facades, tempered air is brought in contact with the inside face of the outer glazing unit (usually a sealed unit). The potential for condensation exists during the winter, when the inside air is warmer than outside air. A first order look will compare the dew point of 22 degree Celsius air at 50% humidity with the temperature of the inner face of the insulating glass unit (the "critical surface"). The winter outdoor temperature Mean of Annual Extremes from ASHRAE 1993 Fundamentals 24.20 gives a design temperature of –6 degrees Celsius. This squares with the typical meteorological data that has –2 degrees Celsius for the minimum annual temperature. A conservative temperature of –15 degrees Celsius is used to test the window. This gives a critical surface (T2) temperature of 10.41 degrees Celsius. This happens to be the dew point of the inside air. It can be concluded that this system is at the very limit of feasibility for a window that will not have condensation in the cavity. Changes to this system, such as allowing the humidity of the space to increase, or the set point to be reduced will increase the risk of condensation. Summer conditions for this system are not subject to condensation risk.

Using an exterior ventilated façade changes the critical conditions for condensation.

The summertime design temperatures are dry-bulb 33 degrees Celsius and wet-bulb 27 degrees Celsius. This is corresponds to approximately 62 % relative humidity, and a dew point of 25 degrees Celsius. A rough approximation may be made by adjusting the R-value of the double-glazing unit between station points 1 and 3 to approximate a single layer of glass. This gives a temperature on the critical surface (T6) of 27.5 degrees Celsius. This is assuming the blinds are closed. If the blinds are open, the critical surface temperature drops to 26.0 degrees Celsius, indicating again that the design is close to allowing for condensation within the cavity. Neither situation implies that the design will not work, but each deserves careful consideration.

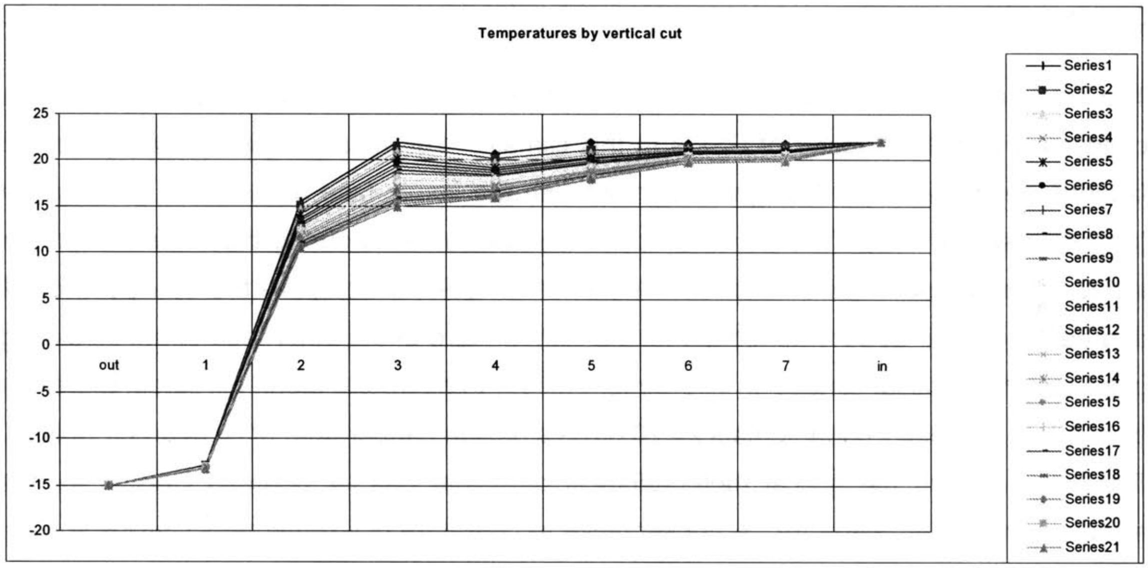


Figure 81 Tokyo: winter conditions for interior ventilated façade

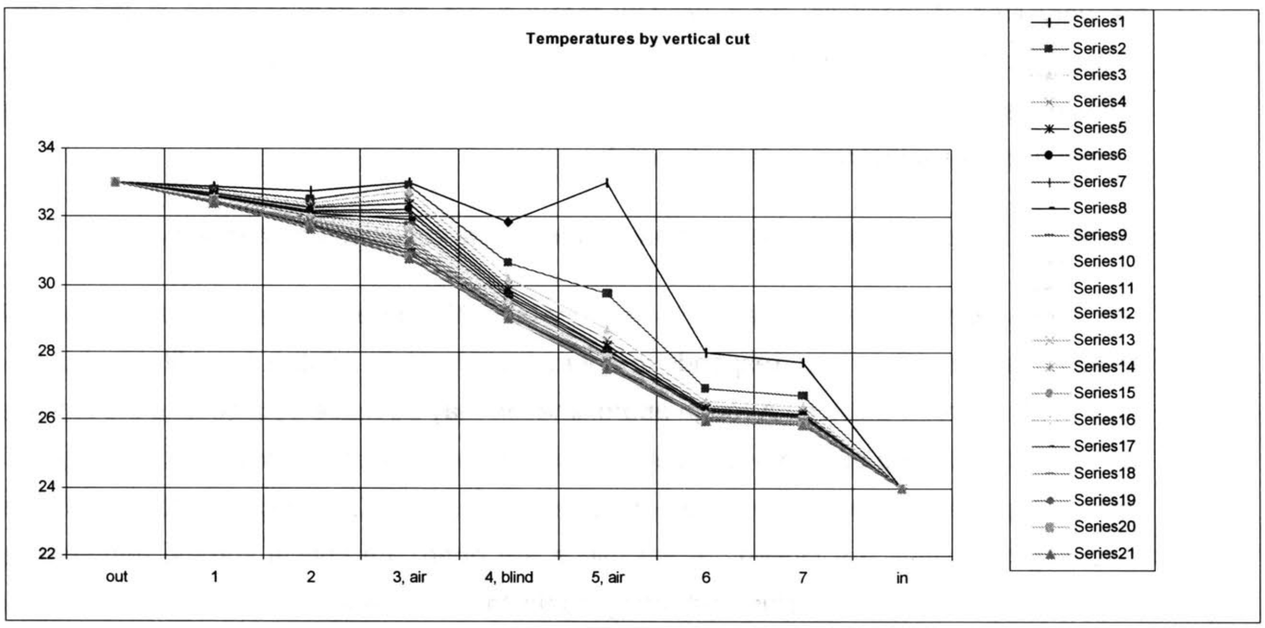


Figure 82 Tokyo: Summer conditions for exterior ventilated façade. Blinds closed.

6.0 Conclusions

> *If the architect can adopt 'green design' principles and take part in the choice of suitable sites where possible, 'green architecture' can become just another element of 'good architecture' and, perhaps as importantly, can be provided as economically for the client and sustainably for the planet [Bolt 1997 p. 34]*

Double-skin facades have made a rapid diffusion into the commercial markets in Germany, the United Kingdom, the Netherlands and other European countries. The acceptance of the facades is linked to the architectural and environmental benefits proclaimed on their behalf. The architectural, high-tech image is compelling in creating deep yet relatively transparent facades that are made dynamic by the movement and variable positions of interstitial blinds.

Remarkably, there are now high-rise buildings that have natural ventilation options that are sympathetic to occupants. The sealed office building is being phased out, in no small part due to the innovations associated with double-skin facades.

The model developed for this report confirms other reports that double-skin facades reduce the U-value and solar heat gain coefficients of static glass façade systems. The appropriateness for particular buildings with specific internal loads and in various climates is not universal. For certain buildings with high internal gains due to equipment or deep floor plans, the significance of an efficient façade may be minimal or even detrimental.

Additional tools must be developed so that designers may easily investigate effects of double-skin facades on comfort and day lighting. More sophisticated models for control sequences should be overlaid on the energy models, and detailed experimental data should be collected for heat transfer coefficients along the blinds and for impacts of entry and exit regions to the cavity.

Additional work is required to investigate the overall environmental effect of double-skin facades. For the skyscrapers that have been studied, the question remains as to whether or not to build high in the first place. Large, tall buildings have barriers to overcome such as allowing natural ventilation and even more substantial hurdles such as embodied energy. While no clear studies have been made of the embodied energy, it might be assumed as Barrie Evans does that embodied energy is proportional to cost, and the skyscrapers are expensive buildings [Evans 1997d]. On the plus side, the density levels obtained with skyscrapers may enhance transportation related energy on an urban scale.

Appropriate application of the technology is still being explored. The Debis building by Piano represents the incorporation of preceding knowledge gained at Commerzbank, RWE and other tall buildings. It embodies the merging paths of innovation of both the double-skin façade and Piano's own explorations with terracotta into one integrated architectural and technical expression. The evolution from here might be to look to cavities in front of opaque walls similar to capture energy. This might involve incorporating photovoltaic panels or adapting the concept of the Trombe wall. This implies an opaque or combined transparent and opaque façade that has air moving through interstitial cavities.

Often, when studying systems, engineers would like to optimize a system for a particular property such as low energy consumption. Particularly in the design of buildings, this is difficult because of conflicting priorities such as optimizing daylight and minimizing solar gain. Thus, co-optimizing is essential. The link between architects, engineers and facility managers must be carefully managed to develop and use complicated control features that do not overwhelm users or the lack of management may render the advanced façades inefficient.

The use of diaphanous walls of double-skin facades must be made with careful attention to energy impacts in parallel with human and urban sensitivities. They offer opportunities that static walls do not offer but must be implemented with foresight of their potential architectural, human, and environmental significance.

7.0 Appendices

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  phone 0171 / 23 487 20

- Stadttor Düsseldorf
  Engel Projektentwicklung
  Stadttor 1
  40219 Düsseldorf
  Mr Engel, Mr Canessa
  Spoke with engel (6/16/1999)
  phone 0049 / 211 / 6000 6020

fax 0049/ 211 / 6000 6016
information available at http://www.stadttor.de/
and http://www.hsp.de/~wiegels/serien/stadttor.htm

- Victoria Insurance Düsseldorf
  Viktoria Platz 2
  Düsseldorf
  Mr Holthausen
  phone 0049 / 211 / 49 34 812
  fax 0049/211/49 34 850
  Mrs Deisinger
  phone 0049 / 211 / 49 34 611
  building manager: Mr. Walden
  measurements by Mueller @ Dortmund University

- Christian.vonLoe@RWE.DE
  Occupant of RWE Building

- RWE Tower Essen
  Opernplatz 1
  45128 Essen
  Mr Weber
  Projekt...
  phone 0049 / 201 / 82 706 26
  fax 0049 / 201 / 22 9 22 1
  measurements by Mueller, Pasquay

- RWE tower (DLZ-Stern) : Mr. Köhler
  [facilities Manager]
  e-mail: matthias.koehler@rwe.de
  Mr. Till Pasquay (a member of U Dortmund chair) knows him very well.

- Dortmund:
  Siemens-Gebäude
  Märkische Strasse 8-14
  44135 Dortmund
  contact Mr. Örtelt, tel.: 0171 3290135 (mobil)

- Düsseldorf:
  Torhaus
  architect: Petzinka, Pink, Kahlen & Partner
  Cecilienallee 17
  40474 Düsseldorf

- Victoria Insurance Building
  Bezirksregierung Düsseldorf
  Mr. Cornelissen [tenant]
  Cecilienallee 2
  40408 Düsseldorf
  Fax: +49 (0) 211 4752971

7.2 Thermal model data for verification

The following sections include backup for the verification and validation of the simplified model of heat transfer presented in Section 4.0 of this report. The following are included

- 7.2.1 Temperature Distribution Verification
- 7.2.2 Cavity Flow Verification
- 7.2.3 Buoyancy Verification
- 7.2.4 U-value Validation
- 7.2.5 SHGC Validation

7.2.1 Temperature Distribution Verification

The following is the backup for the model that compares temperature distribution through the double-skin façade cavity as driven by temperature difference without solar radiation.

Case8 U-value verification

DSF CALCULATOR

Temperature Distribution (dC)

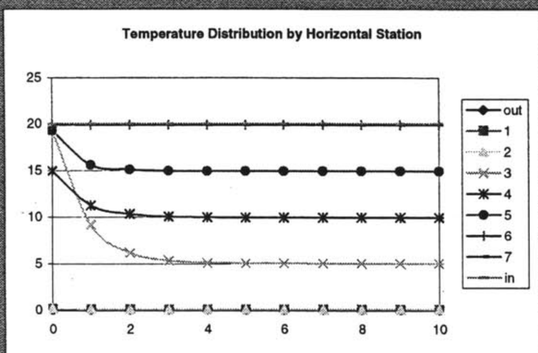
Station	height, y @bottom	out	1	2	3 (d1)	4 (Blind)	5 (d2)	6	7	in
0	0	0	0.19	0.21	19.30	14.97	19.30	19.97	19.97	20
1	0.12	0	0.11	0.12	9.19	11.27	15.60	19.93	19.93	20
2	0.24	0	0.09	0.10	6.18	10.33	15.13	19.92	19.92	20
3	0.36	0	0.08	0.09	5.35	10.08	15.00	19.92	19.92	20
4	0.48	0	0.08	0.09	5.12	10.01	14.96	19.92	19.92	20
5	0.6	0	0.08	0.09	5.06	9.99	14.95	19.92	19.92	20
6	0.72	0	0.08	0.09	5.04	9.98	14.95	19.92	19.92	20
7	0.84	0	0.08	0.09	5.04	9.98	14.95	19.92	19.92	20
8	0.96	0	0.08	0.09	5.04	9.98	14.95	19.92	19.92	20
9	1.08	0	0.08	0.09	5.03	9.98	14.95	19.92	19.92	20
10	1.2	0	0.08	0.09	5.03	9.98	14.95	19.92	19.92	20
11	1.32	0	0.08	0.09	5.03	9.98	14.95	19.92	19.92	20
12	1.44	0	0.08	0.09	5.03	9.98	14.95	19.92	19.92	20
13	1.56	0	0.08	0.09	5.03	9.98	14.95	19.92	19.92	20
14	1.68	0	0.08	0.09	5.03	9.98	14.95	19.92	19.92	20
15	1.8	0	0.08	0.09	5.03	9.98	14.95	19.92	19.92	20
16	1.92	0	0.08	0.09	5.03	9.98	14.95	19.92	19.92	20
17	2.04	0	0.08	0.09	5.03	9.98	14.95	19.92	19.92	20
18	2.16	0	0.08	0.09	5.03	9.98	14.95	19.92	19.92	20
19	2.28	0	0.08	0.09	5.03	9.98	14.95	19.92	19.92	20
20	2.4	0	0.08	0.09	5.03	9.98	14.95	19.92	19.92	20

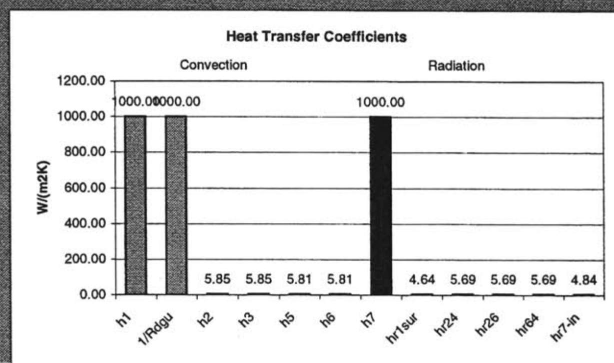
Ave T2: 0.10 | Tcav top: 9.99 | Ave T6: 19.92

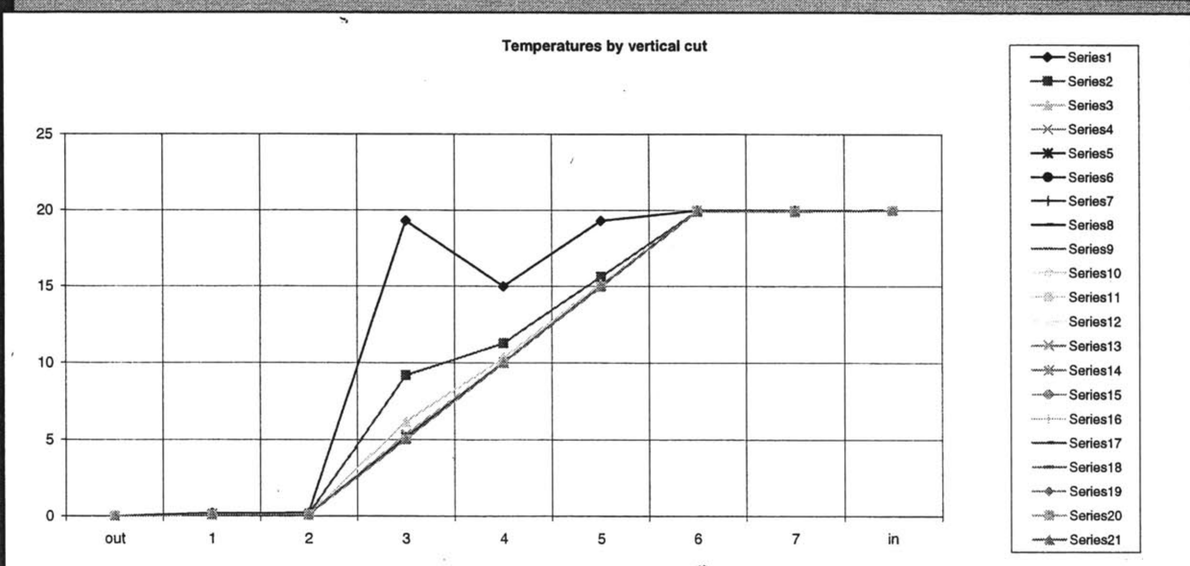
summary

Height (m)	2.40
Solar Rad(W/m2)	0.00
T out	0.00
T in	20.00
Tmax	20.00
Total q to room (W)	-184.77
Total q to duct (W)	-24.01
V3	0.0135
V5	0.0033
Average 2 cavity temp	10.59
SHGC	N/A
Effective U-Value	3.85

Notes:
DGU R-Value set to 0.001
Emissivity of blinds and glass = 1.0
Blinds are closed (Sigma=90)
hc model for channel: HENS







Radiation Heat Transfer Coefficients

Tm 4 to 2	hrad 4 to 2	Tm 6 to 4	hrad 6 to 4	Tm 6 to 2	hrad 6 to 2	Tm 6 to 4	hrad 6 to 4	Tm 7 to in	hrad 7 to in
19.3	5.69	19.30	5.69	19.30	5.69	19.3	5.69	19.30	4.84
7.59	5.04	17.47	5.59	10.09	5.17	17.47	5.59	19.99	4.87
5.70	4.94	15.60	5.48	10.02	5.17	15.60	5.48	19.97	4.87
5.22	4.91	15.13	5.45	10.01	5.17	15.13	5.45	19.96	4.87
5.08	4.90	15.00	5.45	10.00	5.17	15.00	5.45	19.96	4.87
5.06	4.90	14.96	5.44	10.00	5.17	14.96	5.44	19.96	4.87
5.04	4.90	14.95	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.04	4.90	14.95	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.03	4.90	14.96	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.03	4.90	14.95	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.03	4.90	14.95	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.03	4.90	14.95	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.03	4.90	14.95	5.44	10.00	5.17	14.96	5.44	19.96	4.87
5.03	4.90	14.96	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.03	4.90	14.95	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.03	4.90	14.95	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.03	4.90	14.96	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.03	4.90	14.95	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.03	4.90	14.95	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.03	4.90	14.95	5.44	10.00	5.17	14.95	5.44	19.96	4.87
5.03	4.90	14.95	5.44	10.00	5.17	14.96	5.44	19.96	4.87

checked 010499

Convective Heat Transfer Coefficients

	h2	h3	h5	h6
1	5.85	5.85	5.81	5.81
2	5.85	5.85	5.81	5.81
3	5.85	5.85	5.81	5.81
4	5.85	5.85	5.81	5.81
5	5.85	5.85	5.81	5.81
6	5.85	5.85	5.81	5.81
7	5.85	5.85	5.81	5.81
8	5.85	5.85	5.81	5.81
9	5.85	5.85	5.81	5.81
10	5.85	5.85	5.81	5.81
11	5.85	5.85	5.81	5.81
12	5.85	5.85	5.81	5.81
13	5.85	5.85	5.81	5.81
14	5.85	5.85	5.81	5.81
15	5.85	5.85	5.81	5.81
16	5.85	5.85	5.81	5.81
17	5.85	5.85	5.81	5.81
18	5.85	5.85	5.81	5.81
19	5.85	5.85	5.81	5.81
20	5.85	5.85	5.81	5.81
21	5.85	5.85	5.81	5.81

checked 010499

assumptions

Tm4-2 at y=0 is T3=Tin
Tm6-4 at y=0 is T5=Tin
Tm7-4 at y=0 is T5=Tin

note
Tm go with y-1 rather than y

Temperature Coefficients

				unused									
A1	A2	A3	B_1	B_2	B_3	C_1	C_2	C_3	D_1	D_2	E1	E_2	
0.56	120.00	1000.00	0.70	0.68	0.00	0.68	0.70	0.70	0.70	2000.00	0.58	120.00	1
0.56	120.00	1000.00	0.70	0.60	0.00	0.67	0.70	0.70	0.70	2000.00	0.58	120.00	2
0.56	120.00	1000.00	0.70	0.59	0.00	0.66	0.70	0.70	0.70	2000.00	0.58	120.00	3
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	4
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	5
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	6
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	7
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	8
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	9
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	10
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	11
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	12
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	13
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	14
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	15
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	16
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	17
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	18
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	19
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	20
0.56	120.00	1000.00	0.70	0.59	0.00	0.65	0.70	0.70	0.70	2000.00	0.58	120.00	21

Double Glazing Calcs

tm 1,2	hc,gap	Eeff hr	hc+Eeff	C	dgu air gap R,gap	Rglass1 (l/kA)g1	Rglass2 (l/kA)g2	=SUM(E6: R,dgu	Tm 1-sur	hrad 1-sur	2000	Uglass plus hc Uglass	ASHRAE TABLE 27.6-5(1993) hi=8.29, ho=29		DIFFERENCE	
0.20	1.45	4.63	6.08	0.73	1.37	0.00	0.00	0.00	0.09	4.64	1	8333.333333	0.66	2.78	-76.42%	1.525245
0.12	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.06	4.64	2	8333.333333	0.66	2.78	-76.43%	
0.09	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	3	8333.333333	0.66	2.78	-76.44%	
0.09	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	4	8333.333333	0.66	2.78	-76.44%	
0.09	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	5	8333.333333	0.66	2.78	-76.44%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	6	8333.333333	0.66	2.78	-76.44%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	7	8333.333333	0.66	2.78	-76.44%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	8	8333.333333	0.66	2.78	-76.44%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	9	8333.333333	0.66	2.78	-76.44%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	10	8333.333333	0.66	2.78	-76.44%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	11	8333.333333	0.66	2.78	-76.44%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	12	8333.333333	0.66	2.78	-76.44%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	13	8333.333333	0.66	2.78	-76.44%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	14	8333.333333	0.66	2.78	-76.44%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	15	8333.333333	0.66	2.78	-76.44%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	16	8333.333333	0.66	2.78	-76.44%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	17	8333.333333	0.66	3.78	-82.67%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	18	8333.333333	0.66	4.78	-86.30%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	19	8333.333333	0.66	5.78	-88.67%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	20	8333.333333	0.66	6.78	-90.34%	
0.08	1.45	4.62	6.08	0.73	1.37	0.00	0.00	0.00	0.04	4.64	21	8333.333333	0.66	7.78	-91.58%	

=IF(Work!C13>Work!C14,(Work!C13-Work!C14)/2+Work!C14,(Work!C14-Work!C13)/2+Work!C13)

=IF(Work!C13>Work!C14,(Work!C13-Work!C14)/2+Work!C14,(Work!C14-Work!C13)/2+Work!C13)

Blind Factors for Infrared Radiation

		Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
	1										
Sigma	2	90	90	90	90	90	90	90	90	90	60
Height	3	2.4	3	3	2	0.914	2.4	2.4	2.4	2.4	3
No. of Blind Divisions	4	96	120	120	80	35.98425	96	96	96	96	120
Blind Spacing	5	0.025	0.025	0.025	0.025	0.0254	0.025	0.025	0.025	0.025	0.025
Blind Length	6	0.025	0.025	0.025	0.025	0.0254	0.025	0.025	0.025	0.025	0.025
d1	7	0.1	0.0715	0.0715	0.63	0.089	0.1	0.1	0.1	0.1	0.0715
d2	8	0.045	0.0715	0.0715	0.37	0.089	0.045	0.045	0.045	0.045	0.0715
X1	9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006
y1	10	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.011
y2	11	1.175	1.475	1.475	0.975	0.432	1.175	1.175	1.175	1.175	1.477
y3	12	1.200	1.500	1.500	1.000	0.457	1.200	1.200	1.200	1.200	1.498
bd	13	1.179247642	1.476732	1.476732	1.160829445	0.440681	1.179247642	1.179247642	1.179247642	1.179247642	1.478116
fh	14	1.200843454	1.501703	1.501703	1.066255129	0.465586	1.200843454	1.200843454	1.200843454	1.200843454	1.499745
ac	15	1.204159458	1.501703	1.501703	1.181905242	0.465586	1.204159458	1.204159458	1.204159458	1.204159458	1.499745
eg	16	1.175861386	1.476732	1.476732	1.042844667	0.440681	1.175861386	1.175861386	1.175861386	1.175861386	1.478116
de	17	0.05	0.05	0.05	0.05	0.0508	0.05	0.05	0.05	0.05	0.048296
cf	18	1.53144E-18	1.53E-18	1.53E-18	1.53144E-18	1.56E-18	1.53144E-18	1.53144E-18	1.53144E-18	1.53144E-18	0.012941
Aacfh	19	2.405002911	3.003406	3.003406	2.24816037	0.931171	2.405002911	2.405002911	2.405002911	2.405002911	3.012432
Abdeg	20	2.405109028	3.003464	3.003464	2.253674112	0.932162	2.405109028	2.405109028	2.405109028	2.405109028	3.004527
Abdfh	21	2.405091095	3.003435	3.003435	2.252084574	0.931666	2.405091095	2.405091095	2.405091095	2.405091095	3.002861
Aaceg	22	2.405020844	3.003435	3.003435	2.249749909	0.931666	2.405020844	2.405020844	2.405020844	2.405020844	3.002861
cd=ef=Blind Spacing		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
df=Lblind		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
fg		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
dg		1.23	1.53	1.53	1.09	0.49	1.23	1.23	1.23	1.23	1.53
da		1.23	1.53	1.53	1.20	0.49	1.23	1.23	1.23	1.23	1.52
fh		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
Fdf-ce=Flowerblind-upp	$F4_L4_U$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
Fdf-gh=Flowerblind-Gla	$F4_L6$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
Fdf-ab=Flowerblind-Gla	$F4_L2$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
check		1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	1.00
		1	2	3	4	5	6	7	8	9	10
	$F4_U4_L$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
	$F4_U6$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
	$F4_U2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
	$F24_L$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
	$F24_U$	0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.03
	$F64_L$	0.00	0.00	0.00	-0.03	-0.01	0.00	0.00	0.00	0.00	0.03
	$F64_U$	1.00	1.00	1.00	1.03	1.01	1.00	1.00	1.00	1.00	0.74
F26single	23	9.25186E-17	0	0	1.11022E-16	0	9.25186E-17	9.25186E-17	9.25186E-17	9.25186E-17	0.001873
F26	24	8.88178E-15	0	0	8.88178E-15	0	8.88178E-15	8.88178E-15	8.88178E-15	8.88178E-15	0.224745
F62=F26	25	8.88178E-15	0	0	8.88178E-15	0	8.88178E-15	8.88178E-15	8.88178E-15	8.88178E-15	0.224745
AVERAGES/TOTALS											
F24=1-F26	26	1	1	1	1	1	1	1	1	1	0.775255
F42=Fblinds-Glass2	27	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39
F46=Fblinds-Glass3	28	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39
F64=1-F62	29	1	1	1	1	1	1	1	1	1	0.775255
F44		0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.23
F46		0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39
F42		0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39

F6-?

For solar Angle, B=30degrees blind

	emiss	IR reflc	area	Ae
surf2	1	0	0.12	0.12
surf4	1	0	0.12	0.12
surf6	1	0	0.12	0.12
Tmean3	((tout+tin)/2)^3		2E+07	
StefanB	5.7E-08			
sigma	**90**			
sigmaTm3	1.29192			

Case8

	r2	r2 prime	r4 L (lower)	r4 U (upper)	r4 prime	r6	r6 prime	q2-others	q4low-others	q4up-others	q4-others	q6-others	SUM
0	-2.79	73.46	73.46	73.46	96.36	99.32	73.46	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
1	-3.24	54.36	54.36	54.36	95.70	99.10	54.36	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
2	-3.37	49.52	49.52	49.52	95.53	99.06	49.52	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
3	-3.40	48.20	48.20	48.20	95.48	99.04	48.20	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
4	-3.41	47.83	47.83	47.83	95.47	99.04	47.83	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
5	-3.41	47.73	47.73	47.73	95.47	99.04	47.73	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
6	-3.41	47.71	47.71	47.71	95.46	99.04	47.71	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
7	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
8	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
9	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
10	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
11	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
12	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
13	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
14	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
15	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
16	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
17	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
18	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
19	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
20	-3.41	47.70	47.70	47.70	95.46	99.04	47.70	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
21	-3.37	47.75	47.75	47.75	95.52	99.06	47.75	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
s		t	u		v		w						
	5571658264			6876455416		=(Work!O6+273)^4							

Solar Radiation Absorbed

	Q a1	Q a2	Q a4	Q a7
1	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00
16	0.00	0.00	0.00	0.00
17	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00
19	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00

Fsolar Calculations

length factors

	a (l/2)sin(sigma-blinds)	b c x tan(Beta)	c (l/2)cos(sigma-blinds)	Solar Azimuth Beta	Fsolar calculate (S-2(a+b))/S	
1	0.0125	0.0000	0.0000	0.00	0.00	0.00
2	0.0125	0.0000	0.0000	-5.00	0.00	0.00
3	0.0125	0.0000	0.0000	-10.00	0.00	0.00
4	0.0125	0.0000	0.0000	-15.00	0.00	0.00
5	0.0125	0.0000	0.0000	-20.00	0.00	0.00
6	0.0125	0.0000	0.0000	-25.00	0.00	0.00
7	0.0125	0.0000	0.0000	-30.00	0.00	0.00
8	0.0125	0.0000	0.0000	-35.00	0.00	0.00
9	0.0125	0.0000	0.0000	-40.00	0.00	0.00
10	0.0125	0.0000	0.0000	-45.00	0.00	0.00

Need to import from weather data

ed portion from blinds (1-Fsol)

nodel

	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Sigma	90.000000	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	60.00
sin(sigma)	1.000000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.87
cos(sigma)	0.000000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50
Gamma	180.000000	180.00	180.00	180.00	180.00	180.00	180.00	180.00	180.00	120.00
Gamma	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180
X1	0.000000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Sb	0.025000	0.025000	0.025000	0.025000	0.025400	0.025000	0.025000	0.025000	0.025000	0.025000
Sb,perp	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.012500
I,rebound	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
I,blind	0.025000	0.025000	0.025000	0.025000	0.025400	0.025000	0.025000	0.025000	0.025000	0.025000
Ray1	1	2	3	4	5	6	7	8	9	10
R1y	0.009375	0.009375	0.009375	0.009375	0.009525	0.009375	0.009375	0.009375	0.009375	0.008119
R1x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.004688
dYr1L	0.021875	0.021875	0.021875	0.021875	0.022225	0.021875	0.021875	0.021875	0.021875	0.022294
dXr1L	#########	#########	#########	#########	#########	#########	#########	#########	#########	0.012871
dYr1T	0.046875	0.046875	0.046875	0.046875	0.047625	0.046875	0.046875	0.046875	0.046875	0.043944
dXr1T	#########	#########	#########	#########	#########	#########	#########	#########	#########	-0.025371
dXr1L+R1x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1
dXr1T	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1
RAY 1 Bounce 1	out	out	out	out	out	out	out	out	out	out
Ray 1 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 1	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
Ray2	1	2	3	4	5	6	7	8	9	10
R2y	0.003125	0.003125	0.003125	0.003125	0.003175	0.003125	0.003125	0.003125	0.003125	0.002706
R2x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.001563
dYr2L	0.015625	0.015625	0.015625	0.015625	0.015875	0.015625	0.015625	0.015625	0.015625	0.016881
dXr2L	#########	#########	#########	#########	#########	#########	#########	#########	#########	0.009746
dYr2T	0.040625	0.040625	0.040625	0.040625	0.041275	0.040625	0.040625	0.040625	0.040625	0.038532
dXr2T	#########	#########	#########	#########	#########	#########	#########	#########	#########	-0.022246
dXr2L+R2x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1
dXr2T	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1
RAY 2 Bounce 1	out	out	out	out	out	out	out	out	out	out
Ray 2 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 2	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
Ray3	1	2	3	4	5	6	7	8	9	10
R3y	0.003125	0.003125	0.003125	0.003125	0.003175	0.003125	0.003125	0.003125	0.003125	0.002706
R3x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.001563
dYr3L	0.009375	0.009375	0.009375	0.009375	0.009525	0.009375	0.009375	0.009375	0.009375	0.011468
dXr3L	#########	#########	#########	#########	#########	#########	#########	#########	#########	0.006621
dYr3T	0.034375	0.034375	0.034375	0.034375	0.034925	0.034375	0.034375	0.034375	0.034375	0.033119
dXr3T	#########	#########	#########	#########	#########	#########	#########	#########	#########	-0.019121
dXr3L-R3x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	<X1
dXr3T	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X
RAY 3 Bounce 1	out	out	out	out	out	out	out	out	out	hit
Ray 3 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 3	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-hit
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
Ray4	1	2	3	4	5	6	7	8	9	10
R4y	0.009375	0.009375	0.009375	0.009375	0.009525	0.009375	0.009375	0.009375	0.009375	0.008119
R4x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.004688
dYr4L	0.003125	0.003125	0.003125	0.003125	0.003175	0.003125	0.003125	0.003125	0.003125	0.006056
dXr4L	#########	#########	#########	#########	#########	#########	#########	#########	#########	0.003496
dYr4T	0.028125	0.028125	0.028125	0.028125	0.028575	0.028125	0.028125	0.028125	0.028125	0.027706
dXr4T	#########	#########	#########	#########	#########	#########	#########	#########	#########	-0.015996
dXr4L-R4x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	<X1 ##
dXr4T	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X
RAY 4 Bounce 1	out	out	out	out	out	out	out	out	out	hit
Ray 4 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 3	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-hit
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
lit-out	4	4	4	4	4	4	4	4	4	2
lit-hit	0	0	0	0	0	0	0	0	0	2
lit-in	0	0	0	0	0	0	0	0	0	0
hit-hit	0	0	0	0	0	0	0	0	0	0

SUMS

ReflectionTotal Table:	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Rho4,s	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rho4,d	0.15	0.15	0.15	0.15	0.15	0.3	0.15	0.15	0.15	0.1
abs of blind, alpha4	0.75	0.75	0.75	0.75	0.75	0.6	0.75	0.75	0.75	0.6
1/4 sum of "lit-out"	1	1	1	1	1	1	1	1	1	1
1/4 sum of "lit-hit"	0	0	0	0	0	0	0	0	0	1
1/4 sum of "lit-in"	0	0	0	0	0	0	0	0	0	0
1/4 sum of "hit-hit"	0	0	0	0	0	0	0	0	0	0
F4U4L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
F4U6	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
F4U2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
F4L4U	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
F4L6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
F4L2	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
Rho 4, tot-out	0.2497	0.2499	0.2499	0.2387	0.2487	0.3995	0.2497	0.2497	0.2497	0.1243
Alpha 4 tot	0.7500	0.7500	0.7500	0.7500	0.7500	0.6000	0.7500	0.7500	0.7500	0.6441
Rho 4, tot-in	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0167
	0.9997	0.9999	0.9999	0.9887	0.9987	0.9995	0.9997	0.9997	0.9997	0.7851
							1.00			

Buoyancy forces in Air
Calculations

Laminar Case

Ambient conditions:

temp of inside air	20 deg C
temp of outside air	0 deg C
density of inside air	1.20249994 kg/m3
density of outside air	1.290627455 kg/m3

RELATES TO D1: **outer**		RELATES TO D2: **inner**	
Outer Cavity		**Inner Cavity**	
Average Temp	6.29 deg C	Average Temp	15.96 deg C
Average Density	1.26150513 kg/m3	Average Density	1.219149299 kg/m3
Choose Rho infinity	**1.20249994** kg/m3	Choose Rho infinity	**1.20249994** kg/m3
Ave viscosity ,mu	0.00001746	Ave viscosity ,mu	0.00001794
gravity, g	9.81 m/s2		
Height, H	2.4 m		
Area Cross Sec,Acs	0.1 m2	Area Cross Sec,Acs	0.045 m2
delta P Net	**-0.13892182**	**delta P Net**	**-0.01763966**
neglecting entrance and exit effects			
Ave Velocity, Vave	**-2.7627 m/s**	**Ave Velocity, Vave**	**-0.0691 m/s**
Dh	0.20	Dh	0.09
Reynolds, Re	-39921.65304 **LAMINAR**	Reynolds, Re	-422.841243 **LAMINAR**

based on a Re, transition # of 1.00E+05

Turbulent Case			
friction factor, f	0.02	friction factor, f	0.069685552
Head loss, lf	0.052180072	Head loss, lf	0.000226351
delta P Net	**0.64574746**	**delta P Net**	**0.00270713**
Ave velocity, Vave	**12.8418 m/s**	**Ave velocity, Vave**	**0.0106 m/s**

RESULTANT VELOCITIES	**-2.7627** m/s	**-0.0691** m/s

SUMMARY: U-Value Verification. [CalcUValueVerify.xls Case6]

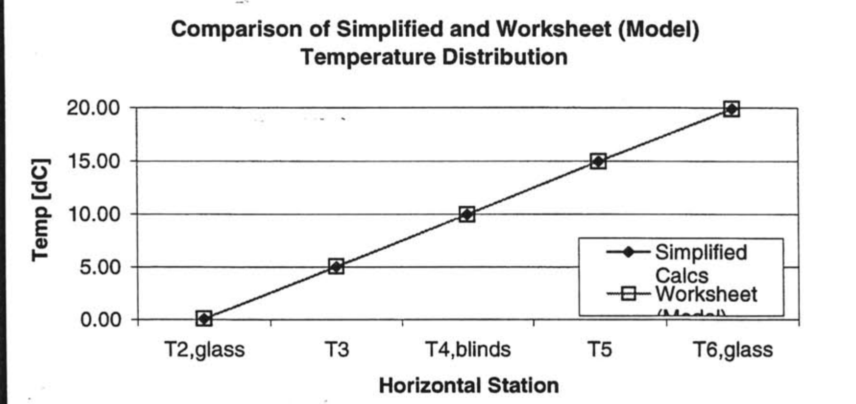
Validation Cases		**R-value validation**				
		flow (m/s)	solar	Blinds	deltaT (dC)	inlet T
Case 8	Basic System	0.02	0.00	"none"	20.00	19.3

Notes:
1. Set cavity temperatures to be temperature balance not dT/dy.
2. Set R(DGU)=.001

SUMMARY: U-Value Verification

Simplified calculations compared to DSF Calculator (worksheet)

	T2,glass	**T3**	**T4,blinds**	**T5**	**T6,glass**	
Simplified Calcs	0.09	5.03	9.97	14.94	19.92	
Worksheet (Model)	0.09	5.03	9.98	14.95	19.92	
	0.00%	0.04%	0.13%	0.14%	0.00%	
	h2	**h3**	**h5**	**h6**	**Ady**	**Ady blind**
	5.85	5.85	5.81	5.81	0.12	0.12



Heat transfer coefficients

h1	1/Rdgu	h2	h3	h5	h6	h7
1000.00	1000.00	5.85	5.85	5.81	5.81	1000.00

hr1sur	hr24	hr26	hr64	hr7-in
4.64	5.69	5.69	5.69	4.84

U-Value Temperature Distribution Verifications

Winter conditions with 40 m3/hm air flow and no solar radiation (delta T is 20 dC)

file: U-Value Verify

Case8

m=0.9

Case Parameters

Blind

	4	6	7
	14.97	19.97	19.97
	11.27	19.93	19.93
	10.33	19.92 m2	
	10.08	19.92	19.92
	10.01	19.92	19.92
	9.99	19.92	19.92
	9.98		
	9.98	19.92	19.92
	9.98	19.92	19.92
	9.98	19.92	19.92
	9.98	19.92	19.92
	9.98	19.92	19.92
	9.98		
	9.98	19.92	19.92

	9.98	
		19.92
	9.98	19.92
Tcav top		Ave T6

Blinds Properties

emissivity,E4	1	nondim
reflectivity, ref_blind	0.25	nondim
Spectral Reflectivity of blind	0.1	nondim
Diffuse Reflectivity of blind	0.15	nondim
Rho 4, tot-out	0.25	nondim
Alpha 4 tot	0.75	nondim
Rho 4, tot-in	7E-16	nondim
absorptivity, abs_blind	0.75	nondim
Length of the blind	0.025	m
Blind Angle from horizontal (Sigm	90	degrees
BlindSpace	0.025	m
F26(IR), geometry factor	9E-15	nondim
F24=1-F(IR), geometry factor	1	nondim
F(sol), geometry factor	0.00	nondim
1-F(sol), geometry factor	1.00	nondim
Area of the blind for convection	0.12	m

Room Properties

emissivity,Ein	0.85	nondim

Heat Transfer, hc

hout=h1	1000	nodim
hin=h7	1000	nodim

Glass #2 ID Number	custom	
k,glass2	100	W/(mK)
l,glass2	0.006	m
abs_front_glass2	0.12	nodim
abs_back_glass2	0.12	nodim
ref_front_glass2	0.09	nodim
ref_back_glass2	0.09	nodim
trans_glass2	0.79	nodim
emissivity_front_glass2	1	nodim
emissivity_back_glass2	1	nodim

Glass # ID Number	custom	
k,glass3	100	W/(mK)
l,glass3	0.006	m
abs_front_glass3	0.12	nodim
abs_back_glass3	0.12	nodim
ref_front_glass3	0.09	nodim
ref_back_glass3	0.09	nodim
trans_glass3	0.79	nodim
emissivity_front_glass3	1	nodim
emissivity_back_glass3	1	nodim

Constants

StefanBoltzman	5.70E-08	W/m2K4

U-Value Temperature Distribution Verifications

Winter conditions with 40 m3/hm air flow and no solar radiation (delta T is 20 dC)
file: U-Value Verify
Case8

Case Parameters

Air Properties	d1
Forced Ventilation? (yes/no)	0.00
Inlet Side	0.00
specific heat Cp	0.00
conductivity,k	0.00
mass flow rate, m	0.00
rho, density of air	0.00
velocity, V	0.00
DH	0.00
Pr	0.00
kinematic viscosity,air	0.00
ReD	0.00
Laminar NuDH	0.00
f	0.00
Turbulent NuDh	0.00
Utilized Nudh	0.00
hconv	0.00

	d2
Forced Ventilation? (yes/no)	yes
Inlet Side	in
specific heat Cp	1005.00
conductivity,k	0.03
mass flow rate, m	0.00
rho, density of air	1.20
velocity, V	0.00
DH	0.09
Pr	0.69
kinematic viscosity,air	0.00
ReD	18.88
Laminar NuDH	8.25
f	2.16
Turbulent NuDh	410.14
Utilized Nudh	8.25
hconv	5.81

#
0
0
0
0
0
0
0
0
0
0

7.2.2 Cavity Flow Verification

The following is the backup for the model that compares temperature distribution through the double-skin façade cavity as driven by forced convection through the cavity without temperature difference between indoors and outdoors.

Case8 Cavity flow verification

DSF CALCULATOR

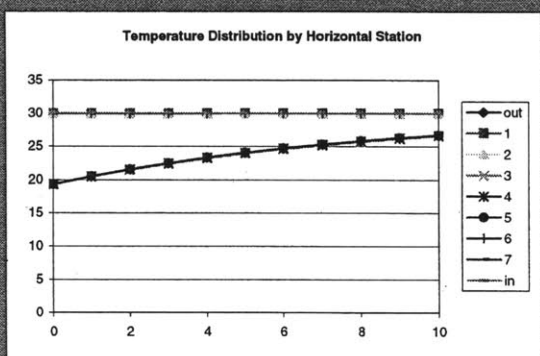
Temperature Distribution (dC)

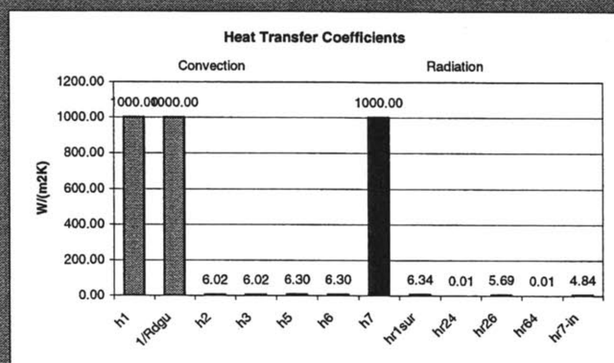
Station	height, y @bottom	out	1	2	d1 3	Blind 4	d2 5	6	7	in
0	0	30	29.94	29.93	19.30	19.31	19.30	29.93	29.93	30
1	0.12	30	29.94	29.94	20.44	20.48	20.49	29.94	29.94	30
2	0.24	30	29.95	29.94	21.47	21.52	21.55	29.94	29.95	30
3	0.36	30	29.95	29.95	22.38	22.44	22.49	29.95	29.95	30
4	0.48	30	29.96	29.95	23.20	23.27	23.32	29.96	29.96	30
5	0.6	30	29.96	29.96	23.93	24.00	24.06	29.96	29.96	30
6	0.72	30	29.97	29.96	24.59	24.66	24.72	29.96	29.97	30
7	0.84	30	29.97	29.97	25.17	25.24	25.30	29.97	29.97	30
8	0.96	30	29.97	29.97	25.69	25.76	25.82	29.97	29.97	30
9	1.08	30	29.98	29.97	26.16	26.22	26.28	29.98	29.98	30
10	1.2	30	29.98	29.98	26.58	26.64	26.69	29.98	29.98	30
11	1.32	30	29.98	29.98	26.95	27.00	27.05	29.98	29.98	30
12	1.44	30	29.98	29.98	27.28	27.33	27.37	29.98	29.98	30
13	1.56	30	29.99	29.98	27.57	27.62	27.66	29.98	29.99	30
14	1.68	30	29.99	29.99	27.84	27.88	27.92	29.99	29.99	30
15	1.8	30	29.99	29.99	28.07	28.11	28.15	29.99	29.99	30
16	1.92	30	29.99	29.99	28.28	28.32	28.35	29.99	29.99	30
17	2.04	30	29.99	29.99	28.47	28.50	28.53	29.99	29.99	30
18	2.16	30	29.99	29.99	28.64	28.66	28.69	29.99	29.99	30
19	2.28	30	29.99	29.99	28.78	28.81	28.83	29.99	29.99	30
20	2.4	30	29.99	29.99	28.92	28.94	28.96	29.99	29.99	30
				Ave T2 29.97		Tcav top 28.94		Ave T6 29.97		

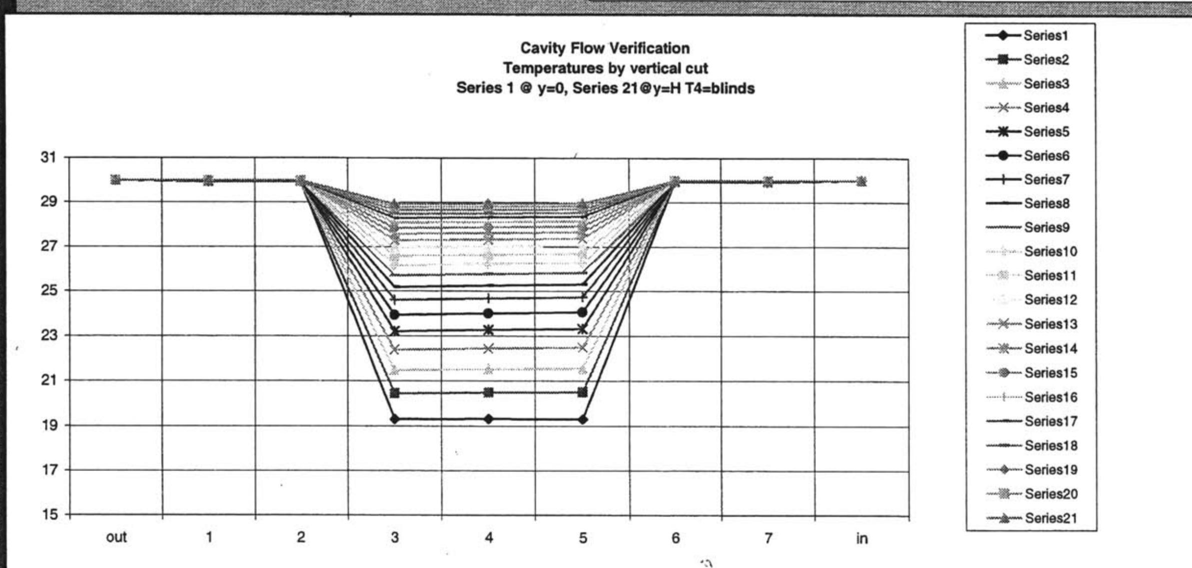
summary

Height (m)	2.40
Solar Rad(W/m2)	0.00
T out	30.00
T in	30.00
Tmax	30.00
Total q to room (W)	-66.45
Total q to duct (W)	93.17
V3	0.0558
V5	0.1241
Average 2 cavity temp	25.74
SHGC	N/A
Effective U-Value	#VALUE!

Notes:
DGU R-Value set to 0.001
Emissivity of glass = 1.0
Emissivity of blinds = 0.001
Blinds are closed (Sigma=90)
hc model for channel: HENS







Radiation Heat Transfer Coefficients

Tm 4 to 2	hrad 4 to 2	Tm 6 to 4	hrad 6 to 4	Tm 6 to 2	hrad 6 to 2	Tm 6 to 4	hrad 6 to 4	Tm 7 to in	hrad 7 to in
19.3	0.01	19.30	0.01	19.30	5.69	19.3	0.01	19.30	4.84
24.62	0.01	24.62	0.01	29.93	6.34	24.62	0.01	29.97	5.39
25.21	0.01	25.21	0.01	29.94	6.34	25.21	0.01	29.97	5.39
25.73	0.01	25.73	0.01	29.94	6.34	25.73	0.01	29.97	5.39
26.20	0.01	26.20	0.01	29.95	6.34	26.20	0.01	29.98	5.39
26.61	0.01	26.61	0.01	29.95	6.34	26.61	0.01	29.98	5.39
26.98	0.01	26.98	0.01	29.96	6.34	26.98	0.01	29.98	5.39
27.31	0.01	27.31	0.01	29.96	6.34	27.31	0.01	29.98	5.39
27.60	0.01	27.60	0.01	29.97	6.34	27.60	0.01	29.99	5.39
27.87	0.01	27.87	0.01	29.97	6.34	27.87	0.01	29.99	5.39
28.10	0.01	28.10	0.01	29.97	6.34	28.10	0.01	29.99	5.39
28.31	0.01	28.31	0.01	29.98	6.34	28.31	0.01	29.99	5.39
28.49	0.01	28.49	0.01	29.98	6.34	28.49	0.01	29.99	5.39
28.66	0.01	28.66	0.01	29.98	6.34	28.66	0.01	29.99	5.39
28.80	0.01	28.80	0.01	29.98	6.34	28.80	0.01	29.99	5.39
28.93	0.01	28.93	0.01	29.99	6.34	28.93	0.01	29.99	5.39
29.05	0.01	29.06	0.01	29.99	6.34	29.05	0.01	29.99	5.39
29.15	0.01	29.15	0.01	29.99	6.34	29.15	0.01	29.99	5.39
29.25	0.01	29.25	0.01	29.99	6.34	29.25	0.01	30.00	5.39
29.33	0.01	29.33	0.01	29.99	6.34	29.33	0.01	30.00	5.39
29.40	0.01	29.40	0.01	29.99	6.34	29.40	0.01	30.00	5.39

checked 010499

Convective Heat Transfer Coefficients

	h2	h3	h5	h6
1	6.02	6.02	6.30	6.30
2	6.02	6.02	6.30	6.30
3	6.02	6.02	6.30	6.30
4	6.02	6.02	6.30	6.30
5	6.02	6.02	6.30	6.30
6	6.02	6.02	6.30	6.30
7	6.02	6.02	6.30	6.30
8	6.02	6.02	6.30	6.30
9	6.02	6.02	6.30	6.30
10	6.02	6.02	6.30	6.30
11	6.02	6.02	6.30	6.30
12	6.02	6.02	6.30	6.30
13	6.02	6.02	6.30	6.30
14	6.02	6.02	6.30	6.30
15	6.02	6.02	6.30	6.30
16	6.02	6.02	6.30	6.30
17	6.02	6.02	6.30	6.30
18	6.02	6.02	6.30	6.30
19	6.02	6.02	6.30	6.30
20	6.02	6.02	6.30	6.30
21	6.02	6.02	6.30	6.30

checked 010499

assumptions
Tm4-2 at y=0 is T3=Tin
Tm6-4 at y=0 is T5=Tin
Tm7-4 at y=0 is T5=Tin

note
Tm go with y-1 rather than y

Temperature Coefficients

A1	A2	A3	B_1	B_2 (unused)	B_3 (unused)	C_1 (unused)	C_2	C_3	D_1	D_2	E1	E_2	
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.58	120.00	1
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	2
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	3
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	4
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	5
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	6
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	7
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	8
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	9
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	10
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	11
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	12
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	13
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	14
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	15
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	16
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	17
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	18
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	19
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	20
0.76	120.00	1000.00	0.72	0.00	0.00	0.00	0.72	0.76	0.76	2000.00	0.65	120.00	21

Double Glazing Calcs

tm 1,2	hc,gap	Eeff hr	hc+Eeff	C	dgu air gap R,gap	Rglass1 (l/kA)g1	Rglass2 (l/kA)g2	=SUM(E6:(R,dgu	Tm 1-sur	hrad 1-sur	2000	Uglass plus hc Uglass	ASHRAE TABLE 27.6-5(1993) hi=8.29, ho=29		DIFFEREN
29.93	1.57	6.31	7.88	0.95	1.06	0.00	0.00	0.00	29.97	6.34	1	8333.333333	0.82	2.78	-70.33%
29.94	1.57	6.31	7.88	0.95	1.06	0.00	0.00	0.00	29.97	6.34	2	8333.333333	0.82	2.78	-70.33%
29.95	1.57	6.31	7.88	0.95	1.06	0.00	0.00	0.00	29.97	6.34	3	8333.333333	0.82	2.78	-70.33%
29.95	1.57	6.31	7.88	0.95	1.06	0.00	0.00	0.00	29.98	6.34	4	8333.333333	0.82	2.78	-70.33%
29.96	1.57	6.31	7.88	0.95	1.06	0.00	0.00	0.00	29.98	6.34	5	8333.333333	0.82	2.78	-70.33%
29.96	1.57	6.31	7.88	0.95	1.06	0.00	0.00	0.00	29.98	6.34	6	8333.333333	0.82	2.78	-70.32%
29.97	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	29.98	6.34	7	8333.333333	0.83	2.78	-70.32%
29.97	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	29.99	6.34	8	8333.333333	0.83	2.78	-70.32%
29.97	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	29.99	6.34	9	8333.333333	0.83	2.78	-70.32%
29.98	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	29.99	6.34	10	8333.333333	0.83	2.78	-70.32%
29.98	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	29.99	6.34	11	8333.333333	0.83	2.78	-70.32%
29.98	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	29.99	6.34	12	8333.333333	0.83	2.78	-70.32%
29.98	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	29.99	6.34	13	8333.333333	0.83	2.78	-70.32%
29.98	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	29.99	6.34	14	8333.333333	0.83	2.78	-70.32%
29.99	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	29.99	6.34	15	8333.333333	0.83	2.78	-70.32%
29.99	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	29.99	6.34	16	8333.333333	0.83	2.78	-70.32%
29.99	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	29.99	6.34	17	8333.333333	0.83	3.78	-78.17%
29.99	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	30.00	6.34	18	8333.333333	0.83	4.78	-82.74%
29.99	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	30.00	6.34	19	8333.333333	0.83	5.78	-85.72%
29.99	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	30.00	6.34	20	8333.333333	0.83	6.78	-87.83%
29.99	1.57	6.31	7.89	0.95	1.06	0.00	0.00	0.00	30.00	6.34	21	8333.333333	0.83	7.78	-89.39%

=IF(Work!C13>Work!C14,(Work!C13-Work!C14)/2+Work!C14,(Work!C14-Work!C13)/2+Work!C13)

=IF(Work!C13>Work!C14,(Work!C13-Work!C14)/2+Work!C14,(Work!C14-Work!C13)/2+Work!C13)

Blind Factors for Infrared Radiation

	1	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10	1
Sigma	2	90	90	90	90	90	90	90	90	90	50	2
Height	3	2.4	3	3	2	0.914	2.4	2.4	2.4	2.4	3	3
No. of Blind Divisions	4	96	120	120	80	35.98425	96	96	96	96	120	4
Blind Spacing	5	0.025	0.025	0.025	0.025	0.0254	0.025	0.025	0.025	0.025	0.025	5
Blind Length	6	0.025	0.025	0.025	0.025	0.0254	0.025	0.025	0.025	0.025	0.025	6
d1	7	0.1	0.0715	0.0715	0.63	0.089	0.1	0.1	0.1	0.1	0.0715	7
d2	8	0.045	0.0715	0.0715	0.37	0.089	0.045	0.045	0.045	0.045	0.0715	8
X1	9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	9
y1	10	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.011	10
y2	11	1.175	1.475	1.475	0.975	0.432	1.175	1.175	1.175	1.175	1.477	11
y3	12	1.200	1.500	1.500	1.000	0.457	1.200	1.200	1.200	1.200	1.498	12
bd	13	1.179247642	1.476732	1.476732	1.160829445	0.440681	1.179247642	1.179247642	1.179247642	1.179247642	1.478116	13
fh	14	1.200843454	1.501703	1.501703	1.066255129	0.465586	1.200843454	1.200843454	1.200843454	1.200843454	1.499745	14
ac	15	1.204159458	1.501703	1.501703	1.181905242	0.465586	1.204159458	1.204159458	1.204159458	1.204159458	1.499745	15
eg	16	1.175861386	1.476732	1.476732	1.042844667	0.440681	1.175861386	1.175861386	1.175861386	1.175861386	1.478116	16
de	17	0.05	0.05	0.05	0.05	0.0508	0.05	0.05	0.05	0.05	0.048296	17
cf	18	1.53144E-18	1.53E-18	1.53E-18	1.53144E-18	1.56E-18	1.53144E-18	1.53144E-18	1.53144E-18	1.53144E-18	0.012941	18
Aacfh	19	2.405002911	3.003406	3.003406	2.24816037	0.931171	2.405002911	2.405002911	2.405002911	2.405002911	3.012432	19
Abdeg	20	2.405109028	3.003464	3.003464	2.253674112	0.932162	2.405109028	2.405109028	2.405109028	2.405109028	3.004527	20
Abdfh	21	2.405091095	3.003435	3.003435	2.252084574	0.931666	2.405091095	2.405091095	2.405091095	2.405091095	3.002861	21
Aaceg	22	2.405020844	3.003435	3.003435	2.249749909	0.931666	2.405020844	2.405020844	2.405020844	2.405020844	3.002861	22
cd=ef=Blind Spacing		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	23
df=Lblind		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	24
fg		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50	25
dg		1.23	1.53	1.53	1.09	0.49	1.23	1.23	1.23	1.23	1.53	26
da		1.23	1.53	1.53	1.20	0.49	1.23	1.23	1.23	1.23	1.52	27
fh		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50	28
Fdf-ce=Flowerblind-upp	$F4_L4_U$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	29
Fdf-gh=Flowerblind-Gla	$F4_L6$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	30
Fdf-ab=Flowerblind-Gla	$F4_L2$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74	31
check		1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	1.00	32
		1	2	3	4	5	6	7	8	9	10	33
	$F4_U4_L$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	34
	$F4_U6$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74	35
	$F4_U2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	36
	$F24_L$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74	37
	$F24_U$	0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.03	38
	$F64_L$	0.00	0.00	0.00	-0.03	-0.01	0.00	0.00	0.00	0.00	0.03	39
	$F64_U$	1.00	1.00	1.00	1.03	1.01	1.00	1.00	1.00	1.00	0.74	40
F26single	23	9.25186E-17	0	0	1.11022E-16	0	9.25186E-17	9.25186E-17	9.25186E-17	9.25186E-17	0.001873	41
F26	24	8.88178E-15	0	0	8.88178E-15	0	8.88178E-15	8.88178E-15	8.88178E-15	8.88178E-15	0.224745	42
F62=F26	25	8.88178E-15	0	0	8.88178E-15	0	8.88178E-15	8.88178E-15	8.88178E-15	8.88178E-15	0.224745	43
												44
AVERAGES/TOTALS												45
F24=1-F26	26	1	1	1	1	1	1	1	1	1	0.775255	46
F42=Fblinds-Glass2	27	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39	47
F46=Fblinds-Glass3	28	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39	48
F64=1-F62	29	1	1	1	1	1	1	1	1	1	0.775255	49
F44		0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.23	50
F46		0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39	51
F42		0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39	52
												53

F6-?

For solar Angle, B=30degrees blind

	emiss	IR reflc	area	Ae
surf2	1	0	0.12	0.12
surf4	0.001	0.999	0.12	1E-04
surf6	1	0	0.12	0.12
Tmean3	((tout+tin)/2)^3		3E+07	
StefanB	5.7E-08			
sigma	**90**			
sigmaTm3	1.58563			

Case8

	r2	r2 prime	r4 L (lower)	r4 U (upper)	r4 prime	r6	r6 prime	q2-others	q4low-others	q4up-others	q4-others	q6-others	SUM
0	185.06	184.68	184.68	184.69	369.51	185.07	184.69	#DIV/0!	-0.01	-0.01	-0.02	#DIV/0!	#DIV/0!
1	185.11	184.74	184.74	184.75	369.60	185.12	184.75	#DIV/0!	-0.01	-0.01	-0.01	#DIV/0!	#DIV/0!
2	185.16	184.79	184.79	184.80	369.69	185.16	184.80	#DIV/0!	-0.01	-0.01	-0.01	#DIV/0!	#DIV/0!
3	185.19	184.83	184.83	184.84	369.77	185.20	184.84	#DIV/0!	-0.01	-0.01	-0.01	#DIV/0!	#DIV/0!
4	185.23	184.87	184.87	184.88	369.84	185.24	184.88	#DIV/0!	-0.01	-0.01	-0.01	#DIV/0!	#DIV/0!
5	185.26	184.91	184.91	184.92	369.90	185.27	184.92	#DIV/0!	0.00	0.00	-0.01	#DIV/0!	#DIV/0!
6	185.29	184.94	184.94	184.95	369.96	185.30	184.95	#DIV/0!	0.00	0.00	-0.01	#DIV/0!	#DIV/0!
7	185.31	184.97	184.97	184.98	370.01	185.32	184.98	#DIV/0!	0.00	0.00	-0.01	#DIV/0!	#DIV/0!
8	185.33	184.99	184.99	185.00	370.05	185.34	185.00	#DIV/0!	0.00	0.00	-0.01	#DIV/0!	#DIV/0!
9	185.35	185.02	185.02	185.02	370.09	185.36	185.02	#DIV/0!	0.00	0.00	-0.01	#DIV/0!	#DIV/0!
10	185.37	185.04	185.04	185.04	370.12	185.38	185.04	#DIV/0!	0.00	0.00	-0.01	#DIV/0!	#DIV/0!
11	185.39	185.06	185.06	185.06	370.15	185.39	185.06	#DIV/0!	0.00	0.00	0.00	#DIV/0!	#DIV/0!
12	185.40	185.07	185.07	185.08	370.18	185.41	185.08	#DIV/0!	0.00	0.00	0.00	#DIV/0!	#DIV/0!
13	185.41	185.09	185.09	185.09	370.21	185.42	185.09	#DIV/0!	0.00	0.00	0.00	#DIV/0!	#DIV/0!
14	185.43	185.10	185.10	185.10	370.23	185.43	185.10	#DIV/0!	0.00	0.00	0.00	#DIV/0!	#DIV/0!
15	185.44	185.11	185.11	185.11	370.25	185.44	185.11	#DIV/0!	0.00	0.00	0.00	#DIV/0!	#DIV/0!
16	185.44	185.12	185.12	185.12	370.26	185.45	185.12	#DIV/0!	0.00	0.00	0.00	#DIV/0!	#DIV/0!
17	185.45	185.13	185.13	185.13	370.28	185.46	185.13	#DIV/0!	0.00	0.00	0.00	#DIV/0!	#DIV/0!
18	185.46	185.14	185.14	185.14	370.29	185.46	185.14	#DIV/0!	0.00	0.00	0.00	#DIV/0!	#DIV/0!
19	185.47	185.14	185.14	185.15	370.31	185.47	185.15	#DIV/0!	0.00	0.00	0.00	#DIV/0!	#DIV/0!
20	185.47	185.15	185.15	185.15	370.32	185.47	185.15	#DIV/0!	0.00	0.00	0.00	#DIV/0!	#DIV/0!
21	185.33	185.02	185.02	185.02	370.05	185.34	185.02	#DIV/0!	0.00	0.00	0.00	#DIV/0!	#DIV/0!
s		t	u		v		w						
	8420914869			7300959387	=(Work!O6+273)^4								

Solar Radiation Absorbed

Q a1	Q a2	Q a4	Q a7
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00

Fsolar Calculations

	length factors a (l/2)sin(sigma-blinds)	b c x tan(Beta)	c (l/2)cos(sigma-blinds)	Solar Azimuth Beta	Fsolar calculate (S-2(a+b))/S	
1	0.0125	0.0000	0.0000	0.00	0.00	0.00
2	0.0125	0.0000	0.0000	-5.00	0.00	0.00
3	0.0125	0.0000	0.0000	-10.00	0.00	0.00
4	0.0125	0.0000	0.0000	-15.00	0.00	0.00
5	0.0125	0.0000	0.0000	-20.00	0.00	0.00
6	0.0125	0.0000	0.0000	-25.00	0.00	0.00
7	0.0125	0.0000	0.0000	-30.00	0.00	0.00
8	0.0125	0.0000	0.0000	-35.00	0.00	0.00
9	0.0125	0.0000	0.0000	-40.00	0.00	0.00
10	0.0125	0.0000	0.0000	-45.00	0.00	0.00
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						

Need to import from weather data

Cavity Verification.xls

Diffuse Solar

		Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Sigma		90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	60.00
Height		2.40	3.00	3.00	2.00	0.91	2.40	2.40	2.40	2.40	3.00
No. of Blind Divisions		96.00	120.00	120.00	80.00	35.98	96.00	96.00	96.00	96.00	120.00
Blind Spacing		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Blind Length		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
d1		0.10	0.07	0.07	0.63	0.09	0.10	0.10	0.10	0.10	0.07
d2		0.05	0.07	0.07	0.37	0.09	0.05	0.05	0.05	0.05	0.07
X1	9.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
y1	10.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
y2	11.00	1.18	1.48	1.48	0.98	0.43	1.18	1.18	1.18	1.18	1.48
y3	12.00	1.20	1.50	1.50	1.00	0.46	1.20	1.20	1.20	1.20	1.50
bd		1.18	1.48	1.48	1.16	0.44	1.18	1.18	1.18	1.18	1.48
fh		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
ac		1.20	1.50	1.50	1.18	0.47	1.20	1.20	1.20	1.20	1.50
eg		1.18	1.48	1.48	1.04	0.44	1.18	1.18	1.18	1.18	1.48
de		0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
cf		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Aacfh		2.41	3.00	3.00	2.25	0.93	2.41	2.41	2.41	2.41	3.01
Abdeg		2.41	3.00	3.00	2.25	0.93	2.41	2.41	2.41	2.41	3.00
Abdfh		2.41	3.00	3.00	2.25	0.93	2.41	2.41	2.41	2.41	3.00
Aaceg		2.41	3.00	3.00	2.25	0.93	2.41	2.41	2.41	2.41	3.00
cd=ef=Blind Spacing		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
df=Lblind		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
fg		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
dg		1.23	1.53	1.53	1.09	0.49	1.23	1.23	1.23	1.23	1.53
da		1.23	1.53	1.53	1.20	0.49	1.23	1.23	1.23	1.23	1.52
fh		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
Fdf-ce=Flowerblind-up	$F4_L4_U$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
Fdf-gh=Flowerblind-Gl	$F4_L6$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
Fdf-ab=Flowerblind-Gl	$F4_L2$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
check		1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	1.00
		1	2	3	4	5	6	7	8	9	10
	$F4_U4_L$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
	$F4_U6$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
	$F4_U2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
totals (averages)	F44	0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.23
totals (averages)	F46	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39
totals (averages)	F42	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39

For reflected portion from blinds (1-Fsol)

Specular model

	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Sigma	90.000000	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	60.00
sin(sigma)	1.000000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.87
cos(sigma)	0.000000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50
Gamma	180.000000	180.00	180.00	180.00	180.00	180.00	180.00	180.00	180.00	120.00
Gamma	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180
X1	0.000000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Sb	0.025000	0.025000	0.025000	0.025000	0.025400	0.025000	0.025000	0.025000	0.025000	0.025000
Sb,perp	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.012500
I,rebound	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
I,blind	0.025000	0.025000	0.025000	0.025000	0.025400	0.025000	0.025000	0.025000	0.025000	0.025000
Ray1	1	2	3	4	5	6	7	8	9	10
R1y	0.009375	0.009375	0.009375	0.009375	0.009525	0.009375	0.009375	0.009375	0.009375	0.008119
R1x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.004688
dYr1L	0.021875	0.021875	0.021875	0.021875	0.022225	0.021875	0.021875	0.021875	0.021875	0.022294
dXr1L	#########	#########	#########	#########	##########	##########	##########	##########	#########	0.012871
dYr1T	0.046875	0.046875	0.046875	0.046875	0.047625	0.046875	0.046875	0.046875	0.046875	0.043944
dXr1T	#########	#########	#########	#########	##########	##########	##########	##########	#########	-0.025371
dXr1L+R1x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1
dXr1T	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1
RAY 1 Bounce 1	out	out	out	out	out	out	out	out	out	out
Ray 1 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 1	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
Ray2	1	2	3	4	5	6	7	8	9	10
R2y	0.003125	0.003125	0.003125	0.003125	0.003175	0.003125	0.003125	0.003125	0.003125	0.002706
R2x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.001563
dYr2L	0.015625	0.015625	0.015625	0.015625	0.015875	0.015625	0.015625	0.015625	0.015625	0.016881
dXr2L	#########	#########	#########	#########	##########	##########	##########	##########	#########	0.009746
dYr2T	0.040625	0.040625	0.040625	0.040625	0.041275	0.040625	0.040625	0.040625	0.040625	0.038532
dXr2T	#########	#########	#########	#########	##########	##########	##########	##########	#########	-0.022246
dXr2L+R2x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1
dXr2T	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1
RAY 2 Bounce 1	out	out	out	out	out	out	out	out	out	out
Ray 2 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 2	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
Ray3	1	2	3	4	5	6	7	8	9	10
R3y	0.003125	0.003125	0.003125	0.003125	0.003175	0.003125	0.003125	0.003125	0.003125	0.002706
R3x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.001563
dYr3L	0.009375	0.009375	0.009375	0.009375	0.009525	0.009375	0.009375	0.009375	0.009375	0.011468
dXr3L	#########	#########	#########	#########	##########	##########	##########	##########	#########	0.006621
dYr3T	0.034375	0.034375	0.034375	0.034375	0.034925	0.034375	0.034375	0.034375	0.034375	0.033119
dXr3T	#########	#########	#########	#########	##########	##########	##########	##########	#########	-0.019121
dXr3L-R3x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	<X1
dXr3T	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X
RAY 3 Bounce 1	out	out	out	out	out	out	out	out	out	hit
Ray 3 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 3	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-hit
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
Ray4	1	2	3	4	5	6	7	8	9	10
R4y	0.009375	0.009375	0.009375	0.009375	0.009525	0.009375	0.009375	0.009375	0.009375	0.008119
R4x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.004688
dYr4L	0.003125	0.003125	0.003125	0.003125	0.003175	0.003125	0.003125	0.003125	0.003125	0.006056
dXr4L	#########	#########	#########	#########	##########	##########	##########	##########	#########	0.003496
dYr4T	0.028125	0.028125	0.028125	0.028125	0.028575	0.028125	0.028125	0.028125	0.028125	0.027706
SUMS dXr4T	#########	#########	#########	#########	##########	##########	##########	##########	#########	-0.015996
dXr4L-R4x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	<X1 ##
dXr4T	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X
RAY 4 Bounce 1	out	out	out	out	out	out	out	out	out	hit
Ray 4 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 3	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-hit
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
lit-out	4	4	4	4	4	4	4	4	4	2
lit-hit	0	0	0	0	0	0	0	0	0	2
lit-in	0	0	0	0	0	0	0	0	0	0
hit-hit	0	0	0	0	0	0	0	0	0	0

ReflectionTotal Table:	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Rho4,s	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rho4,d	0.15	0.15	0.15	0.15	0.15	0.3	0.15	0.15	0.15	0.1
abs of blind, alpha4	0.75	0.75	0.75	0.75	0.75	0.6	0.75	0.75	0.75	0.6
1/4 sum of "lit-out"	1	1	1	1	1	1	1	1	1	1
1/4 sum of "lit-hit"	0	0	0	0	0	0	0	0	0	1
1/4 sum of "lit-in"	0	0	0	0	0	0	0	0	0	0
1/4 sum of "hit-hit"	0	0	0	0	0	0	0	0	0	0
F4U4L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
F4U6	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
F4U2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
F4L4U	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
F4L6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
F4L2	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
Rho 4, tot-out	0.2497	0.2499	0.2499	0.2387	0.2487	0.3995	0.2497	0.2497	0.2497	0.1243
Alpha 4 tot	0.7500	0.7500	0.7500	0.7500	0.7500	0.6000	0.7500	0.7500	0.7500	0.6441
Rho 4, tot-in	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0167
	0.9997	0.9999	0.9999	0.9887	0.9987	0.9995	0.9997	0.9997	0.9997	0.7851

Buoyancy forces in Air
Calculations

Laminar Case

Ambient conditions:

temp of inside air	30 deg C
temp of outside air	30 deg C
density of inside air	1.162800371 kg/m3
density of outside air	1.162800371 kg/m3

RELATES TO D1: **outer**		RELATES TO D2: **Inner**		
Outer Cavity		**Inner Cavity**		
Average Temp	26.99 deg C	Average Temp	27.08 deg C	
Average Density	1.174432252 kg/m3	Average Density	1.174040775 kg/m3	
Choose Rho infinity	**1.162800371** kg/m3	Choose Rho infinity	**1.162800371** kg/m3	
Ave viscosity ,mu	0.00001848	Ave viscosity ,mu	0.00001848	
gravity, g	9.81 m/s2			
Height, H	2.4 m			
Area Cross Sec,Acs	0.1 m2	Area Cross Sec,Acs	0.045 m2	
delta P Net	-0.027386101	**delta P Net**	-0.01190898	
neglecting entrance and exit effects				
Ave Velocity, Vave	**-0.5146 m/s**	**Ave Velocity, Vave**	**-0.0453 m/s**	< Velocity if Laminar
Dh	0.20	Dh	0.09	
Reynolds, Re	-6540.210749 **LAMINAR**	Reynolds, Re	-259.077062 **LAMINAR**	< If this says "laminar" then the velocity above is okay. Otherwise see Turbulent case

based on a Re, transition # of 1.00E+05

100,000

Turbulent Case				
friction factor, f	0.04	friction factor, f	0.078764377	
Head loss, lf	0.002845201	Head loss, lf	0.000109896	
delta P Net	**0.032780069**	**delta P Net**	**0.001265704**	
Ave velocity, Vave	**0.6159 m/s**	**Ave velocity, Vave**	**0.0048 m/s**	< Velocity if Turbulent

RESULTANT VELOCITIES	**-0.5146** m/s	**-0.0453** m/s

For outside air coming into 1 cavity: | Total for 2 cavities

Toutside	delta T	T of cavity	velocity -0.5146	mass flow	volumetric flow rate
30	0.25	30.25	0.050568	0.005939	18.20432
30	1	31.00	0.167809	0.019708	60.41139
30	2	32.00	0.333802	0.039203	120.1686
30	3	33.00	0.497999	0.058487	179.2798
30	4	34.00	0.660425	0.077562	237.7528
30	5	35.00	0.821099	0.096432	295.5955
30	6	36.00	0.979004	0.114977	352.4415
30	7	37.00	1.134876	0.133283	408.5552
30	8	38.00	1.288742	0.151354	463.9471
30	9	39.00	1.440632	0.169192	518.6276
30	10	40.00	1.590574	0.186802	572.6068
30	11	41.00	1.744058	0.204828	627.8609
30	12	42.00	1.896557	0.222739	682.764

forced ave velocy	buoyancy Ave Velocit	AveDensity	Area	mass flow
0.0558333	-0.5146	1.17	0.1	-0.060432

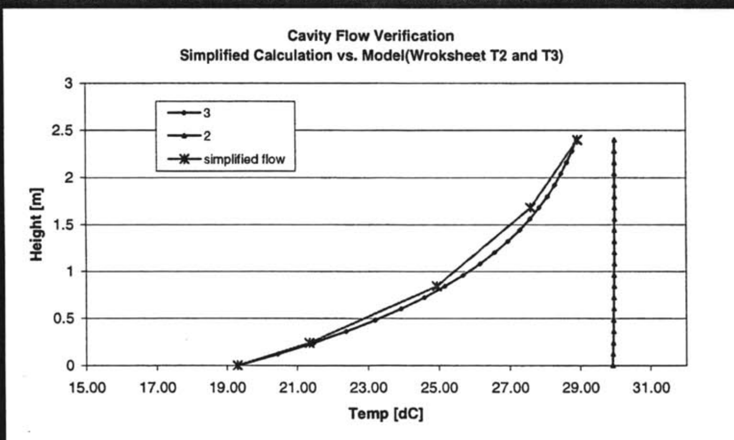
Cavity Verification.xls

SUMMARY: Validation set 2

Validation Cases		Cavity Flow with Forced Convection				
		flow	solar	Blinds	delta T	inlet T
Case1	Basic System	40 m3/hrm	0	"none" (closed,noE)	0dC	10dC low
Notes:	1. Set cavity inlet temperatures to be below inside and outside temperatures					
	2. Set R(DGU)=.001					

Simplified Model: Validation set 2

			T3, .3H	21.349156	Tw,.3H	29.94
			T3, .3H	24.939115	Tw,.3H	29.97
variable	**value**		T3, .6H	27.593477	Tw,.6H	29.99
T3,i	19.30		**T3,f**	28.724088		
Tw	29.97		**program**	28.9387		
hc	6.02		**error**	-2.23%		
w	2	this is the perimeter: (2 sides)				
y	2.4				height	Temp
m	0.0134	This is mass flow for 2 cavities			0	19.3
cp	1005.00				0.24	21.3492
					0.84	24.9391
					1.68	27.5935
					2.4	28.9387



Hens Temperature Distribution Verifications

Winter conditions with 40 m3/hm air flow and no solar radiation (delta T is 20 dC)

file: CalculatorCavFlowVerify.xls

Case8

m=0.9

Case Parameters

Geometry

Height, H	2.4	m
Num divisions	20	each
delta y	0.12	m
Area,Ady	0.12	m2
d0	15	mm
d1	0.1	m
d2	0.045	m

Design Temps

Tout	30.00	deg C
Tin	30.00	deg C
delta T	0.00	deg C
Tmrt	30.00	deg C
Tsur	30.00	deg C

Incident Radiation

qr,incident	0.00	W/m2

Blinds Properties

emissivity,E4	0.001	nondim
reflectivity, ref_blind	0.25	nondim
Spectral Reflectivity of blind	0.1	nondim
Diffuse Reflectivity of blind	0.15	nondim
Rho 4, tot-out	0.25	nondim
Alpha 4 tot	0.75	nondim
Rho 4, tot-in	7E-16	nondim
absorptivity, abs_blind	0.75	nondim
Length of the blind	0.025	m
Blind Angle from horizontal (Sigm	90	degrees
BlindSpace	0.025	m
F26(IR), geometry factor	9E-15	nondim
F24=1-F(IR), geometry factor	1	nondim
F(sol), geometry factor	0.00	nondim
1-F(sol), geometry factor	1.00	nondim
Area of the blind for convection	0.12	m

Room Properties

emissivity,Ein	0.85	nondim

Heat Transfer, hc

hout=h1	1000	nodim
hin=h7	1000	nodim

Glass Properties

1/Eeff=1/E12+1/E21-1	1.00	
Eeff	1.00	
Glass #1 ID Number	custom	
k,glass1	100.00	W/(mK)
l,glass1	0.01	mm
abs_front_glass1	0.26	nondim
abs_back_glass1	0.26	nondim
ref_front_glass1	0.19	nondim
ref_back_glass1	0.19	nondim
trans_glass1	0.55	nondim
emissivity_front_glass1	1.00	nondim
emissivity_back_glass1	1.00	nondim

Glass #2 ID Number	custom	
k,glass2	100	W/(mK)
l,glass2	0.006	m
abs_front_glass2	0.12	nodim
abs_back_glass2	0.12	nodim
ref_front_glass2	0.09	nodim
ref_back_glass2	0.09	nodim
trans_glass2	0.79	nodim
emissivity_front_glass2	1	nodim
emissivity_back_glass2	1	nodim

Glass # ID Number	custom	
k,glass3	100	W/(mK)
l,glass3	0.006	m
abs_front_glass3	0.12	nodim
abs_back_glass3	0.12	nodim
ref_front_glass3	0.09	nodim
ref_back_glass3	0.09	nodim
trans_glass3	0.79	nodim
emissivity_front_glass3	1	nodim
emissivity_back_glass3	1	nodim

Constants

StefanBoltzman	5.70E-08	W/m2K4

Hens Temperature Distribution Verifications

Winter conditions with 40 m3/hm air flow and no solar radiation (delta T is 20 dC)

file: CalculatorCavFlowVerify.xls

Case8

Case Parameters

Air Properties	d1			d2
Forced Ventilation? (yes/no)	yes		Forced Ventilation? (yes/no)	yes
Inlet Side	out		Inlet Side	in
specific heat Cp	1005.00	J/kgK	specific heat Cp	1005.00
conductivity,k	0.03	W/m2K	conductivity,k	0.03
mass flow rate, m	0.01	kg/s	mass flow rate, m	0.01
rho, density of air	1.20	could be	rho, density of air	1.20
velocity, V	0.06	m/s	velocity, V	0.12
DH	0.20	m	DH	0.09
Pr	0.69		Pr	0.69
kinematic viscosity,air	0.00		kinematic viscosity,air	0.00
ReD	702.75		ReD	702.75
Laminar NuDH	9.26		Laminar NuDH	8.73
f	0.08		f	0.08
Turbulent NuDh	-2.84		Turbulent NuDh	-2.84
Utilized Nudh	9.26		Utilized Nudh	8.73
hconv	6.02		hconv	6.30

#
0
0
0
0
0
0
0
0
0
0

7.2.3 *Buoyancy Verification*

The following is the backup for the model that compares temperature distribution and buoyant flow through the double-skin façade cavity as driven by solar radiation difference without a temperature between indoors and outdoors.

Case8 Cavity flow verification

DSF CALCULATOR

Temperature Distribution (dC)

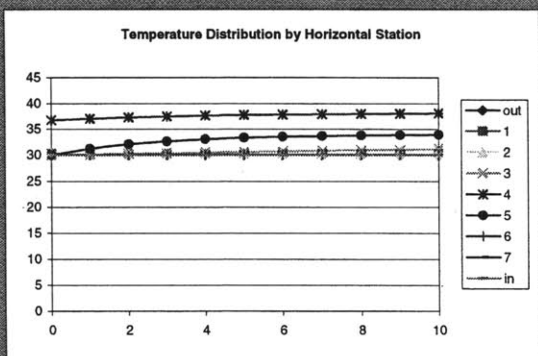
Station	height, y @bottom	out	1	2	d1 3	Blind 4	d2 5	6	7	in
0	0	30	30.22	30.23	30.00	36.71	30.00	30.04	30.04	30
1	0.12	30	30.22	30.23	30.12	37.06	31.23	30.05	30.04	30
2	0.24	30	30.22	30.23	30.24	37.31	32.07	30.05	30.05	30
3	0.36	30	30.23	30.24	30.37	37.50	32.66	30.06	30.06	30
4	0.48	30	30.23	30.24	30.49	37.64	33.07	30.06	30.06	30
5	0.6	30	30.23	30.24	30.61	37.75	33.35	30.06	30.06	30
6	0.72	30	30.23	30.24	30.72	37.83	33.55	30.07	30.06	30
7	0.84	30	30.23	30.24	30.84	37.91	33.70	30.07	30.06	30
8	0.96	30	30.23	30.24	30.95	37.97	33.80	30.07	30.06	30
9	1.08	30	30.23	30.24	31.06	38.02	33.88	30.07	30.07	30
10	1.2	30	30.23	30.25	31.17	38.07	33.94	30.07	30.07	30
11	1.32	30	30.24	30.25	31.27	38.11	33.99	30.07	30.07	30
12	1.44	30	30.24	30.25	31.37	38.15	34.03	30.07	30.07	30
13	1.56	30	30.24	30.25	31.47	38.19	34.06	30.07	30.07	30
14	1.68	30	30.24	30.25	31.57	38.23	34.08	30.07	30.07	30
15	1.8	30	30.24	30.25	31.66	38.26	34.11	30.07	30.07	30
16	1.92	30	30.24	30.25	31.75	38.30	34.13	30.07	30.07	30
17	2.04	30	30.24	30.25	31.84	38.33	34.15	30.07	30.07	30
18	2.16	30	30.24	30.25	31.92	38.36	34.17	30.07	30.07	30
19	2.28	30	30.24	30.25	32.01	38.39	34.19	30.07	30.07	30
20	2.4	30	30.24	30.25	32.09	38.42	34.20	30.07	30.07	30
				Ave T2 30.24		Tcav top 33.15		Ave T6 30.07		

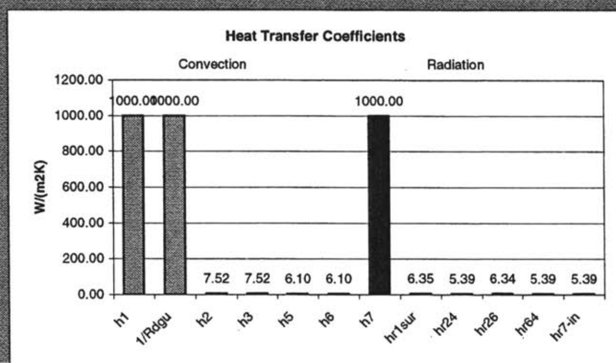
summary

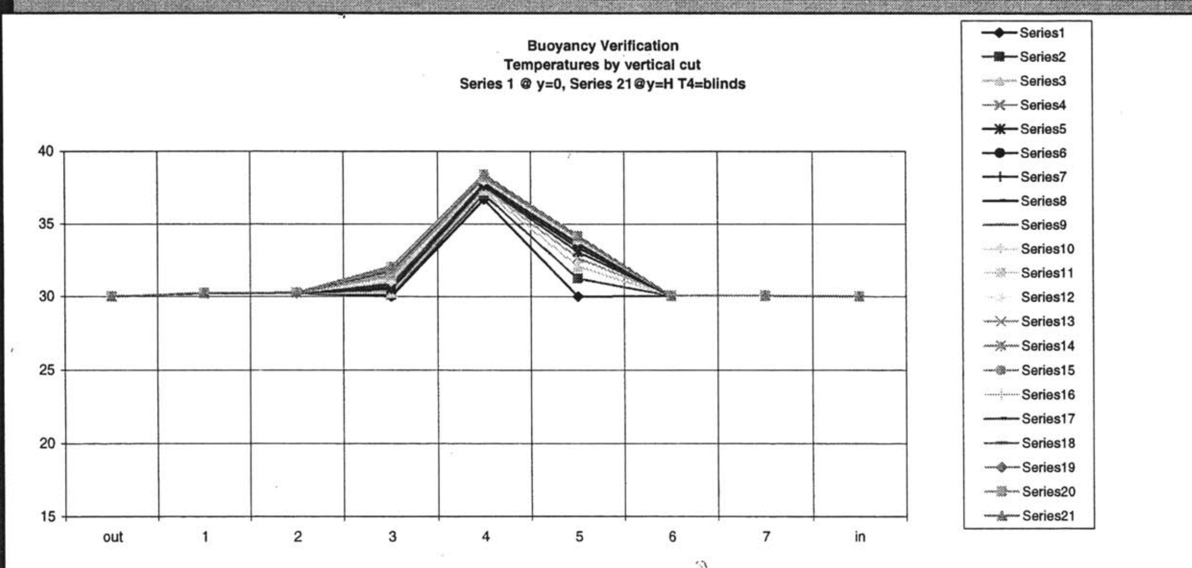
Height (m)	2.40
Solar Rad(W/m2)	500.00
T out	30.00
T in	30.00
Tmax	38.02
Total q to room (W)	150.22
Total q to duct (W)	70.79
V3	0.4309
V5	0.0741
Average 2 cavity temp	32.28
SHGC	0.13
Effective U-Value	N/A

Notes:

DGU R-Value set to 0.001
Emissivity of glass = 1.0
Emissivity of blinds = 0.001
Blinds are closed (Sigma=90)
hc model for channel: HENS







User Input and Given Parameters	input cases here	>>									
	case1	case2	case3	case4	case5	case6	case7	case8	case6	case10	
Geometry	u-value T's shgc Q		mixed T Q	P winter	Experiment	Hens basic	Hens basic	Cavity Flow	dynamic shgc		
Height, H height	2.4	3	3	2	0.914	2.4	2.4	2.4	2.4	3	m
Num divisions visions	20	20	20	20	20.000	20	20	20	20	20	each
delta y dy	0.12	0.15	0.15	0.1	0.0457	0.12	0.12	0.12	0.12	0.15	m
Area,A area	0.12	0.15	0.15	0.1	0.0457	0.12	0.12	0.12	0.12	0.15	m^2
d0 _do	15	13	13	13	13	15	15	15	15	13	mm
d1 _d1	0.100	0.072	0.072	0.630	0.089	0.100	0.100	0.100	0.100	0.072	m
d2 _d2	0.045	0.072	0.072	0.370	0.089	0.045	0.045	0.045	0.045	0.072	m
Design Temps						Hens basic	Hens basic	Cavity Flow	dynamic shgc		
T_{out} Tout	0	24	20	20	42	30	0	30	30	0	deg C
T_{in} tin	20	24	24	24	22	20	0	30	30	24	deg C
delta T deltaT	-20	0	-4	-4	20	10	0	0	0	-24	deg C
Tmrt Tmrt	20	24	24	24	22	20	0	30	30	24	deg C
Tsur Tsky	0	24	20	20	42	30	0	30	30	0	deg C
						30	Tinlet=0.0	30	30		
Incident Radiation											
qr,incident ıcident	0	800	800	0	0	500	500	500	500	0	W/m^2
Glass Properties	1	2	3	4	5	6	7	8	6	10	
1/Eeff=1/E1+1/E2-1	1.00	1.58	1.38	1.36	1.19	1.00	6.84	1.00	1.00	1.38	
Eeff	1.00	0.72	0.72	0.72	0.84	1.00	0.15	1.00	1.00	0.72	
Glass ID Number	custom	1300	1300	4001	custom	custom	custom	custom	custom	1300	
k,glass1 glass1	1	1	1	1	100	1	1	100	1	1	W/(mK)
l,glass1 glass1	0.01	0.008	0.008	0.008	0.002	0.01	0.01	0.01	0.01	0.008	mm
abs_front_glass1 glass1	0.26	0.08906	0.08906	0.2971	0	0.26	0.26	0.26	0.26	0.08906	nondim
abs_back_glass1	0.26	0.08906	0.08906	0.2209	0	0.26	0.26	0.26	0.26	0.08906	nondim
ref_front_glass1 glass1	0.19	0.07344	0.07344	0.1556	0.001	0.19	0.19	0.19	0.19	0.07344	nondim
ref_back_glass1	0.19	0.07344	0.07344	0.2318	0.001	0.19	0.19	0.19	0.19	0.07344	nondim
trans_glass1 glass1	0.55	0.8375	0.8375	0.5473	0.999	0.55	0.55	0.55	0.55	0.8375	nondim
emissivity_front_glass1	0.999	0.84	0.84	0.84	0.999	1	0.85	1	1	0.84	nondim
emissivity_back_glass1 glass1	0.999	0.84	0.84	0.09	0.999	1	0.15	1	1	0.84	nondim
Glass ID Number	custom	1300	1300	5012	1300	custom	custom	custom	custom	1300	
k,glass2 glass2	1	1	1	1	1	1	1	100	1	1	W/(mK)
l,glass2 glass2	0.006	0.008	0.008	0.008	0.003	0.006	0.006	0.006	0.006	0.008	m
abs_front_glass2 glass2	0.12	0.08906	0.08906	0.15815	0.08906	0.12	0.12	0.12	0.12	0.08906	nodim
abs_back_glass2	0.12	0.08906	0.08906	0.15755	0.08906	0.12	0.12	0.12	0.12	0.08906	nodim
ref_front_glass2	0.09	0.07344	0.07344	0.07195	0.07344	0.09	0.09	0.09	0.09	0.07344	nodim
ref_back_glass2 glass2	0.09	0.07344	0.07344	0.07255	0.07344	0.09	0.09	0.09	0.09	0.07344	nodim
trans_glass2 glass2	0.79	0.8375	0.8375	0.7699	0.8375	0.79	0.79	0.79	0.79	0.8375	nodim
emissivity_front_glass2	0.999	0.84	0.84	0.84	0.84	1	0.85	1	1	0.84	nodim
emissivity_back_glass2 glass1	0.999	0.84	0.84	0.84	0.84	1	0.85	1	1	0.84	nodim
Glass ID Number	custom	1300	1300	1305	1300	custom	custom	custom	custom	1300	
k,glass3 glass3	1	1	1	1	1	1	1	100	1	1	W/(mK)
l,glass3 glass3	0.006	0.008	0.008	0.008	0.003	0.006	0.006	0.006	0.006	0.008	m
abs_front_glass3 glass3	0.12	0.08906	0.08906	0.28255	0.08906	0.12	0.12	0.12	0.12	0.08906	nodim
abs_back_glass3	0.12	0.08906	0.08906	0.28255	0.08906	0.12	0.12	0.12	0.12	0.08906	nodim
ref_front_glass3	0.09	0.07344	0.07344	0.06215	0.07344	0.09	0.09	0.09	0.09	0.07344	nodim
ref_back_glass3 glass3	0.09	0.07344	0.07344	0.06215	0.07344	0.09	0.09	0.09	0.09	0.07344	nodim
trans_glass3 glass3	0.79	0.8375	0.8375	0.6553	0.8375	0.79	0.79	0.79	0.79	0.8375	nodim
emissivity_front_glass3	0.0067	0.84	0.84	0.84	0.84	1	0.85	1	1	0.84	nodim
emissivity_back_glass3 glass3	0.999	0.84	0.84	0.84	0.84	1	0.85	1	1	0.84	nodim
Heat Transfer, hc	1	2	3	4	5	Hens basic	Hens basic	Cavity Flow	dynamic sh	10	
$h_{out}=h_1$ hout1	23	29	29	29	8.29	1000	23	1000	1000	29	W/m^2K
$h_{in}=h_7$ hin	8	8.29	8.29	8.29	8.29	1000	8	1000	1000	8.29	W/m^2K
Blinds Properties	1	2	3	4	5	6	7	8	9	10	
emissivity,E4 sivity4	0.999	0.9	0.9	0.01	0.85	0.85	0.85	0.85	0.85	0.9	nondim
reflectivity, ref_blind efblind	0.25	0.25	0.25	0.25	0.25	0.4	0.25	0.25	0.25	0.2	nondim
Spectral Reflectivity of blind R4s	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	nondim
Diffuse Reflectivity of blind R4d	0.15	0.15	0.15	0.15	0.15	0.3	0.15	0.15	0.15	0.1	nondim
Rho 4, tot-out	0.25	0.25	0.25	0.24	0.25	0.40	0.25	0.25	0.25	0.12	nondim
Alpha 4 tot	0.75	0.75	0.75	0.75	0.75	0.60	0.75	0.75	0.75	0.64	nondim
Rho 4, tot-in	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	nondim
absorptivity, abs_blind bsblind	0.75	0.75	0.75	0.75	0.75	0.6	0.75	0.75	0.75	0.6	nondim
Length of the blind Lblind	0.025	0.025	0.025	0.025	0.0254	0.025	0.025	0.025	0.025	0.025	m
Blind Angle from horizontal (Sigma) _Angle	90	90	90	90	90	90	90	90	90	60	degrees
BlindSpace lSpace	0.025	0.025	0.025	0.025	0.0254	0.025	0.025	0.025	0.025	0.025	m
F26(IR), geometry factor F_IR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2247	nondim
F24=1-F(IR), geometry factor _F_IR	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.78	nondim
F(sol), geometry factor F_sol											
1-F(sol), geometry factor _F_sol											
Area of blind for convection Ady,blind Ablind	0.12	0.15	0.15	0.1	0.0457	0.12	0.12	0.12	0.12	0.15	m
Room Properties						Hens basic	Hens basic	Cavity Flow	dynamic shgc		
emissivity,Ein sivityin	1	0.9	0.9	0.9	0.9	0.85	0.85	0.85	0.85	0.9	nondim
Air Properties Cavity	1	2	3	4	5	6	7	8	9	10	
Forced Ventilation? (yes/no) :ASE>	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	
Inlet side (in/out) :ASE>	in	in	in	in	in	out	out	out	out	out	
specific heat Cp air_d1	1005	1005	1005	1005	1005	1005	1005	1005	1005	1005	J/kgK
conductivity,k air_d1	0.025	0.027	0.027	0.027	0.025	0.025	0.025	0.025	0.025	0.027	W/m2K
mass flow rate, m ow_d1	0.0092	0.0092	0.0092	0.0092	0.0092	0.0092	0.0092	0.0517	0.0058	0.0092	kg/s
rho, density of air sity_d1	1.2	1.18	1.18	1.18	1.2	1.2	1.2	1.2	1.2	1.18	could be look
velocity, V city_d1	0.08	0.11	0.11	0.01	0.09	0.0771	0.08	0.43	0.05	0.11	m/s
D_H DH_d1	0.2	0.143	0.143	1.26	0.178	0.2	0.2	0.2	0.2	0.143	m
P_r Pr_d1	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	
kinematic viscosity,air isc_d1	1.59E-05	1.59E-05	1.59E-05	1.59E-05	1.59E-05	1.59E-05	1.59E-05	1.59E-05	1.59E-05	1.59E-05	0.07705
Re_D eD_d1	969.79	966.23	966.23	966.23	969.79	969.79	969.79	5423.42	608.35	966.23	0.076926
Laminar Nu_{DH} am_d1	9.59	9.07	9.07	14.97	11.01	9.59	9.59	13.62	9.13	9.07	m=
f f_d1	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.04	0.09	0.07	m(1)=
Turbulent Nu_{Dh} am_d1	-0.24	-0.11	-0.11	-0.11	-0.24	-0.24	-0.24	17.76	-4.04	-0.11	m(2)=
Utilized Nu_{dh} NU_d1	9.59	9.07	9.07	14.97	11.01	9.59	9.59	17.76	9.13	9.07	
h_{conv} h_d1	6.00	1.71	1.71	5.85	6.15	6.11	6.11	7.52	5.99	1.71	
volumetric flow this side:	27.738	28.20814	28.20814	28.20814	27.738	27.738	27.738	155.1207	17.4	28.20814	
Inner Cavity	1	2	3	4	5	6	7	8	9	10	Case8
Forced Ventilation? (yes/no) :ASE>	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	
Inlet side (in/out) :ASE>	in	in	in	in	in	in	in	in	in	out	
specific heat Cp air_d2	1005	1005	1005	1005	1005	1005	1005	1005	1005	1005	J/kgK
conductivity,k air_d2	0.025	0.027	0.027	0.027	0.025	0.025	0.025	0.025	0.025	0.027	W/m2K
mass flow rate, m ow_d2	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042	0.0042	0.0040	0.0058	0.0042	kg/s
rho, density of air sity_d2	1.2	1.18	1.18	1.18	1.2	1.2	1.2	1.2	1.2	1.18	should be lool
velocity, V city_d2	0.08	0.05	0.05	0.01	0.04	0.0769	0.08	0.07	0.11	0.05	m/s
D_H DH_d2	0.09	0.143	0.143	0.74	0.178	0.09	0.09	0.09	0.09	0.143	m
P_r Pr_d2	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.69	
kinematic viscosity,air isc_d2	1.59E-05	1.59E-05	1.59E-05	1.59E-05	1.59E-05	1.59E-05	1.59E-05	1.59E-05	1.59E-05	1.59E-05	
Re_D eD_d2	435.70	443.09	443.09	443.09	435.70	435.70	435.70	419.60	608.35	443.09	
Laminar Nu_{DH} am_d2	8.55	8.63	8.63	10.70	9.65	8.55	8.55	8.54	8.66	8.63	
f f_d2	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.10	
Turbulent Nu_{Dh} am_d2	-7.07	-6.91	-6.91	-6.91	-7.07	-7.07	-7.07	-7.45	-4.04	-6.91	
Utilized Nu_{dh} NU_d2	8.55	8.63	8.63	10.70	9.65	8.55	8.55	8.54	8.66	8.63	
h_{conv} h_d2	80.00	1.63	1.63	5.84	5.96	6.11	6.11	6.10	6.23	1.63	
volumetric flow this side:	12.462	12.67322	12.67322	12.67322	12.462	12.462	12.462	12.00137	17.4	12.67322	
TOTAL VOLUMETRIC FLOW	40.2	40.88136	40.88136	40.88136	40.2	40.2	40.2	167.1221	34.8	40.88136	
Constants	1	2	3	4	6	6	7	8	9	10	
StefanBoltzman Stefan	5.70E-08	5.70E-08	5.70E-08	5.70E-08	5.70E-08	5.70E-08	5.70E-08	5.70E-08	5.70E-08	5.70E-08	W/m^2K^4

Radiation Heat Transfer Coefficients

Tm 4 to 2	hrad 4 to 2	Tm 6 to 4	hrad 6 to 4	Tm 6 to 2	hrad 6 to 2	Tm 6 to 4	hrad 6 to 4	Tm 7 to in	hrad 7 to in
30	5.39	30.00	5.39	30.00	6.34	30	5.39	30.00	5.39
33.47	5.58	33.38	5.57	30.13	6.35	33.38	5.57	30.02	5.39
33.65	5.59	33.55	5.58	30.14	6.35	33.55	5.58	30.02	5.39
33.77	5.60	33.68	5.59	30.14	6.35	33.68	5.59	30.03	5.39
33.87	5.60	33.78	5.60	30.15	6.35	33.78	5.60	30.03	5.39
33.94	5.60	33.86	5.60	30.15	6.35	33.85	5.60	30.03	5.39
33.99	5.61	33.91	5.60	30.15	6.35	33.91	5.60	30.03	5.39
34.04	5.61	33.95	5.60	30.15	6.35	33.95	5.60	30.03	5.39
34.07	5.61	33.99	5.61	30.15	6.35	33.99	5.61	30.03	5.39
34.11	5.61	34.02	5.61	30.16	6.35	34.02	5.61	30.03	5.39
34.13	5.61	34.05	5.61	30.16	6.35	34.05	5.61	30.03	5.39
34.16	5.62	34.07	5.61	30.16	6.35	34.07	5.61	30.03	5.39
34.18	5.62	34.09	5.61	30.16	6.35	34.09	5.61	30.03	5.39
34.20	5.62	34.11	5.61	30.16	6.35	34.11	5.61	30.03	5.39
34.22	5.62	34.13	5.61	30.16	6.35	34.13	5.61	30.03	5.39
34.24	5.62	34.15	5.62	30.16	6.35	34.15	5.62	30.03	5.39
34.26	5.62	34.17	5.62	30.16	6.35	34.17	5.62	30.03	5.39
34.27	5.62	34.19	5.62	30.16	6.35	34.19	5.62	30.03	5.39
34.29	5.62	34.20	5.62	30.16	6.35	34.20	5.62	30.03	5.39
34.31	5.62	34.22	5.62	30.16	6.35	34.22	5.62	30.03	5.39
34.32	5.63	34.23	5.62	30.16	6.35	34.23	5.62	30.03	5.39

checked 010499

Convective Heat Transfer Coefficients

	h2	h3	h5	h6
1	7.52	7.52	6.10	6.10
2	7.52	7.52	6.10	6.10
3	7.52	7.52	6.10	6.10
4	7.52	7.52	6.10	6.10
5	7.52	7.52	6.10	6.10
6	7.52	7.52	6.10	6.10
7	7.52	7.52	6.10	6.10
8	7.52	7.52	6.10	6.10
9	7.52	7.52	6.10	6.10
10	7.52	7.52	6.10	6.10
11	7.52	7.52	6.10	6.10
12	7.52	7.52	6.10	6.10
13	7.52	7.52	6.10	6.10
14	7.52	7.52	6.10	6.10
15	7.52	7.52	6.10	6.10
16	7.52	7.52	6.10	6.10
17	7.52	7.52	6.10	6.10
18	7.52	7.52	6.10	6.10
19	7.52	7.52	6.10	6.10
20	7.52	7.52	6.10	6.10
21	7.52	7.52	6.10	6.10

checked 010499

assumptions
Tm4-2 at y=0 is T3=Tin
Tm6-4 at y=0 is T5=Tin
Tm7-4 at y=0 is T5=Tin

note
Tm go with y-1 rather than y

Temperature Coefficients

A1	A2	A3	B_1	B_2 (unused)	B_3 (unused)	C_1 (unused)	C_2	C_3	D_1	D_2	E1	E_2	
0.76	120.00	1000.00	0.90	0.65	0.00	0.65	0.90	0.73	0.73	2000.00	0.65	120.00	1
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	2
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	3
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	4
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	5
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	6
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	7
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	8
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	9
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	10
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	11
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	12
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	13
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	14
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	15
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	16
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	17
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	18
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	19
0.76	120.00	1000.00	0.90	0.67	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	20
0.76	120.00	1000.00	0.90	0.68	0.00	0.67	0.90	0.73	0.73	2000.00	0.65	120.00	21

Double Glazing Calcs

tm 1,2	hc,gap	Eeff hr	hc+Eeff	C	dgu air gap R,gap	Rglass1 (l/kA)g1	Rglass2 (l/kA)g2	=SUM(E6:(R,dgu	Tm 1-sur	hrad 1-sur	2000	Uglass plus hc Uglass	ASHRAE TABLE 27.6-5(1993) hi=8.29, ho=29		DIFFEREN
30.22	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.11	6.35	1	8333.333333	0.83	2.78	-70.27%
30.23	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.11	6.35	2	8333.333333	0.83	2.78	-70.27%
30.23	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.11	6.35	3	8333.333333	0.83	2.78	-70.27%
30.23	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.11	6.35	4	8333.333333	0.83	2.78	-70.27%
30.23	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.11	6.35	5	8333.333333	0.83	2.78	-70.26%
30.23	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.11	6.35	6	8333.333333	0.83	2.78	-70.26%
30.24	1.57	6.33	7.90	0.96	1.05	0.00	0.00	0.00	30.12	6.35	7	8333.333333	0.83	2.78	-70.26%
30.24	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	8	8333.333333	0.83	2.78	-70.26%
30.24	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	9	8333.333333	0.83	2.78	-70.26%
30.24	1.67	8.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	10	8333.333333	0.83	2.78	-70.26%
30.24	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	11	8333.333333	0.83	2.78	-70.26%
30.24	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	12	8333.333333	0.83	2.78	-70.26%
30.24	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	13	8333.333333	0.83	2.78	-70.26%
30.24	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	14	8333.333333	0.83	2.78	-70.26%
30.24	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	15	8333.333333	0.83	2.78	-70.26%
30.24	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	16	8333.333333	0.83	2.78	-70.26%
30.25	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	17	8333.333333	0.83	3.78	-78.13%
30.25	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	18	8333.333333	0.83	4.78	-82.70%
30.25	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	19	8333.333333	0.83	5.78	-85.70%
30.25	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	20	8333.333333	0.83	6.78	-87.81%
30.25	1.57	6.33	7.90	0.95	1.05	0.00	0.00	0.00	30.12	6.35	21	8333.333333	0.83	7.78	-89.37%

=IF(Work!C13>Work!C14,(Work!C13-Work!C14)/2+Work!C14,(Work!C14-Work!C13)/2+Work!C13)
=IF(Work!C13>Work!C14,(Work!C13-Work!C14)/2+Work!C14,(Work!C14-Work!C13)/2+Work!C13)

Blind Factors for Infrared Radiation

	1	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Sigma	2	90	90	90	90	90	90	90	90	90	60
Height	3	2.4	3	3	2	0.914	2.4	2.4	2.4	2.4	3
No. of Blind Divisions	4	96	120	120	80	35.98425	96	96	96	96	120
Blind Spacing	5	0.025	0.025	0.025	0.025	0.0254	0.025	0.025	0.025	0.025	0.025
Blind Length	6	0.025	0.025	0.025	0.025	0.0254	0.025	0.025	0.025	0.025	0.025
d1	7	0.1	0.0715	0.0715	0.63	0.089	0.1	0.1	0.1	0.1	0.0715
d2	8	0.045	0.0715	0.0715	0.37	0.089	0.045	0.045	0.045	0.045	0.0715
X1	9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006
y1	10	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.011
y2	11	1.175	1.475	1.475	0.975	0.432	1.175	1.175	1.175	1.175	1.477
y3	12	1.200	1.500	1.500	1.000	0.457	1.200	1.200	1.200	1.200	1.498
bd	13	1.179247642	1.476732	1.476732	1.160829445	0.440681	1.179247642	1.179247642	1.179247642	1.179247642	1.478116
fh	14	1.200843454	1.501703	1.501703	1.066255129	0.465586	1.200843454	1.200843454	1.200843454	1.200843454	1.499745
ac	15	1.204159458	1.501703	1.501703	1.181905242	0.465586	1.204159458	1.204159458	1.204159458	1.204159458	1.499745
eg	16	1.175861386	1.476732	1.476732	1.042844667	0.440681	1.175861386	1.175861386	1.175861386	1.175861386	1.478116
de	17	0.05	0.05	0.05	0.05	0.0508	0.05	0.05	0.05	0.05	0.048296
cf	18	1.53144E-18	1.53E-18	1.53E-18	1.53144E-18	1.56E-18	1.53144E-18	1.53144E-18	1.53144E-18	1.53144E-18	0.012941
Aacfh	19	2.405002911	3.003406	3.003406	2.24816037	0.931171	2.405002911	2.405002911	2.405002911	2.405002911	3.012432
Abdeg	20	2.405109028	3.003464	3.003464	2.253674112	0.932162	2.405109028	2.405109028	2.405109028	2.405109028	3.004527
Abdfh	21	2.405091095	3.003435	3.003435	2.252084574	0.931666	2.405091095	2.405091095	2.405091095	2.405091095	3.002861
Aaceg	22	2.405020844	3.003435	3.003435	2.249749909	0.931666	2.405020844	2.405020844	2.405020844	2.405020844	3.002861
cd=ef=Blind Spacing		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
df=Lblind		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
fg		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
dg		1.23	1.53	1.53	1.09	0.49	1.23	1.23	1.23	1.23	1.53
da		1.23	1.53	1.53	1.20	0.49	1.23	1.23	1.23	1.23	1.52
fh		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
Fdf-ce=Flowerblind-upp	$F4_L4_U$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
Fdf-gh=Flowerblind-Gla	$F4_L6$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
Fdf-ab=Flowerblind-Gla	$F4_L2$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
check		1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	1.00
		1	2	3	4	5	6	7	8	9	10
	$F4_U4_L$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
	$F4_U6$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
	$F4_U2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
	$F24_L$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
	$F24_U$	0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.03
	$F64_L$	0.00	0.00	0.00	-0.03	-0.01	0.00	0.00	0.00	0.00	0.03
	$F64_U$	1.00	1.00	1.00	1.03	1.01	1.00	1.00	1.00	1.00	0.74
F26single	23	9.25186E-17	0	0	1.11022E-16	0	9.25186E-17	9.25186E-17	9.25186E-17	9.25186E-17	0.001873
F26	24	8.88178E-15	0	0	8.88178E-15	0	8.88178E-15	8.88178E-15	8.88178E-15	8.88178E-15	-0.224745
F62=F26	25	8.88178E-15	0	0	8.88178E-15	0	8.88178E-15	8.88178E-15	8.88178E-15	8.88178E-15	0.224745
AVERAGES/TOTALS											
F24=1-F26	26	1	1	1	1	1	1	1	1	1	0.775255
F42=Fblinds-Glass2	27	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39
F46=Fblinds-Glass3	28	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39
F64=1-F62	29	1	1	1	1	1	1	1	1	1	0.775255
F44		0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.23
F46		0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39
F42		0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39

F6-?

For solar Angle, B=30degrees blind

	emiss	IR reflc	area	Ae
surf2	1	0	0.12	0.12
surf4	0.85	0.15	0.12	0.102
surf6	1	0	0.12	0.12
Tmean3	((tout+tin)/2)^3		3E+07	
StefanB	5.7E-08			
sigma	**90**			
sigmaTm3	1.58563			

Case8

	r2	r2 prime	r4 L (lower)	r4 U (upper)	r4 prime	r6	r6 prime	q2-others	q4low-others	q4up-others	q4-others	q6-others	SUM
0	186.96	221.88	221.88	221.70	372.09	185.76	221.70	#DIV/0!	4.23	4.35	8.58	#DIV/0!	#DIV/0!
1	186.98	223.76	223.76	223.58	372.17	185.82	223.58	#DIV/0!	4.45	4.57	9.02	#DIV/0!	#DIV/0!
2	187.00	225.11	225.11	224.94	372.23	185.86	224.94	#DIV/0!	4.61	4.73	9.34	#DIV/0!	#DIV/0!
3	187.01	226.12	226.12	225.95	372.27	185.89	225.95	#DIV/0!	4.73	4.84	9.57	#DIV/0!	#DIV/0!
4	187.02	226.87	226.87	226.71	372.31	185.91	226.71	#DIV/0!	4.82	4.93	9.75	#DIV/0!	#DIV/0!
5	187.03	227.46	227.46	227.30	372.33	185.93	227.30	#DIV/0!	4.89	5.00	9.89	#DIV/0!	#DIV/0!
6	187.04	227.94	227.94	227.77	372.35	185.94	227.77	#DIV/0!	4.95	5.06	10.00	#DIV/0!	#DIV/0!
7	187.05	228.33	228.33	228.16	372.37	185.95	228.16	#DIV/0!	4.99	5.10	10.09	#DIV/0!	#DIV/0!
8	187.06	228.66	228.66	228.49	372.38	185.96	228.49	#DIV/0!	5.03	5.14	10.17	#DIV/0!	#DIV/0!
9	187.07	228.95	228.95	228.78	372.40	185.96	228.78	#DIV/0!	5.06	5.18	10.24	#DIV/0!	#DIV/0!
10	187.07	229.21	229.21	229.04	372.41	185.97	229.04	#DIV/0!	5.09	5.21	10.30	#DIV/0!	#DIV/0!
11	187.08	229.45	229.45	229.28	372.42	185.97	229.28	#DIV/0!	5.12	5.24	10.36	#DIV/0!	#DIV/0!
12	187.09	229.67	229.67	229.50	372.43	185.97	229.50	#DIV/0!	5.15	5.26	10.41	#DIV/0!	#DIV/0!
13	187.10	229.88	229.88	229.71	372.44	185.97	229.71	#DIV/0!	5.17	5.29	10.46	#DIV/0!	#DIV/0!
14	187.10	230.08	230.08	229.91	372.45	185.98	229.91	#DIV/0!	5.20	5.31	10.50	#DIV/0!	#DIV/0!
15	187.11	230.27	230.27	230.10	372.46	185.98	230.10	#DIV/0!	5.22	5.33	10.55	#DIV/0!	#DIV/0!
16	187.11	230.45	230.45	230.28	372.46	185.98	230.28	#DIV/0!	5.24	5.35	10.59	#DIV/0!	#DIV/0!
17	187.12	230.62	230.62	230.45	372.47	185.98	230.45	#DIV/0!	5.26	5.37	10.63	#DIV/0!	#DIV/0!
18	187.13	230.79	230.79	230.62	372.48	185.98	230.62	#DIV/0!	5.28	5.39	10.67	#DIV/0!	#DIV/0!
19	187.13	230.96	230.96	230.79	372.49	185.99	230.79	#DIV/0!	5.30	5.41	10.71	#DIV/0!	#DIV/0!
20	187.14	231.12	231.12	230.94	372.49	185.99	230.94	#DIV/0!	5.32	5.43	10.75	#DIV/0!	#DIV/0!
21	187.07	202.66	202.66	202.49	372.38	185.94	202.49	#DIV/0!	1.91	2.02	3.93	#DIV/0!	#DIV/0!

s		t	u		v	w
8454250468				9201153563	=(Work!O6+273)^4	

Solar Radiation Absorbed

Q a1	Q a2	Q a4	Q a7
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00

Fsolar Calculations

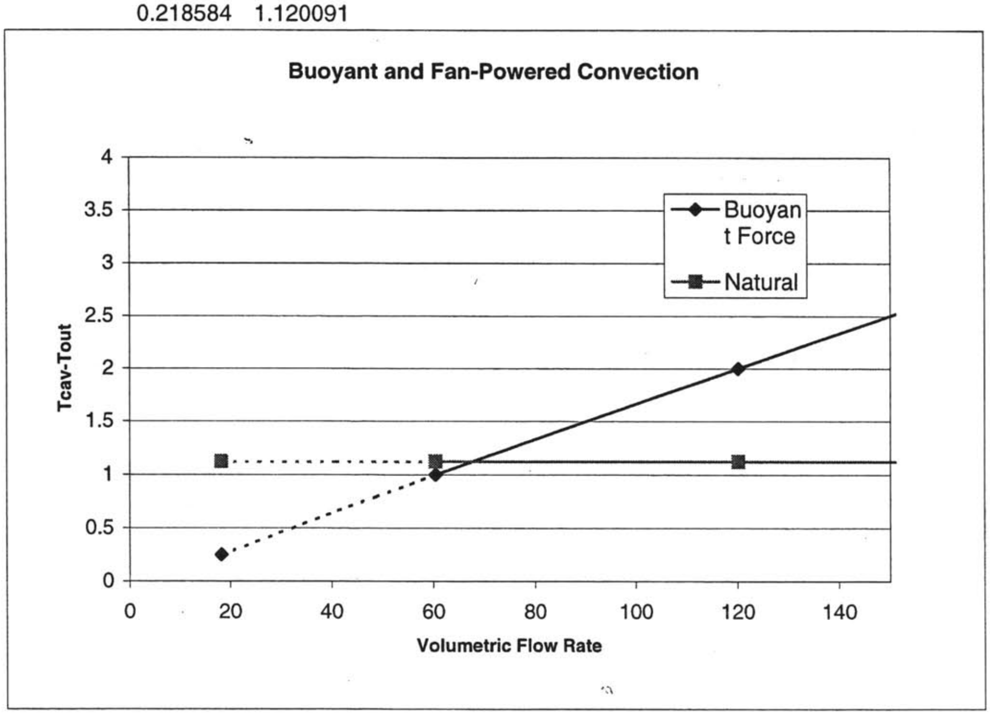
length factors

	a (l/2)sin(sigma-blinds)	b c x tan(Beta)	c (l/2)cos(sigma-blinds)	Solar Azimuth Beta	Fsolar calculate (S-2(a+b))/S	
1	0.0125	0.0000	0.0000	0.00	0.00	0.00
2	0.0125	0.0000	0.0000	-5.00	0.00	0.00
3	0.0125	0.0000	0.0000	-10.00	0.00	0.00
4	0.0125	0.0000	0.0000	-15.00	0.00	0.00
5	0.0125	0.0000	0.0000	-20.00	0.00	0.00
6	0.0125	0.0000	0.0000	-25.00	0.00	0.00
7	0.0125	0.0000	0.0000	-30.00	0.00	0.00
8	0.0125	0.0000	0.0000	-35.00	0.00	0.00
9	0.0125	0.0000	0.0000	-40.00	0.00	0.00
10	0.0125	0.0000	0.0000	-45.00	0.00	0.00
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						

Need to import from weather data

For outside air coming into 1 cavity:				Total for Cavity d1	
	Buoyant Fc	T of cavity	velocity	m3	volumetric
Toutside	delta T		0.4486	mass flow	flow rate
30	0.25	30.25	0.050568	0.005828	18.20432
30	1	31.00	0.167809	0.01934	60.41139
30	2	32.00	0.333802	0.038472	120.1686
30	3	33.00	0.497999	0.057396	179.2798
30	4	34.00	0.660425	0.076116	237.7528
30	5	35.00	0.821099	0.094634	295.5955
30	6	36.00	0.979004	0.112833	352.4415
30	7	37.00	1.134876	0.130797	408.5552
30	8	38.00	1.288742	0.148531	463.9471
30	9	39.00	1.440632	0.166037	518.6276
30	10	40.00	1.590574	0.183318	572.6068
30	11	41.00	1.744058	0.201007	627.8609
30	12	42.00	1.896567	0.218584	682.764

	USE CASE 9		
	Natural Co	deltaT	deltaT
M3	m3	1.120091	1.120091
0.0058	0.0058	1.12	
	0.02	1.120091	
	0.04	1.120091	
	0.06	1.120091	
	0.08	1.120091	
	0.09	1.120091	
	0.11	1.120091	
	0.130797	1.120091	
	0.148531	1.120091	
	0.166037	1.120091	
	0.183318	1.120091	
	0.201007	1.120091	
	0.218584	1.120091	



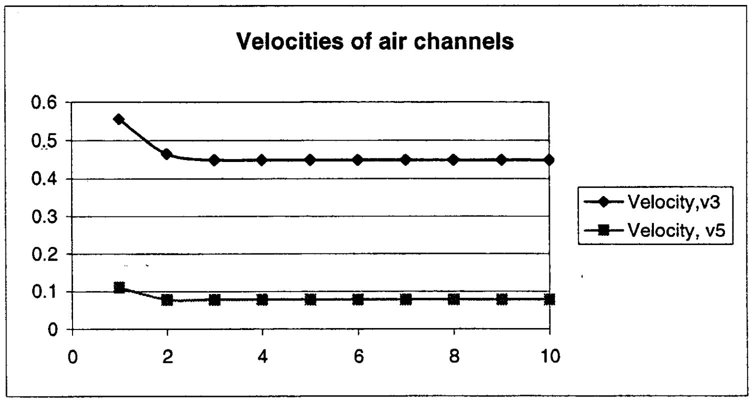
USE CASE 8

	Iteration	Velocity,v3	Velocity, v5
Forced	1	0.5556493	0.11086794
Natural	2	0.4651036	0.07776502
Natural	3	0.4486395	0.07776502
Natural	4	0.4486395	0.07776502
Natural	5	0.4486395	0.07776502
Natural	6	0.4486395	0.07776502
Natural	7	0.4486395	0.07776502
Natural	8	0.4486395	0.07776502
Natural	9	0.4486395	0.07776502
Natural	10	0.4486395	0.07776502

Live Velocities (Forced)	
v3	v5
0.4309	0.0741

Live Velocities (natural)	
v3	v5
0.4486	0.0778

Live massflow (natural)	
v3	v5
0.0517	0.0040



7.2.4 U-value Validation

The following is the backup for the comparison of the model predictions with [Saelens 1998] for U-value.

Case6

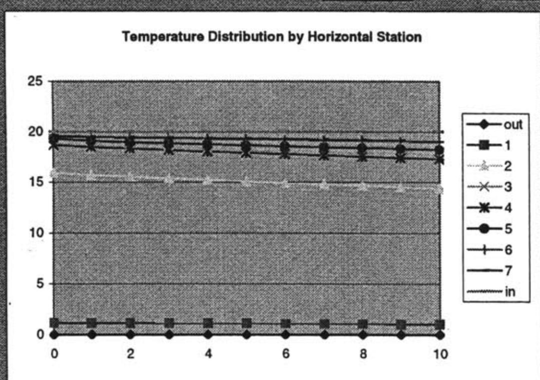
Hens basic U-value verify

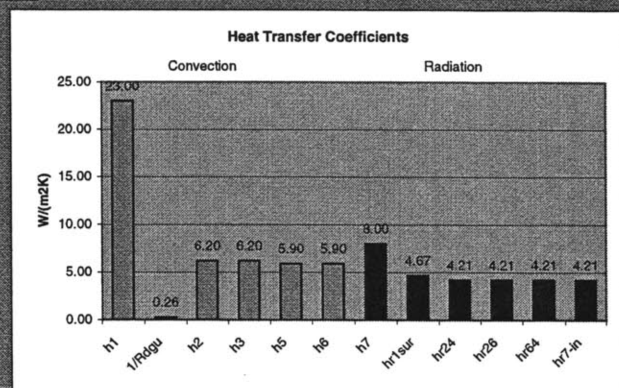
Temperature Distribution (dC)

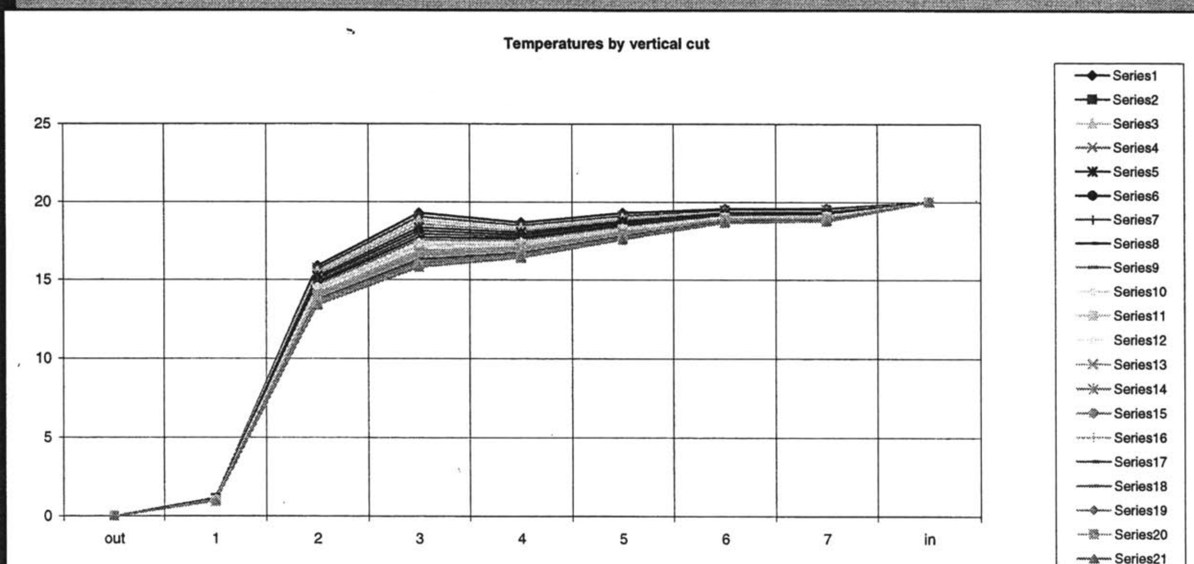
	height, y @bottom	out	1	2	d1 3	Blind 4	d2 5	6	7	in
0	0	0	1.15	15.90	19.30	18.68	19.30	19.56	19.59	20
1	0.12	0	1.13	15.71	19.05	18.49	19.11	19.48	19.51	20
2	0.24	0	1.12	15.54	18.81	18.33	18.98	19.41	19.45	20
3	0.36	0	1.11	15.37	18.58	18.18	18.87	19.35	19.40	20
4	0.48	0	1.10	15.21	18.36	18.04	18.76	19.30	19.35	20
5	0.6	0	1.08	15.06	18.15	17.91	18.67	19.25	19.30	20
6	0.72	0	1.07	14.92	17.94	17.78	18.57	19.20	19.25	20
7	0.84	0	1.06	14.78	17.75	17.65	18.48	19.15	19.21	20
8	0.96	0	1.05	14.64	17.56	17.53	18.40	19.10	19.17	20
9	1.08	0	1.04	14.51	17.38	17.42	18.31	19.06	19.12	20
10	1.2	0	1.03	14.39	17.20	17.31	18.23	19.02	19.08	20
11	1.32	0	1.02	14.27	17.04	17.20	18.16	18.98	19.05	20
12	1.44	0	1.02	14.15	16.88	17.10	18.08	18.94	19.01	20
13	1.56	0	1.01	14.04	16.72	17.00	18.01	18.90	18.98	20
14	1.68	0	1.00	13.94	16.58	16.91	17.95	18.87	18.94	20
15	1.8	0	0.99	13.84	16.43	16.82	17.88	18.83	18.91	20
16	1.92	0	0.99	13.74	16.30	16.73	17.82	18.80	18.88	20
17	2.04	0	0.98	13.65	16.17	16.65	17.76	18.77	18.85	20
18	2.16	0	0.97	13.56	16.04	16.57	17.70	18.74	18.82	20
19	2.28	0	0.97	13.47	15.92	16.49	17.65	18.71	18.79	20
20	2.4	0	0.96	13.39	15.81	16.42	17.60	18.68	18.77	20
				14.47991		16.70165		19.05147	16.76569	19.11626

summary

Height (m)	2.40
Solar Rad(W/m2)	0.00
T out	0.00
T in	20.00
Tmax	20.00
Total q to room (W)	-25.41
Total q to duct (W)	-24.62
V3	0.10
V5	0.02
Average 2 cavity temp	17.82
SHGC	N/A
Effective U-Value	0.53







Radiation Heat Transfer Coefficients

Tm 4 to 2	hrad 4 to 2	Tm 6 to 4	hrad 6 to 4	Tm 6 to 2	hrad 6 to 2	Tm 6 to 4	hrad 6 to 4	Tm 7 to in	hrad 7 to in
19.3	4.21	19.30	4.21	19.30	4.21	19.3	4.21	19.30	4.21
17.29	4.12	19.12	4.20	17.73	4.14	19.12	4.20	19.80	4.23
17.10	4.11	18.99	4.20	17.59	4.14	18.99	4.20	19.76	4.23
16.93	4.11	18.87	4.19	17.47	4.13	18.87	4.19	19.73	4.23
16.78	4.10	18.77	4.19	17.36	4.13	18.77	4.19	19.70	4.23
16.63	4.09	18.67	4.18	17.26	4.12	18.67	4.18	19.67	4.22
16.48	4.09	18.58	4.18	17.15	4.12	18.58	4.18	19.65	4.22
16.35	4.08	18.49	4.17	17.06	4.11	18.49	4.17	19.63	4.22
16.21	4.08	18.40	4.17	16.96	4.11	18.40	4.17	19.60	4.22
16.09	4.07	18.32	4.17	16.87	4.10	18.32	4.17	19.58	4.22
15.96	4.07	18.24	4.16	16.79	4.10	18.24	4.16	19.56	4.22
15.85	4.06	18.16	4.16	16.70	4.10	18.16	4.16	19.54	4.22
15.73	4.06	18.09	4.16	16.62	4.09	18.09	4.16	19.52	4.22
15.63	4.05	18.02	4.15	16.55	4.09	18.02	4.15	19.51	4.22
15.52	4.05	17.95	4.15	16.47	4.09	17.95	4.15	19.49	4.22
15.42	4.04	17.89	4.15	16.40	4.08	17.89	4.15	19.47	4.22
15.33	4.04	17.82	4.15	16.33	4.08	17.82	4.15	19.46	4.22
15.24	4.04	17.76	4.14	16.27	4.08	17.76	4.14	19.44	4.21
15.15	4.03	17.71	4.14	16.21	4.08	17.71	4.14	19.43	4.21
15.06	4.03	17.65	4.14	16.15	4.07	17.65	4.14	19.41	4.21
14.98	4.02	17.60	4.14	16.09	4.07	17.60	4.14	19.40	4.21

checked 010499

Convective Heat Transfer Coefficients

	h2	h3	h5	h6
1	6.20	6.20	5.90	5.90
2	6.20	6.20	5.90	5.90
3	6.20	6.20	5.90	5.90
4	6.20	6.20	5.90	5.90
5	6.20	6.20	5.90	5.90
6	6.20	6.20	5.90	5.90
7	6.20	6.20	5.90	5.90
8	6.20	6.20	5.90	5.90
9	6.20	6.20	5.90	5.90
10	6.20	6.20	5.90	5.90
11	6.20	6.20	5.90	5.90
12	6.20	6.20	5.90	5.90
13	6.20	6.20	5.90	5.90
14	6.20	6.20	5.90	5.90
15	6.20	6.20	5.90	5.90
16	6.20	6.20	5.90	5.90
17	6.20	6.20	5.90	5.90
18	6.20	6.20	5.90	5.90
19	6.20	6.20	5.90	5.90
20	6.20	6.20	5.90	5.90
21	6.20	6.20	5.90	5.90

checked 010499

assumptions

Tm4-2 at y=0 is T3=Tin

Tm6-4 at y=0 is T5=Tin

Tm7-4 at y=0 is T5=Tin

note

Tm go with y-1 rather than y

Temperature Coefficients

A1	A2	A3	B_1	B_2 (unused)	B_3 (unused)	C_1 (unused)	C_2	C_3	D_1	D_2	E1	E_2	
0.56	2.76	0.26	0.74	0.51	0.00	0.51	0.74	0.71	0.71	20.00	0.51	0.96	1
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	2
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	3
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	4
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	5
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	6
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	7
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	8
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	9
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	10
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	11
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	12
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	13
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	14
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	15
0.56	2.76	0.26	0.74	0.49	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	16
0.56	2.76	0.26	0.74	0.48	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	17
0.56	2.76	0.26	0.74	0.48	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	18
0.56	2.76	0.26	0.74	0.48	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	19
0.56	2.76	0.26	0.74	0.48	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	20
0.56	2.76	0.26	0.74	0.48	0.00	0.50	0.74	0.71	0.71	20.00	0.51	0.96	21

Double Glazing Calcs

tm 1,2	hc,gap	Eeff hr	hc+Eeff	C	dgu air gap R,gap	Rglass1 (l/kA)g1	Rglass2 (l/kA)g2	=SUM(E6:(R,dgu	Tm 1-sur	hrad 1-sur	20	Uglass plus hc Uglass	ASHRAE TABLE 27.6-5(1993) hi=8.29, ho=29		DIFFEREN
8.52	1.49	0.74	2.23	0.27	3.74	0.08	0.05	3.87	0.57	4.67	1	2.150744378	0.26	2.78	-90.81%
8.42	1.49	0.74	2.23	0.27	3.74	0.08	0.05	3.88	0.57	4.67	2	2.149642151	0.26	2.78	-90.81%
8.33	1.49	0.74	2.23	0.27	3.75	0.08	0.05	3.88	0.56	4.67	3	2.148609291	0.26	2.78	-90.81%
8.24	1.49	0.74	2.22	0.27	3.75	0.08	0.05	3.88	0.55	4.67	4	2.147626004	0.26	2.78	-90.82%
8.15	1.49	0.74	2.22	0.27	3.75	0.08	0.05	3.88	0.55	4.67	5	2.146684899	0.26	2.78	-90.82%
8.07	1.49	0.74	2.22	0.27	3.75	0.08	0.05	3.88	0.54	4.67	6	2.14578252	0.26	2.78	-90.83%
7.99	1.49	0.74	2.22	0.27	3.75	0.08	0.05	3.89	0.54	4.67	7	2.144916728	0.25	2.78	-90.83%
7.92	1.48	0.74	2.22	0.27	3.75	0.08	0.05	3.89	0.53	4.67	8	2.144085851	0.25	2.78	-90.83%
7.85	1.48	0.73	2.22	0.27	3.75	0.08	0.05	3.89	0.53	4.67	9	2.143288413	0.25	2.78	-90.84%
7.78	1.48	0.73	2.22	0.27	3.76	0.08	0.05	3.89	0.52	4.67	10	2.142523036	0.25	2.78	-90.84%
7.71	1.48	0.73	2.22	0.27	3.76	0.08	0.05	3.89	0.52	4.67	11	2.141788412	0.25	2.78	-90.84%
7.65	1.48	0.73	2.22	0.27	3.76	0.08	0.05	3.89	0.51	4.67	12	2.141083293	0.25	2.78	-90.85%
7.59	1.48	0.73	2.22	0.27	3.76	0.08	0.05	3.89	0.51	4.66	13	2.140406482	0.25	2.78	-90.85%
7.53	1.48	0.73	2.22	0.27	3.76	0.08	0.05	3.89	0.50	4.66	14	2.139756832	0.25	2.78	-90.85%
7.47	1.48	0.73	2.21	0.27	3.76	0.08	0.05	3.90	0.50	4.66	15	2.139133246	0.25	2.78	-90.86%
7.42	1.48	0.73	2.21	0.27	3.76	0.08	0.05	3.90	0.50	4.66	16	2.138534668	0.25	2.78	-90.86%
7.36	1.48	0.73	2.21	0.27	3.76	0.08	0.05	3.90	0.49	4.66	17	2.137960088	0.25	3.78	-93.28%
7.31	1.48	0.73	2.21	0.27	3.77	0.08	0.05	3.90	0.49	4.66	18	2.137408537	0.25	4.78	-94.69%
7.27	1.48	0.73	2.21	0.27	3.77	0.08	0.05	3.90	0.49	4.66	19	2.136879086	0.25	5.78	-95.61%
7.22	1.48	0.73	2.21	0.27	3.77	0.08	0.05	3.90	0.48	4.66	20	2.136370843	0.25	6.78	-96.26%
7.17	1.48	0.73	2.21	0.27	3.77	0.08	0.05	3.90	0.48	4.66	21	2.135882953	0.25	7.78	-96.74%

=IF(Work!C13>Work!C14,(Work!C13-Work!C14)/2+Work!C14,(Work!C14-Work!C13)/2+Work!C13)

=IF(Work!C13>Work!C14,(Work!C13-Work!C14)/2+Work!C14,(Work!C14-Work!C13)/2+Work!C13)

Blind Factors for Infrared Radiation

Label			Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10	
		1	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10	1
Sigma		2	90	90	90	90	90	90	90	90	90	50	2
Height		3	2.4	3	3	2	0.914	2.4	2.4	2.4	2.4	3	3
No. of Blind Divisions		4	96	120	120	80	35.98425	96	96	96	96	120	4
Blind Spacing		5	0.025	0.025	0.025	0.025	0.0254	0.025	0.025	0.025	0.025	0.025	5
Blind Length		6	0.025	0.025	0.025	0.025	0.0254	0.025	0.025	0.025	0.025	0.025	6
d1		7	0.1	0.0715	0.0715	0.63	0.089	0.1	0.1	0.1	0.1	0.0715	7
d2		8	0.045	0.0715	0.0715	0.37	0.089	0.045	0.045	0.045	0.045	0.0715	8
X1		9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	9
y1		10	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.011	10
y2		11	1.175	1.475	1.475	0.975	0.432	1.175	1.175	1.175	1.175	1.477	11
y3		12	1.200	1.500	1.500	1.000	0.457	1.200	1.200	1.200	1.200	1.498	12
bd		13	1.179247642	1.476732	1.476732	1.160829445	0.440681	1.179247642	1.179247642	1.179247642	1.179247642	1.478116	13
fh		14	1.200843454	1.501703	1.501703	1.066255129	0.465586	1.200843454	1.200843454	1.200843454	1.200843454	1.499745	14
ac		15	1.204159458	1.501703	1.501703	1.181905242	0.465586	1.204159458	1.204159458	1.204159458	1.204159458	1.499745	15
eg		16	1.175861386	1.476732	1.476732	1.042844667	0.440681	1.175861386	1.175861386	1.175861386	1.175861386	1.478116	16
de		17	0.05	0.05	0.05	0.05	0.0508	0.05	0.05	0.05	0.05	0.048296	17
cf		18	1.53144E-18	1.53E-18	1.53E-18	1.53144E-18	1.56E-18	1.53144E-18	1.53144E-18	1.53144E-18	1.53144E-18	0.012941	18
Aacfh		19	2.405002911	3.003406	3.003406	2.24816037	0.931171	2.405002911	2.405002911	2.405002911	2.405002911	3.012432	19
Abdeg		20	2.405109028	3.003464	3.003464	2.253674112	0.932162	2.405109028	2.405109028	2.405109028	2.405109028	3.004527	20
Abdfh		21	2.405091095	3.003435	3.003435	2.252084574	0.931666	2.405091095	2.405091095	2.405091095	2.405091095	3.002861	21
Aaceg		22	2.405020844	3.003435	3.003435	2.249749909	0.931666	2.405020844	2.405020844	2.405020844	2.405020844	3.002861	22
cd=ef=Blind Spacing			0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	23
df=Lblind			0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	24
fg			1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50	25
dg			1.23	1.53	1.53	1.09	0.49	1.23	1.23	1.23	1.23	1.53	26
da			1.23	1.53	1.53	1.20	0.49	1.23	1.23	1.23	1.23	1.52	27
fh			1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50	28
Fdf-ce=Flowerblind-upp	$F4_L4_U$		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	29
Fdf-gh=Flowerblind-Gla	$F4_L6$		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	30
Fdf-ab=Flowerblind-Gla	$F4_L2$		1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74	31
check			1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	1.00	32
			1	2	3	4	5	6	7	8	9	10	33
	$F4_U4_L$		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	34
	$F4_U6$		1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74	35
	$F4_U2$		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	36
	$F24_L$		1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74	37
	$F24_U$		0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.03	38
	$F64_L$		0.00	0.00	0.00	-0.03	-0.01	0.00	0.00	0.00	0.00	0.03	39
	$F64_U$		1.00	1.00	1.00	1.03	1.01	1.00	1.00	1.00	1.00	0.74	40
F26single		23	9.25186E-17	0	0	1.11022E-16	0	9.25186E-17	9.25186E-17	9.25186E-17	9.25186E-17	0.001873	41
F26		24	8.88178E-15	0	0	8.88178E-15	0	8.88178E-15	8.88178E-15	8.88178E-15	8.88178E-15	0.224745	42
F62=F26		25	8.88178E-15	0	0	8.88178E-15	0	8.88178E-15	8.88178E-15	8.88178E-15	8.88178E-15	0.224745	43
													44
AVERAGES/TOTALS													45
F24=1-F26		26	1	1	1	1	1	1	1	1	1	0.775255	46
F42=Fblinds-Glass2		27	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39	47
F46=Fblinds-Glass3		28	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39	48
F64=1-F62		29	1	1	1	1	1	1	1	1	1	0.775255	49
F44			0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.23	50
F46			0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39	51
F42			0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39	52
													53

F6-?

	emiss	IR reflc	area	Ae
surf2	0.85	0.15	0.12	0.102
surf4	0.85	0.15	0.12	0.102
surf6	0.85	0.15	0.12	0.102
Tmean3	((tout+tin)/2)^3		2E+07	
StefanB	5.7E-08			
sigma	**90**			
sigmaTm3	1.29192			

Case6

	r2	r2 prime	r4 L (lower)	r4 U (upper)	r4 prime	r6	r6 prime	q2-others	q4low-others	q4up-others	q4-others	q6-others	SUM
0	80.15	90.76	90.76	93.22	176.47	96.63	93.23	-1.27	1.29	-0.39	0.90	0.41	3.53E-02
1	79.19	89.80	89.80	92.33	175.01	96.12	92.33	-1.27	1.29	-0.43	0.85	0.45	3.50E-02
2	78.30	88.96	88.95	91.56	173.71	95.71	91.56	-1.28	1.29	-0.48	0.82	0.50	3.47E-02
3	77.45	88.18	88.17	90.85	172.50	95.34	90.85	-1.29	1.30	-0.52	0.78	0.54	3.44E-02
4	76.65	87.43	87.43	90.18	171.36	95.00	90.18	-1.29	1.31	-0.56	0.75	0.58	3.42E-02
5	75.87	86.72	86.72	89.53	170.26	94.68	89.53	-1.30	1.32	-0.60	0.72	0.62	3.39E-02
6	75.13	86.04	86.03	88.91	169.21	94.37	88.92	-1.31	1.32	-0.64	0.69	0.65	3.37E-02
7	74.41	85.38	85.38	88.32	168.20	94.07	88.32	-1.32	1.33	-0.67	0.66	0.69	3.35E-02
8	73.73	84.76	84.75	87.75	167.23	93.78	87.76	-1.32	1.34	-0.70	0.63	0.72	3.33E-02
9	73.07	84.15	84.15	87.21	166.30	93.51	87.21	-1.33	1.34	-0.74	0.61	0.76	3.31E-02
10	72.44	83.57	83.57	86.68	165.40	93.24	86.69	-1.34	1.35	-0.77	0.58	0.79	3.29E-02
11	71.83	83.02	83.01	86.18	164.55	92.99	86.18	-1.34	1.36	-0.80	0.56	0.82	3.27E-02
12	71.25	82.48	82.48	85.70	163.72	92.75	85.70	-1.35	1.36	-0.83	0.53	0.85	3.25E-02
13	70.69	81.97	81.97	85.23	162.93	92.51	85.24	-1.35	1.37	-0.85	0.51	0.87	3.23E-02
14	70.16	81.48	81.47	84.79	162.17	92.29	84.79	-1.36	1.37	-0.88	0.49	0.90	3.22E-02
15	69.64	81.01	81.00	84.36	161.44	92.08	84.36	-1.36	1.38	-0.91	0.47	0.93	3.20E-02
16	69.15	80.55	80.55	83.95	160.74	91.87	83.95	-1.37	1.38	-0.93	0.45	0.95	3.19E-02
17	68.67	80.12	80.11	83.56	160.07	91.67	83.56	-1.37	1.39	-0.96	0.43	0.97	3.17E-02
18	68.22	79.70	79.69	83.18	159.42	91.48	83.18	-1.38	1.39	-0.98	0.41	1.00	3.16E-02
19	67.78	79.30	79.29	82.81	158.81	91.30	82.82	-1.38	1.40	-1.00	0.40	1.02	3.14E-02
20	67.36	78.91	78.91	82.47	158.21	91.12	82.47	-1.39	1.40	-1.02	0.38	1.04	3.13E-02
21	72.45	80.92	80.92	83.99	165.16	92.99	83.99	-1.02	1.03	-1.06	-0.03	1.08	3.28E-02
s		t	u		v		w						
	6965775749			7238077692	=(Work!O6+273)^4								

Solar Radiation Absorbed					Fsolar Calculations					
					length factors			Solar	Fsolar	
Q	Q	Q	Q		a	b	c	Azimuth	calculate	
a1	a2	a4	a7		(l/2)sin(sigma-blinds)	c x tan(Beta)	(l/2)cos(sigma-blinds)	Beta	(S-2(a+b))/S	
0.00	0.00	0.00	0.00	1	0.0125	0.0000	0.0000	0.00	0.00	0.00
0.00	0.00	0.00	0.00	2	0.0125	0.0000	0.0000	-5.00	0.00	0.00
0.00	0.00	0.00	0.00	3	0.0125	0.0000	0.0000	-10.00	0.00	0.00
0.00	0.00	0.00	0.00	4	0.0125	0.0000	0.0000	-15.00	0.00	0.00
0.00	0.00	0.00	0.00	5	0.0125	0.0000	0.0000	-20.00	0.00	0.00
0.00	0.00	0.00	0.00	6	0.0125	0.0000	0.0000	-25.00	0.00	0.00
0.00	0.00	0.00	0.00	7	0.0125	0.0000	0.0000	-30.00	0.00	0.00
0.00	0.00	0.00	0.00	8	0.0125	0.0000	0.0000	-35.00	0.00	0.00
0.00	0.00	0.00	0.00	9	0.0125	0.0000	0.0000	-40.00	0.00	0.00
0.00	0.00	0.00	0.00	10	0.0125	0.0000	0.0000	-45.00	0.00	0.00
0.00	0.00	0.00	0.00	11						
0.00	0.00	0.00	0.00	12						
0.00	0.00	0.00	0.00	13						
0.00	0.00	0.00	0.00	14						
0.00	0.00	0.00	0.00	15						
0.00	0.00	0.00	0.00	16						
0.00	0.00	0.00	0.00	17						
0.00	0.00	0.00	0.00	18						
0.00	0.00	0.00	0.00	19						
0.00	0.00	0.00	0.00	20						
0.00	0.00	0.00	0.00	21						

Need to import from weather data

Diffuse Solar

		Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Sigma		90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	60.00
Height		2.40	3.00	3.00	2.00	0.91	2.40	2.40	2.40	2.40	3.00
No. of Blind Divisions		96.00	120.00	120.00	80.00	35.98	96.00	96.00	96.00	96.00	120.00
Blind Spacing		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Blind Length		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
d1		0.10	0.07	0.07	0.63	0.09	0.10	0.10	0.10	0.10	0.07
d2		0.05	0.07	0.07	0.37	0.09	0.05	0.05	0.05	0.05	0.07
X1	9.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
y1	10.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
y2	11.00	1.18	1.48	1.48	0.98	0.43	1.18	1.18	1.18	1.18	1.48
y3	12.00	1.20	1.50	1.50	1.00	0.46	1.20	1.20	1.20	1.20	1.50
bd		1.18	1.48	1.48	1.16	0.44	1.18	1.18	1.18	1.18	1.48
fh		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
ac		1.20	1.50	1.50	1.18	0.47	1.20	1.20	1.20	1.20	1.50
eg		1.18	1.48	1.48	1.04	0.44	1.18	1.18	1.18	1.18	1.48
de		0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
cf		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Aacfh		2.41	3.00	3.00	2.25	0.93	2.41	2.41	2.41	2.41	3.01
Abdeg		2.41	3.00	3.00	2.25	0.93	2.41	2.41	2.41	2.41	3.00
Abdfh		2.41	3.00	3.00	2.25	0.93	2.41	2.41	2.41	2.41	3.00
Aaceg		2.41	3.00	3.00	2.25	0.93	2.41	2.41	2.41	2.41	3.00
cd=ef=Blind Spacing		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
df=Lblind		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
fg		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
dg		1.23	1.53	1.53	1.09	0.49	1.23	1.23	1.23	1.23	1.53
da		1.23	1.53	1.53	1.20	0.49	1.23	1.23	1.23	1.23	1.52
fh		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
Fdf-ce=Flowerblind-up	$F4_L4_U$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
Fdf-gh=Flowerblind-Gl	$F4_L6$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
Fdf-ab=Flowerblind-Gl	$F4_L2$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
check		1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	1.00
		1	2	3	4	5	6	7	8	9	10
	$F4_U4_L$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
	$F4_U6$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
	$F4_U2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
totals (averages)	F44	0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.23
totals (averages)	F46	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39
totals (averages)	F42	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39

For reflected portion from blinds (1-Fsol)

Specular model

	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Sigma	90.000000	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	60.00
sin(sigma)	1.000000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.87
cos(sigma)	0.000000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50
Gamma	180.000000	180.00	180.00	180.00	180.00	180.00	180.00	180.00	180.00	120.00
Gamma	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180
X1	0.000000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Sb	0.025000	0.025000	0.025000	0.025000	0.025400	0.025000	0.025000	0.025000	0.025000	0.025000
Sb,perp	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.012500
l,rebound	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
l,blind	0.025000	0.025000	0.025000	0.025000	0.025400	0.025000	0.025000	0.025000	0.025000	0.025000
Ray1	1	2	3	4	5	6	7	8	9	10
R1y	0.009375	0.009375	0.009375	0.009375	0.009525	0.009375	0.009375	0.009375	0.009375	0.008119
R1x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.004688
dYr1L	0.021875	0.021875	0.021875	0.021875	0.022225	0.021875	0.021875	0.021875	0.021875	0.022294
dXr1L	#########	#########	#########	#########	##########	##########	##########	##########	#########	0.012871
dYr1T	0.046875	0.046875	0.046875	0.046875	0.047625	0.046875	0.046875	0.046875	0.046875	0.043944
dXr1T	#########	#########	#########	#########	##########	##########	##########	##########	#########	-0.025371
dXr1L+R1x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1
dXr1T	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1
RAY 1 Bounce 1	out	out	out	out	out	out	out	out	out	out
Ray 1 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 1	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
Ray2	1	2	3	4	5	6	7	8	9	10
R2y	0.003125	0.003125	0.003125	0.003125	0.003175	0.003125	0.003125	0.003125	0.003125	0.002706
R2x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.001563
dYr2L	0.015625	0.015625	0.015625	0.015625	0.015875	0.015625	0.015625	0.015625	0.015625	0.016881
dXr2L	#########	#########	#########	#########	##########	##########	##########	##########	#########	0.009746
dYr2T	0.040625	0.040625	0.040625	0.040625	0.041275	0.040625	0.040625	0.040625	0.040625	0.038532
dXr2T	#########	#########	#########	#########	##########	##########	##########	##########	#########	-0.022246
dXr2L+R2x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1
dXr2T	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1
RAY 2 Bounce 1	out	out	out	out	out	out	out	out	out	out
Ray 2 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 2	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
Ray3	1	2	3	4	5	6	7	8	9	10
R3y	0.003125	0.003125	0.003125	0.003125	0.003175	0.003125	0.003125	0.003125	0.003125	0.002706
R3x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.001563
dYr3L	0.009375	0.009375	0.009375	0.009375	0.009525	0.009375	0.009375	0.009375	0.009375	0.011468
dXr3L	#########	#########	#########	#########	##########	##########	##########	##########	#########	0.006621
dYr3T	0.034375	0.034375	0.034375	0.034375	0.034925	0.034375	0.034375	0.034375	0.034375	0.033119
dXr3T	#########	#########	#########	#########	##########	##########	##########	##########	#########	-0.019121
dXr3L-R3x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	<X1
dXr3T	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X
RAY 3 Bounce 1	out	out	out	out	out	out	out	out	out	hit
Ray 3 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 3	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-hit
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
Ray4	1	2	3	4	5	6	7	8	9	10
R4y	0.009375	0.009375	0.009375	0.009375	0.009525	0.009375	0.009375	0.009375	0.009375	0.008119
R4x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.004688
dYr4L	0.003125	0.003125	0.003125	0.003125	0.003175	0.003125	0.003125	0.003125	0.003125	0.006056
dXr4L	#########	#########	#########	#########	##########	##########	##########	##########	#########	0.003496
dYr4T	0.028125	0.028125	0.028125	0.028125	0.028575	0.028125	0.028125	0.028125	0.028125	0.027706
SUMS dXr4T	#########	#########	#########	#########	##########	##########	##########	##########	#########	-0.015996
dXr4L-R4x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	<X1 ##
dXr4T	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X
RAY 4 Bounce 1	out	out	out	out	out	out	out	out	out	hit
Ray 4 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 3	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-hit
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
lit-out	4	4	4	4	4	4	4	4	4	2
lit-hit	0	0	0	0	0	0	0	0	0	2
lit-in	0	0	0	0	0	0	0	0	0	0
hit-hit	0	0	0	0	0	0	0	0	0	0

ReflectionTotal Table:	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Rho4,s	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rho4,d	0.15	0.15	0.15	0.15	0.15	0.3	0.15	0.15	0.15	0.1
abs of blind, alpha4	0.75	0.75	0.75	0.75	0.75	0.6	0.75	0.75	0.75	0.6
1/4 sum of "lit-out"	1	1	1	1	1	1	1	1	1	1
1/4 sum of "lit-hit"	0	0	0	0	0	0	0	0	0	1
1/4 sum of "lit-in"	0	0	0	0	0	0	0	0	0	0
1/4 sum of "hit-hit"	0	0	0	0	0	0	0	0	0	0
F4U4L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
F4U6	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
F4U2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
F4L4U	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
F4L6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
F4L2	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
Rho 4, tot-out	0.2497	0.2499	0.2499	0.2387	0.2487	0.3995	0.2497	0.2497	0.2497	0.1243
Alpha 4 tot	0.7500	0.7500	0.7500	0.7500	0.7500	0.6000	0.7500	0.7500	0.7500	0.6441
Rho 4, tot-in	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0167
	0.9997	0.9999	0.9999	0.9887	0.9987	0.9995	0.9997	0.9997	0.9997	0.7851

Buoyancy forces in Air
Calculations

Laminar Case

Ambient conditions:

temp of inside air	20 deg C
temp of outside air	0 deg C
density of inside air	1.20249994 kg/m3
density of outside air	1.290627455 kg/m3

RELATES TO D1: **outer**		RELATES TO D2: **inner**	
Outer Cavity		**Inner Cavity**	
Average Temp	18.20 deg C	Average Temp	19.22 deg C
Average Density	1.209935529 kg/m3	Average Density	1.205380672 kg/m3
Choose Rho infinity	**1.20249994** kg/m3	Choose Rho infinity	**1.20249994** kg/m3
Ave viscosity ,mu	0.00001802	Ave viscosity ,mu	0.00001806
gravity, g	9.81 m/s2		
Height, H	2.4 m		
Area Cross Sec,Acs	0.1 m2	Area Cross Sec,Acs	0.045 m2
delta P Net	**-0.01750635**	**delta P Net**	**-0.00305208**
neglecting entrance and exit effects			
Ave Velocity, Vave	**-0.3373 m/s**	**Ave Velocity, Vave**	**-0.0119 m/s**
Dh	0.20	Dh	0.09
Reynolds, Re	-4529.870392 **LAMINAR**	Reynolds, Re	-71.3771882 **LAMINAR**

based on a Re, transition # of 1.00E+05

Turbulent Case			
friction factor, f	0.04	friction factor, f	0.108716941
Head loss, lf	0.001340339	Head loss, lf	1.04318E-05
delta P Net	**0.015909107**	**delta P Net**	**0.000123353**
Ave velocity, Vave	**0.3065 m/s**	**Ave velocity, Vave**	**0.0005 m/s**

RESULTANT VELOCITIES	**-0.3373** m/s	**-0.0119** m/s

Mirror of Hens' Night-time Model:

U-value Determination

file: CalcHENSVerify.xls

Case6

Case Parameters

Geometry

Height, H	2.4	m
Num divisions	20	each
delta y	0.12	m
Area,Ady	0.12	m2
d0	15	mm
d1	0.1	m
d2	0.045	m

Design Temps

Tout	0	deg C
Tin	20	deg C
delta T	-20	deg C
Tmrt	20	deg C
Tsur	0	deg C

Incident Radiation

qr,incident	0	W/m2

Blinds Properties

emissivity,E4	0.85	nondim
reflectivity, ref_blind	0.4	nondim
Spectral Reflectivity of blind	0.1	nondim
Diffuse Reflectivity of blind	0.3	nondim
Rho 4, tot-out	0.399	nondim
Alpha 4 tot	0.6	nondim
Rho 4, tot-in	1E-15	nondim
absorptivity, abs_blind	0.6	nondim
Length of the blind	0.025	m
Blind Angle from horizontal (Sigm	90	degrees
BlindSpace	0.025	m
F26(IR), geometry factor	9E-15	nondim
F24=1-F(IR), geometry factor	1	nondim
F(sol), geometry factor	0.00	nondim
1-F(sol), geometry factor	1.00	nondim
Area of the blind for convection	0.12	m

Room Properties

emissivity,Ein	1	nondim

Heat Transfer, hc

hout=h1	23	nodim
hin=h7	8	nodim

Glass Properties

1/Eeff=1/E12+1/E21-1	6.84		0
Eeff	0.15		0

Glass #1 ID Number	custom	
k,glass1	1	W/(mK)
l,glass1	0.01	mm
abs_front_glass1	0.26	nondim
abs_back_glass1	0.26	nondim
ref_front_glass1	0.19	nondim
ref_back_glass1	0.19	nondim
trans_glass1	0.55	nondim
emissivity_front_glass1	0.85	nondim
emissivity_back_glass1	0.15	nondim

Glass #2 ID Number	custom	
k,glass2	1	W/(mK)
l,glass2	0.006	m
abs_front_glass2	0.12	nodim
abs_back_glass2	0.12	nodim
ref_front_glass2	0.09	nodim
ref_back_glass2	0.09	nodim
trans_glass2	0.79	nodim
emissivity_front_glass2	0.85	nodim
emissivity_back_glass2	0.85	nodim

Glass # ID Number	custom	
k,glass3	1	W/(mK)
l,glass3	0.006	m
abs_front_glass3	0.12	nodim
abs_back_glass3	0.12	nodim
ref_front_glass3	0.09	nodim
ref_back_glass3	0.09	nodim
trans_glass3	0.79	nodim
emissivity_front_glass3	0.85	nodim
emissivity_back_glass3	0.85	nodim

Constants

StefanBoltzman	5.70E-08	W/m2K4

Mirror of Hens' Night-time Model:

U-value Determination

file: CalcHENSVerify.xls

Case6

Case Parameters

Air Properties	d1		d2
Forced Ventilation? (yes/no)	yes	Forced Ventilation? (yes/no)	yes
Inlet Side	in	Inlet Side	in
specific heat Cp	1005.00	specific heat Cp	1005.00
conductivity,k	0.03	conductivity,k	0.03
mass flow rate, m	0.0121	mass flow rate, m	0.0013
rho, density of air	1.20	rho, density of air	1.20
velocity, V	0.10	velocity, V	0.02
DH	0.20	DH	0.09
Pr	0.69	Pr	0.69
kinematic viscosity,air	0.00	kinematic viscosity,air	0.00
ReD	1264.95	ReD	140.55
Laminar NuDH	9.94	Laminar NuDH	8.34
f	0.06	f	0.19
Turbulent NuDh	1.89	Turbulent NuDh	-25.49
Utilized Nudh	9.94	Utilized Nudh	8.34
hconv	1.24	hconv	2.32

Mirror of Hens' Night-time Model:

U-value Determination

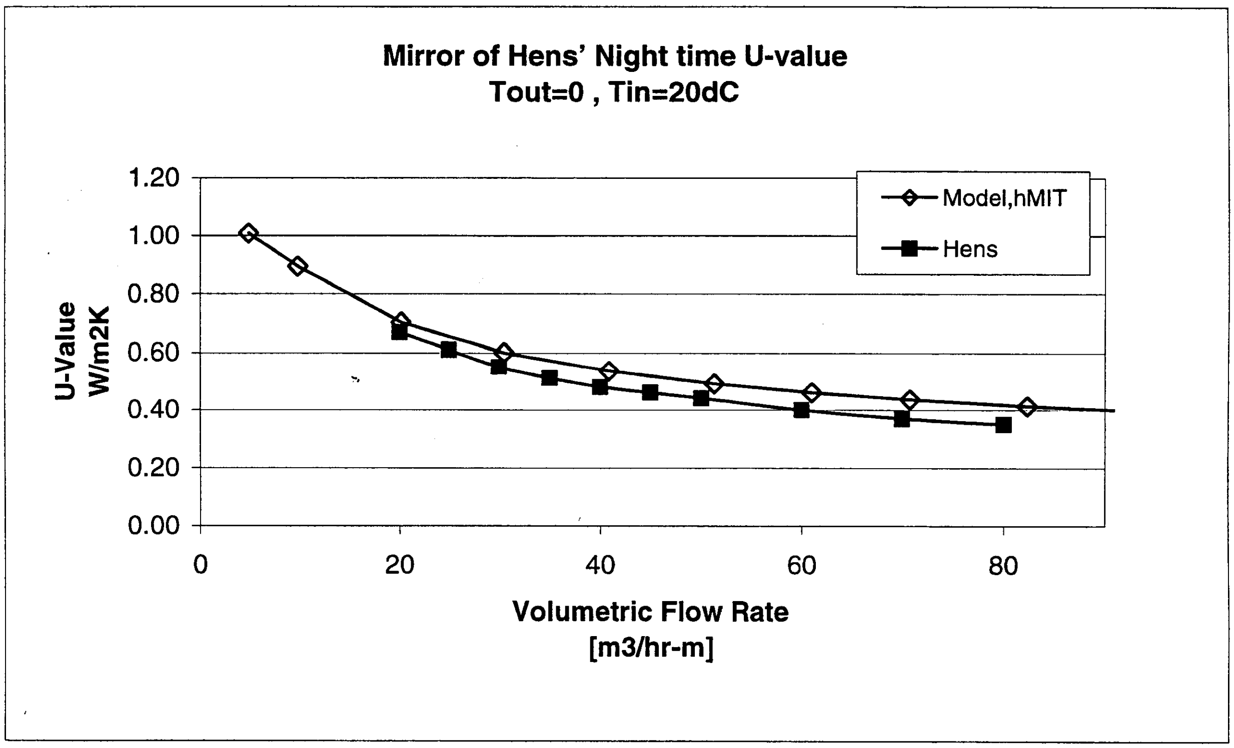
file: CalcHENSVerify.xls

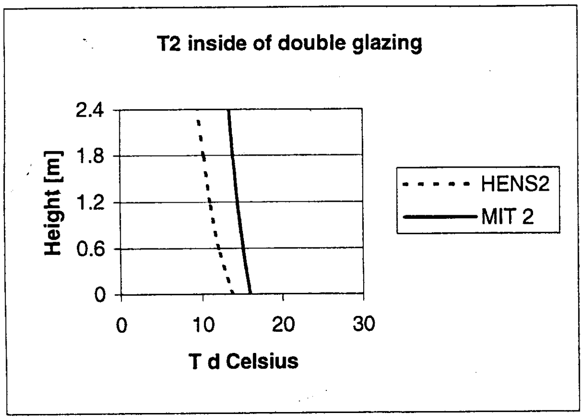
Case6 Height=2.4m Hens

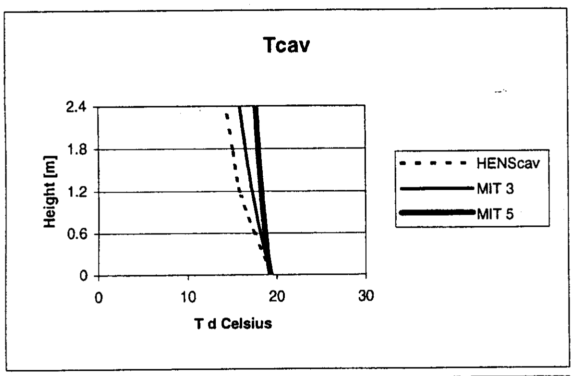
m=.5

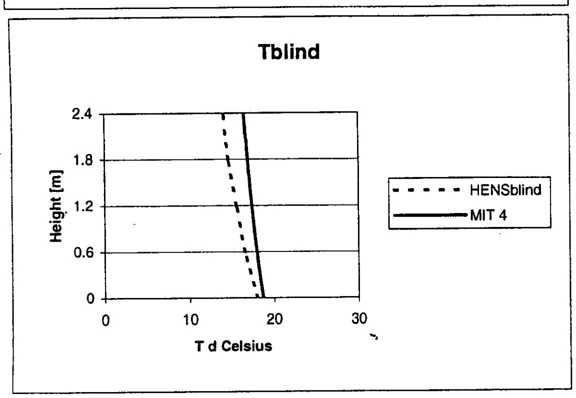
Case Results

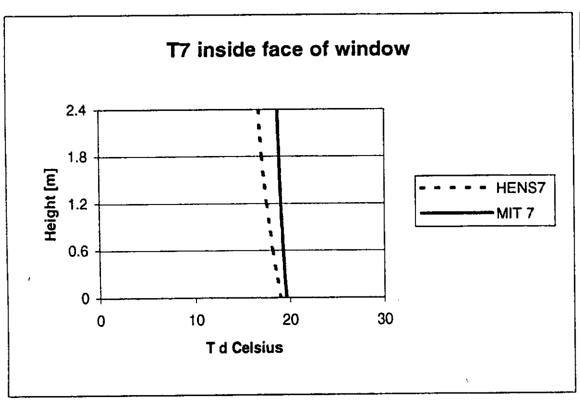
m/s	m3/hm	kg/s	Tout=0, Tin=20 d Celsius		m=0.9	
	2 cavities		Model,hMIT	Model,hHe	2 cavities	U-value
0.009482	4.881356	0.0008	1.01	0.85	20	0.67
0.018964	9.762712	0.0016	0.89	0.78	25	0.61
0.039113	20.13559	0.0033	0.70	0.71	30	0.55
0.059263	30.50847	0.005	0.60	0.67	35	0.51
0.079412	40.88136	0.0067	0.54	0.64	40	0.48
0.099561	51.25424	0.0084	0.49	0.61	45	0.46
0.118526	61.01695	0.01	0.46	0.60	50	0.44
0.13749	70.77966	0.0116	0.44	0.58	60	0.4
0.160009	82.37288	0.0135	0.41	0.56	70	0.37
0.201493	103.7288	0.017	0.38	0.56	80	0.35



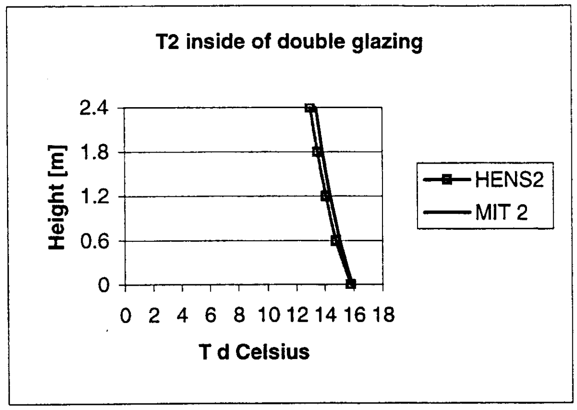


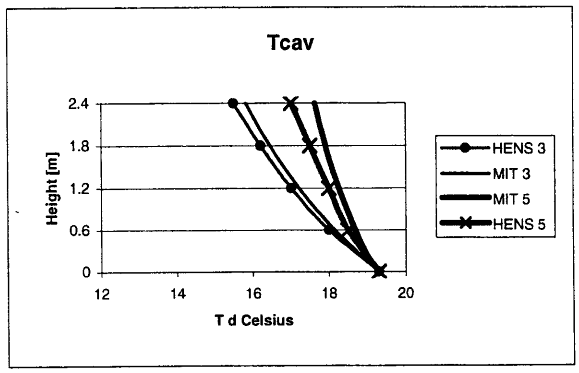


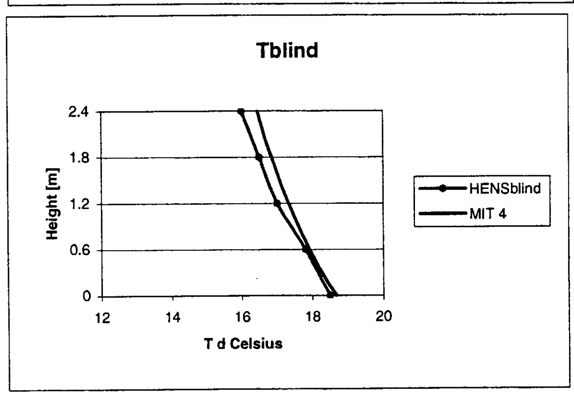


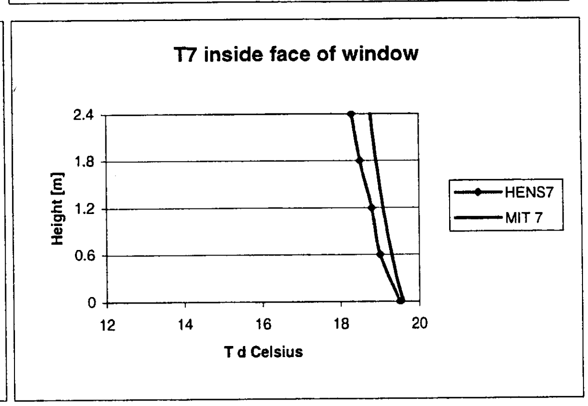


MIT vs. HENS Const. T Model
One cavity balance
Well mixed?









MIT vs. HENS Double Cav. Model
Airflow in each cavity.
No exchange

7.2.5 SHGC Validation

The following is the backup for the comparison of the model predictions with [Saelens 1998] for solar heat gain coefficient.

Case7

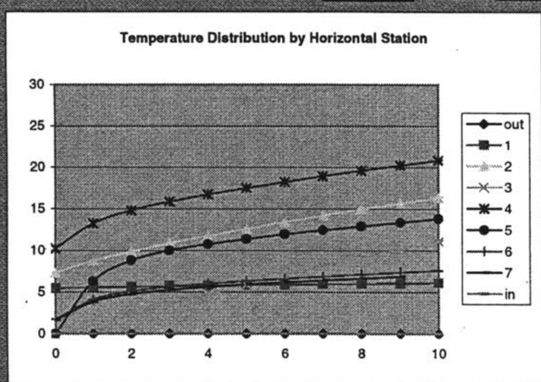
Hens basic SHGC verify

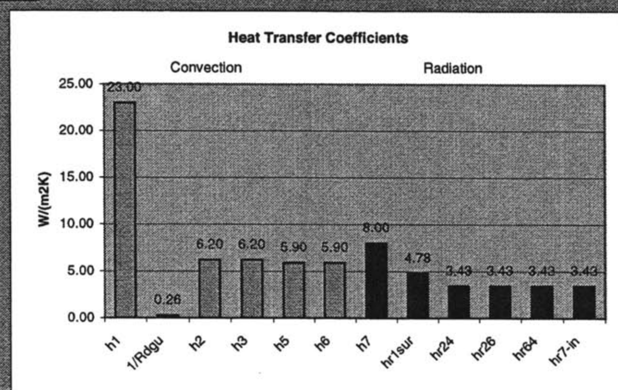
Temperature Distribution (dC)

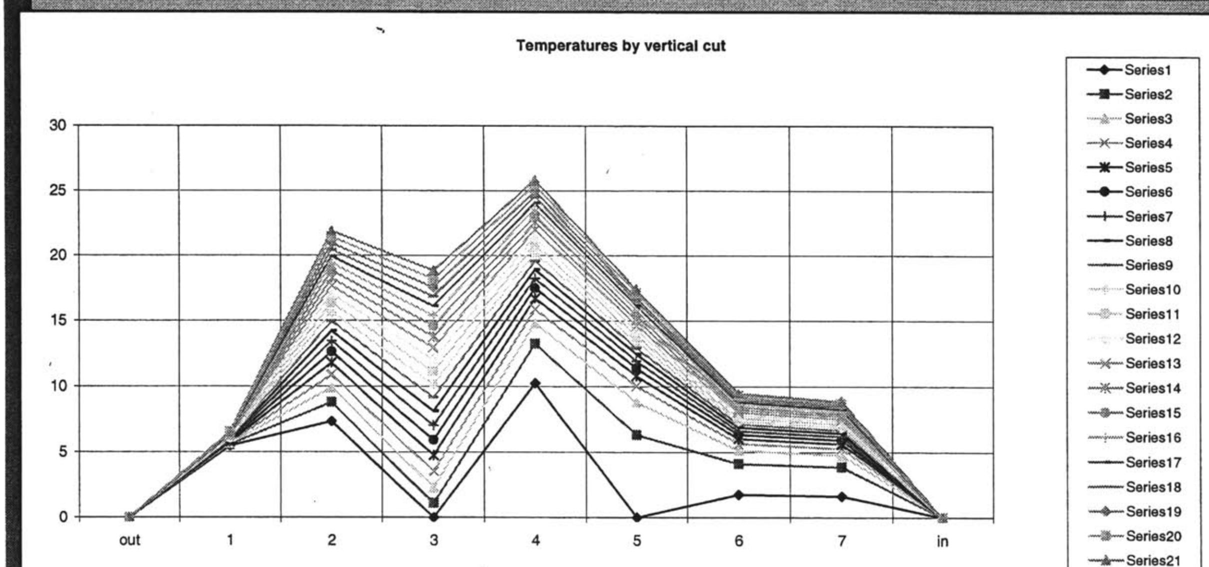
	height, y @bottom	out	1	2	d1 3	Blind 4	d2 5	6	7	in
0	0	0	5.46	7.33	0.00	10.23	0.00	1.75	1.64	0
1	0.12	0	5.56	8.79	1.08	13.24	6.30	4.12	3.85	0
2	0.24	0	5.64	9.90	2.30	14.79	8.80	5.11	4.78	0
3	0.36	0	5.71	10.87	3.53	15.84	10.01	5.64	5.27	0
4	0.48	0	5.77	11.76	4.74	16.71	10.78	6.01	5.62	0
5	0.6	0	5.84	12.61	5.91	17.49	11.39	6.32	5.91	0
6	0.72	0	5.90	13.42	7.03	18.22	11.93	6.60	6.17	0
7	0.84	0	5.95	14.20	8.11	18.92	12.43	6.87	6.42	0
8	0.96	0	6.01	14.95	9.15	19.59	12.92	7.12	6.66	0
9	1.08	0	6.06	15.66	10.14	20.23	13.38	7.36	6.89	0
10	1.2	0	6.11	16.35	11.10	20.85	13.82	7.60	7.10	0
11	1.32	0	6.16	17.01	12.02	21.44	14.24	7.82	7.31	0
12	1.44	0	6.21	17.65	12.91	22.01	14.65	8.04	7.51	0
13	1.56	0	6.26	18.26	13.76	22.56	15.04	8.24	7.71	0
14	1.68	0	6.30	18.84	14.57	23.08	15.42	8.44	7.89	0
15	1.8	0	6.34	19.41	15.36	23.59	15.78	8.63	8.07	0
16	1.92	0	6.38	19.94	16.11	24.07	16.13	8.81	8.24	0
17	2.04	0	6.42	20.46	16.84	24.54	16.46	8.99	8.40	0
18	2.16	0	6.46	20.96	17.53	24.99	16.78	9.16	8.56	0
19	2.28	0	6.50	21.44	18.20	25.42	17.09	9.32	8.71	0
20	2.4	0	6.53	21.90	18.84	25.83	17.38	9.47	8.86	0
				15.79606		18.112		7.210522	11.50329	6.742826

summary

Height (m)	2.40
Solar Rad(W/m2)	500.00
T out	0.00
T in	0.00
Tmax	20.23
Total q to room (W)	184.11
Total q to duct (W)	140.95
V3	0.10
V5	0.02
Average 2 cavity temp	11.67
SHGC	0.15
Effective U-Value	N/A







Radiation Heat Transfer Coefficients

Tm 4 to 2	hrad 4 to 2	Tm 6 to 4	hrad 6 to 4	Tm 6 to 2	hrad 6 to 2	Tm 6 to 4	hrad 6 to 4	Tm 7 to in	hrad 7 to in
0	3.43	0.00	3.43	0.00	3.43	0	3.43	0.00	3.43
8.78	3.77	5.99	3.66	4.54	3.60	5.99	3.66	0.82	3.46
11.01	3.86	8.68	3.77	6.45	3.68	8.68	3.77	1.83	3.50
12.35	3.92	9.95	3.82	7.50	3.72	9.95	3.82	2.39	3.52
13.36	3.96	10.74	3.85	8.25	3.75	10.74	3.85	2.64	3.53
14.23	3.99	11.36	3.87	8.89	3.77	11.36	3.87	2.81	3.54
15.05	4.03	11.90	3.90	9.46	3.80	11.90	3.90	2.96	3.54
15.82	4.06	12.41	3.92	10.01	3.82	12.41	3.92	3.09	3.55
16.56	4.09	12.89	3.94	10.53	3.84	12.89	3.94	3.21	3.55
17.27	4.12	13.35	3.96	11.03	3.86	13.35	3.96	3.33	3.56
17.95	4.15	13.80	3.98	11.51	3.88	13.80	3.98	3.44	3.56
18.60	4.18	14.22	3.99	11.98	3.90	14.22	3.99	3.55	3.56
19.23	4.21	14.63	4.01	12.42	3.92	14.63	4.01	3.66	3.57
19.83	4.23	15.02	4.03	12.84	3.94	15.02	4.03	3.76	3.57
20.41	4.26	15.40	4.04	13.25	3.95	15.40	4.04	3.85	3.58
20.96	4.28	15.76	4.06	13.64	3.97	15.76	4.06	3.95	3.58
21.50	4.30	16.11	4.07	14.02	3.98	16.11	4.07	4.04	3.58
22.01	4.33	16.44	4.09	14.38	4.00	16.44	4.09	4.12	3.59
22.50	4.35	16.76	4.10	14.73	4.01	16.76	4.10	4.20	3.59
22.97	4.37	17.07	4.11	15.06	4.03	17.07	4.11	4.28	3.59
23.43	4.39	17.37	4.13	15.38	4.04	17.37	4.13	4.36	3.60

checked 010499

Convective Heat Transfer Coefficients

	h2	h3	h5	h6
1	6.20	6.20	5.90	5.90
2	6.20	6.20	5.90	5.90
3	6.20	6.20	5.90	5.90
4	6.20	6.20	5.90	5.90
5	6.20	6.20	5.90	5.90
6	6.20	6.20	5.90	5.90
7	6.20	6.20	5.90	5.90
8	6.20	6.20	5.90	5.90
9	6.20	6.20	5.90	5.90
10	6.20	6.20	5.90	5.90
11	6.20	6.20	5.90	5.90
12	6.20	6.20	5.90	5.90
13	6.20	6.20	5.90	5.90
14	6.20	6.20	5.90	5.90
15	6.20	6.20	5.90	5.90
16	6.20	6.20	5.90	5.90
17	6.20	6.20	5.90	5.90
18	6.20	6.20	5.90	5.90
19	6.20	6.20	5.90	5.90
20	6.20	6.20	5.90	5.90
21	6.20	6.20	5.90	5.90

checked 010499

assumptions

Tm4-2 at y=0 is T3=Tin

Tm6-4 at y=0 is T5=Tin

Tm7-4 at y=0 is T5=Tin

note

Tm go with y-1 rather than y

Temperature Coefficients

A1	A2	A3	B_1	B_2 (unused)	B_3 (unused)	C_1 (unused)	C_2	C_3	D_1	D_2	E1	E_2	
0.57	2.76	0.26	0.74	0.41	0.00	0.41	0.74	0.71	0.71	20.00	0.41	0.96	1
0.57	2.76	0.26	0.74	0.45	0.00	0.44	0.74	0.71	0.71	20.00	0.42	0.96	2
0.57	2.76	0.26	0.74	0.46	0.00	0.45	0.74	0.71	0.71	20.00	0.42	0.96	3
0.57	2.76	0.26	0.74	0.47	0.00	0.46	0.74	0.71	0.71	20.00	0.42	0.96	4
0.57	2.76	0.26	0.74	0.47	0.00	0.46	0.74	0.71	0.71	20.00	0.42	0.96	5
0.57	2.76	0.26	0.74	0.48	0.00	0.46	0.74	0.71	0.71	20.00	0.42	0.96	6
0.57	2.76	0.26	0.74	0.48	0.00	0.47	0.74	0.71	0.71	20.00	0.42	0.96	7
0.58	2.76	0.26	0.74	0.49	0.00	0.47	0.74	0.71	0.71	20.00	0.43	0.96	8
0.58	2.76	0.26	0.74	0.49	0.00	0.47	0.74	0.71	0.71	20.00	0.43	0.96	9
0.58	2.76	0.26	0.74	0.49	0.00	0.47	0.74	0.71	0.71	20.00	0.43	0.96	10
0.58	2.76	0.26	0.74	0.50	0.00	0.48	0.74	0.71	0.71	20.00	0.43	0.96	11
0.58	2.76	0.26	0.74	0.50	0.00	0.48	0.74	0.71	0.71	20.00	0.43	0.96	12
0.58	2.76	0.26	0.74	0.50	0.00	0.48	0.74	0.71	0.71	20.00	0.43	0.96	13
0.58	2.76	0.26	0.74	0.51	0.00	0.48	0.74	0.71	0.71	20.00	0.43	0.96	14
0.58	2.76	0.26	0.74	0.51	0.00	0.49	0.74	0.71	0.71	20.00	0.43	0.96	15
0.58	2.76	0.26	0.74	0.51	0.00	0.49	0.74	0.71	0.71	20.00	0.43	0.96	16
0.58	2.76	0.26	0.74	0.52	0.00	0.49	0.74	0.71	0.71	20.00	0.43	0.96	17
0.58	2.76	0.26	0.74	0.52	0.00	0.49	0.74	0.71	0.71	20.00	0.43	0.96	18
0.58	2.76	0.27	0.74	0.52	0.00	0.49	0.74	0.71	0.71	20.00	0.43	0.96	19
0.58	2.76	0.27	0.74	0.52	0.00	0.49	0.74	0.71	0.71	20.00	0.43	0.96	20
0.58	2.76	0.27	0.74	0.53	0.00	0.50	0.74	0.71	0.71	20.00	0.43	0.96	21

Double Glazing Calcs

tm 1,2	hc,gap	Eeff hr	hc+Eeff	C	dgu air gap R,gap	Rglass1 (l/kA)g1	Rglass2 (l/kA)g2	=SUM(E6:(R,dgu	Tm 1-sur	hrad 1-sur	20	Uglass plus hc Uglass	ASHRAE TABLE 27.6-5(1993) hi=8.29, ho=29		DIFFEREN
6.39	1.48	0.72	2.20	0.26	3.78	0.08	0.05	3.92	2.73	4.78	1	2.127302005	0.25	2.78	-90.91%
7.18	1.48	0.73	2.21	0.27	3.77	0.08	0.05	3.90	2.78	4.78	2	2.135899647	0.25	2.78	-90.87%
7.77	1.48	0.73	2.22	0.27	3.76	0.08	0.05	3.89	2.82	4.78	3	2.142444052	0.25	2.78	-90.84%
8.29	1.49	0.74	2.22	0.27	3.75	0.08	0.05	3.88	2.85	4.79	4	2.148163541	0.26	2.78	-90.82%
8.77	1.49	0.74	2.23	0.27	3.74	0.08	0.05	3.87	2.89	4.79	5	2.153476367	0.26	2.78	-90.79%
9.22	1.49	0.75	2.24	0.27	3.73	0.08	0.05	3.86	2.92	4.79	6	2.158526178	0.26	2.78	-90.77%
9.66	1.49	0.75	2.24	0.27	3.72	0.08	0.05	3.85	2.95	4.79	7	2.163365043	0.26	2.78	-90.75%
10.08	1.49	0.75	2.25	0.27	3.71	0.08	0.05	3.84	2.98	4.79	8	2.168014534	0.26	2.78	-90.73%
10.48	1.50	0.76	2.25	0.27	3.70	0.08	0.05	3.84	3.00	4.79	9	2.172485999	0.26	2.78	-90.71%
10.86	1.50	0.76	2.26	0.27	3.69	0.08	0.05	3.83	3.03	4.80	10	2.176787283	0.26	2.78	-90.70%
11.23	1.50	0.76	2.26	0.27	3.69	0.08	0.05	3.82	3.06	4.80	11	2.180924949	0.26	2.78	-90.68%
11.59	1.50	0.76	2.26	0.27	3.68	0.08	0.05	3.81	3.08	4.80	12	2.184905016	0.26	2.78	-90.66%
11.93	1.50	0.77	2.27	0.27	3.67	0.08	0.05	3.81	3.10	4.80	13	2.188733203	0.26	2.78	-90.65%
12.26	1.50	0.77	2.27	0.27	3.67	0.08	0.05	3.80	3.13	4.80	14	2.192415014	0.26	2.78	-90.63%
12.57	1.50	0.77	2.28	0.27	3.66	0.08	0.05	3.79	3.15	4.80	15	2.195955766	0.26	2.78	-90.61%
12.87	1.50	0.77	2.28	0.27	3.66	0.08	0.05	3.79	3.17	4.80	16	2.199360599	0.26	2.78	-90.60%
13.16	1.51	0.78	2.28	0.27	3.65	0.08	0.05	3.78	3.19	4.80	17	2.20263449	0.26	3.78	-93.08%
13.44	1.51	0.78	2.29	0.27	3.64	0.08	0.05	3.78	3.21	4.80	18	2.20578225	0.26	4.78	-94.52%
13.71	1.51	0.78	2.29	0.27	3.64	0.08	0.05	3.77	3.23	4.81	19	2.20880853	0.26	5.78	-95.46%
13.97	1.51	0.78	2.29	0.28	3.63	0.08	0.05	3.77	3.25	4.81	20	2.211717827	0.26	6.78	-96.12%
14.21	1.51	0.79	2.30	0.28	3.63	0.08	0.05	3.76	3.27	4.81	21	2.214514488	0.26	7.78	-96.62%

=IF(Work!C13>Work!C14,(Work!C13-Work!C14)/2+Work!C14,(Work!C14-Work!C13)/2+Work!C13)
=IF(Work!C13>Work!C14,(Work!C13-Work!C14)/2+Work!C14,(Work!C14-Work!C13)/2+Work!C13)

Blind Factors for Infrared Radiation

	1	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Sigma	2	90	90	90	90	90	90	90	90	90	60
Height	3	2.4	3	3	2	0.914	2.4	2.4	2.4	2.4	3
No. of Blind Divisions	4	96	120	120	80	35.98425	96	96	96	96	120
Blind Spacing	5	0.025	0.025	0.025	0.025	0.0254	0.025	0.025	0.025	0.025	0.025
Blind Length	6	0.025	0.025	0.025	0.025	0.0254	0.025	0.025	0.025	0.025	0.025
d1	7	0.1	0.0715	0.0715	0.63	0.089	0.1	0.1	0.1	0.1	0.0715
d2	8	0.045	0.0715	0.0715	0.37	0.089	0.045	0.045	0.045	0.045	0.0715
X1	9	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006
y1	10	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.011
y2	11	1.175	1.475	1.475	0.975	0.432	1.175	1.175	1.175	1.175	1.477
y3	12	1.200	1.500	1.500	1.000	0.457	1.200	1.200	1.200	1.200	1.498
bd	13	1.179247642	1.476732	1.476732	1.160829445	0.440681	1.179247642	1.179247642	1.179247642	1.179247642	1.478116
fh	14	1.200843454	1.501703	1.501703	1.066255129	0.465586	1.200843454	1.200843454	1.200843454	1.200843454	1.499745
ac	15	1.204159458	1.501703	1.501703	1.181905242	0.465586	1.204159458	1.204159458	1.204159458	1.204159458	1.499745
eg	16	1.175861386	1.476732	1.476732	1.042844667	0.440681	1.175861386	1.175861386	1.175861386	1.175861386	1.478116
de	17	0.05	0.05	0.05	0.05	0.0508	0.05	0.05	0.05	0.05	0.048296
cf	18	1.53144E-18	1.53E-18	1.53E-18	1.53144E-18	1.56E-18	1.53144E-18	1.53144E-18	1.53144E-18	1.53144E-18	0.012941
Aacfh	19	2.405002911	3.003406	3.003406	2.24816037	0.931171	2.405002911	2.405002911	2.405002911	2.405002911	3.012432
Abdeg	20	2.405109028	3.003464	3.003464	2.253674112	0.932162	2.405109028	2.405109028	2.405109028	2.405109028	3.004527
Abdfh	21	2.405091095	3.003435	3.003435	2.252084574	0.931666	2.405091095	2.405091095	2.405091095	2.405091095	3.002861
Aaceg	22	2.405020844	3.003435	3.003435	2.249749909	0.931666	2.405020844	2.405020844	2.405020844	2.405020844	3.002861
cd=ef=Blind Spacing		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
df=Lblind		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
fg		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
dg		1.23	1.53	1.53	1.09	0.49	1.23	1.23	1.23	1.23	1.53
da		1.23	1.53	1.53	1.20	0.49	1.23	1.23	1.23	1.23	1.52
fh		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
Fdf-ce=Flowerblind-upp	$F4_L4_U$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
Fdf-gh=Flowerblind-Gla	$F4_L6$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
Fdf-ab=Flowerblind-Gla	$F4_L2$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
check		1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	1.00
		1	2	3	4	5	6	7	8	9	10
	$F4_U4_L$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
	$F4_U6$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
	$F4_U2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
	$F24_L$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
	$F24_U$	0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.03
	$F64_L$	0.00	0.00	0.00	-0.03	-0.01	0.00	0.00	0.00	0.00	0.03
	$F64_U$	1.00	1.00	1.00	1.03	1.01	1.00	1.00	1.00	1.00	0.74
F26single	23	9.25186E-17	0	0	1.11022E-16	0	9.25186E-17	9.25186E-17	9.25186E-17	9.25186E-17	0.001873
F26	24	8.88178E-15	0	0	8.88178E-15	0	8.88178E-15	8.88178E-15	8.88178E-15	8.88178E-15	0.224745
F62=F26	25	8.88178E-15	0	0	8.88178E-15	0	8.88178E-15	8.88178E-15	8.88178E-15	8.88178E-15	0.224745
AVERAGES/TOTALS											
F24=1-F26	26	1	1	1	1	1	1	1	1	1	0.775255
F42=Fblinds-Glass2	27	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39
F46=Fblinds-Glass3	28	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39
F64=1-F62	29	1	1	1	1	1	1	1	1	1	0.775255
F44		0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.23
F46		0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39
F42		0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39

F6-?

For solar Angle, B=30degrees blind

surf2	0.85	0.15	0.12	0.102
surf4	0.85	0.15	0.12	0.102
surf6	0.85	0.15	0.12	0.102
Tmean3	((tout+tin)/2)^3		2E+07	
StefanB	5.7E-08			
sigma	**90**			
sigmaTm3	1.15975			

	r2	r2 prime	r4 L (lower)	r4 U (upper)	r4 prime	r6	r6 prime	q2-others	q4low-others	q4up-others	q4-others	q6-others	SUM
0	32.28	42.22	42.23	38.86	41.99	9.78	38.86	-1.19	1.20	3.49	4.69	-3.49	9.37E-03
1	39.99	55.22	55.23	52.41	61.03	21.14	52.40	-1.83	1.84	3.76	5.59	-3.75	1.31E-02
2	45.41	62.17	62.17	59.28	71.37	26.08	59.28	-2.01	2.02	3.99	6.01	-3.98	1.52E-02
3	49.94	66.99	66.99	63.84	78.66	28.86	63.84	-2.05	2.06	4.20	6.26	-4.20	1.68E-02
4	54.07	71.01	71.01	67.54	84.80	30.87	67.54	-2.03	2.04	4.41	6.45	-4.40	1.81E-02
5	57.97	74.67	74.67	70.87	90.41	32.59	70.87	-2.00	2.02	4.60	6.62	-4.59	1.93E-02
6	61.69	78.11	78.12	74.00	95.70	34.17	74.00	-1.97	1.98	4.79	6.77	-4.78	2.05E-02
7	65.25	81.40	81.41	76.98	100.74	35.67	76.98	-1.94	1.95	4.96	6.92	-4.96	2.16E-02
8	68.66	84.55	84.56	79.84	105.58	37.10	79.83	-1.91	1.92	5.14	7.06	-5.13	2.26E-02
9	71.95	87.58	87.59	82.58	110.23	38.47	82.57	-1.88	1.89	5.30	7.19	-5.29	2.37E-02
10	75.10	90.49	90.50	85.21	114.68	39.78	85.21	-1.85	1.86	5.46	7.32	-5.45	2.46E-02
11	78.12	93.28	93.29	87.73	118.96	41.04	87.73	-1.82	1.84	5.61	7.45	-5.60	2.56E-02
12	81.03	95.96	95.97	90.16	123.07	42.25	90.16	-1.79	1.81	5.76	7.57	-5.75	2.65E-02
13	83.82	98.53	98.54	92.49	127.02	43.42	92.49	-1.77	1.78	5.90	7.68	-5.89	2.73E-02
14	86.50	101.01	101.02	94.73	130.81	44.53	94.73	-1.74	1.76	6.03	7.79	-6.02	2.82E-02
15	89.07	103.38	103.39	96.89	134.45	45.61	96.88	-1.72	1.74	6.16	7.90	-6.15	2.89E-02
16	91.54	105.66	105.67	98.95	137.94	46.64	98.95	-1.70	1.72	6.29	8.00	-6.28	2.97E-02
17	93.91	107.85	107.87	100.94	141.29	47.63	100.93	-1.67	1.69	6.41	8.10	-6.40	3.04E-02
18	96.18	109.96	109.97	102.84	144.51	48.58	102.84	-1.65	1.67	6.52	8.20	-6.51	3.11E-02
19	98.37	111.98	111.99	104.67	147.61	49.49	104.67	-1.63	1.65	6.63	8.29	-6.62	3.18E-02
20	100.47	113.92	113.93	106.43	150.58	50.36	106.43	-1.61	1.64	6.74	8.37	-6.73	3.25E-02
21	71.20	79.11	79.12	73.94	107.58	36.56	73.93	-0.95	0.97	4.49	5.46	-4.48	2.32E-02
	s		t	u		v		w					
	6175646316			6435455600		=(Work!O6+273)^4							

Solar Radiation Absorbed

Q a1	Q a2	Q a4	Q a7
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00
17.71	4.74	19.55	0.00

Fsolar Calculations

length factors

	a (l/2)sin(sigma-blinds)	b c x tan(Beta)	c (l/2)cos(sigma-blinds)	Solar Azimuth Beta	Fsolar calculate (S-2(a+b))/S	
1	0.0125	0.0000	0.0000	0.00	0.00	0.00
2	0.0125	0.0000	0.0000	-5.00	0.00	0.00
3	0.0125	0.0000	0.0000	-10.00	0.00	0.00
4	0.0125	0.0000	0.0000	-15.00	0.00	0.00
5	0.0125	0.0000	0.0000	-20.00	0.00	0.00
6	0.0125	0.0000	0.0000	-25.00	0.00	0.00
7	0.0125	0.0000	0.0000	-30.00	0.00	0.00
8	0.0125	0.0000	0.0000	-35.00	0.00	0.00
9	0.0125	0.0000	0.0000	-40.00	0.00	0.00
10	0.0125	0.0000	0.0000	-45.00	0.00	0.00
11						
12						
13						
14		Need to import from weather data				
15						
16						
17						
18						
19						
20						
21						

Diffuse Solar

		Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Sigma		90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	60.00
Height		2.40	3.00	3.00	2.00	0.91	2.40	2.40	2.40	2.40	3.00
No. of Blind Divisions		96.00	120.00	120.00	80.00	35.98	96.00	96.00	96.00	96.00	120.00
Blind Spacing		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Blind Length		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
d1		0.10	0.07	0.07	0.63	0.09	0.10	0.10	0.10	0.10	0.07
d2		0.05	0.07	0.07	0.37	0.09	0.05	0.05	0.05	0.05	0.07
X1	9.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
y1	10.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
y2	11.00	1.18	1.48	1.48	0.98	0.43	1.18	1.18	1.18	1.18	1.48
y3	12.00	1.20	1.50	1.50	1.00	0.46	1.20	1.20	1.20	1.20	1.50
bd		1.18	1.48	1.48	1.16	0.44	1.18	1.18	1.18	1.18	1.48
fh		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
ac		1.20	1.50	1.50	1.18	0.47	1.20	1.20	1.20	1.20	1.50
eg		1.18	1.48	1.48	1.04	0.44	1.18	1.18	1.18	1.18	1.48
de		0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
cf		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Aacfh		2.41	3.00	3.00	2.25	0.93	2.41	2.41	2.41	2.41	3.01
Abdeg		2.41	3.00	3.00	2.25	0.93	2.41	2.41	2.41	2.41	3.00
Abdfh		2.41	3.00	3.00	2.25	0.93	2.41	2.41	2.41	2.41	3.00
Aaceg		2.41	3.00	3.00	2.25	0.93	2.41	2.41	2.41	2.41	3.00
cd=ef=Blind Spacing		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
df=Lblind		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
fg		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
dg		1.23	1.53	1.53	1.09	0.49	1.23	1.23	1.23	1.23	1.53
da		1.23	1.53	1.53	1.20	0.49	1.23	1.23	1.23	1.23	1.52
fh		1.20	1.50	1.50	1.07	0.47	1.20	1.20	1.20	1.20	1.50
Fdf-ce=Flowerblind-up	$F4_L4_U$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
Fdf-gh=Flowerblind-Gl	$F4_L6$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
Fdf-ab=Flowerblind-Gl	$F4_L2$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
check		1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	1.00
		1	2	3	4	5	6	7	8	9	10
	$F4_U4_L$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
	$F4_U6$	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
	$F4_U2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
totals (averages)	F44	0.00	0.00	0.00	0.08	0.01	0.00	0.00	0.00	0.00	0.23
totals (averages)	F46	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39
totals (averages)	F42	0.50	0.50	0.50	0.46	0.50	0.50	0.50	0.50	0.50	0.39

For reflected portion from blinds (1-Fsol)

Specular model

	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Sigma	90.000000	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00	60.00
sin(sigma)	1.000000	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.87
cos(sigma)	0.000000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50
Gamma	180.000000	180.00	180.00	180.00	180.00	180.00	180.00	180.00	180.00	120.00
Gamma	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180	90<G<180
X1	0.000000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Sb	0.025000	0.025000	0.025000	0.025000	0.025400	0.025000	0.025000	0.025000	0.025000	0.025000
Sb,perp	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.012500
l,rebound	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
l,blind	0.025000	0.025000	0.025000	0.025000	0.025400	0.025000	0.025000	0.025000	0.025000	0.025000
Ray1	1	2	3	4	5	6	7	8	9	10
R1y	0.009375	0.009375	0.009375	0.009375	0.009525	0.009375	0.009375	0.009375	0.009375	0.008119
R1x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.004688
dYr1L	0.021875	0.021875	0.021875	0.021875	0.022225	0.021875	0.021875	0.021875	0.021875	0.022294
dXr1L	#########	#########	#########	#########	##########	##########	##########	##########	#########	0.012871
dYr1T	0.046875	0.046875	0.046875	0.046875	0.047625	0.046875	0.046875	0.046875	0.046875	0.043944
dXr1T	#########	#########	#########	#########	##########	##########	##########	##########	#########	-0.025371
dXr1L+R1x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1
dXr1T	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1	<r1X+X1
RAY 1 Bounce 1	out	out	out	out	out	out	out	out	out	out
Ray 1 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 1	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
Ray2	1	2	3	4	5	6	7	8	9	10
R2y	0.003125	0.003125	0.003125	0.003125	0.003175	0.003125	0.003125	0.003125	0.003125	0.002706
R2x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.001563
dYr2L	0.015625	0.015625	0.015625	0.015625	0.015875	0.015625	0.015625	0.015625	0.015625	0.016881
dXr2L	#########	#########	#########	#########	##########	##########	##########	##########	#########	0.009746
dYr2T	0.040625	0.040625	0.040625	0.040625	0.041275	0.040625	0.040625	0.040625	0.040625	0.038532
dXr2T	#########	#########	#########	#########	##########	##########	##########	##########	#########	-0.022246
dXr2L+R2x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1
dXr2T	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1	<r2X+X1
RAY 2 Bounce 1	out	out	out	out	out	out	out	out	out	out
Ray 2 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 2	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
Ray3	1	2	3	4	5	6	7	8	9	10
R3y	0.003125	0.003125	0.003125	0.003125	0.003175	0.003125	0.003125	0.003125	0.003125	0.002706
R3x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.001563
dYr3L	0.009375	0.009375	0.009375	0.009375	0.009525	0.009375	0.009375	0.009375	0.009375	0.011468
dXr3L	#########	#########	#########	#########	##########	##########	##########	##########	#########	0.006621
dYr3T	0.034375	0.034375	0.034375	0.034375	0.034925	0.034375	0.034375	0.034375	0.034375	0.033119
dXr3T	#########	#########	#########	#########	##########	##########	##########	##########	#########	-0.019121
dXr3L-R3x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	<X1
dXr3T	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X	<X1-r3X
RAY 3 Bounce 1	out	out	out	out	out	out	out	out	out	hit
Ray 3 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 3	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-hit
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
Ray4	1	2	3	4	5	6	7	8	9	10
R4y	0.009375	0.009375	0.009375	0.009375	0.009525	0.009375	0.009375	0.009375	0.009375	0.008119
R4x	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.004688
dYr4L	0.003125	0.003125	0.003125	0.003125	0.003175	0.003125	0.003125	0.003125	0.003125	0.006056
dXr4L	#########	#########	#########	#########	##########	##########	##########	##########	#########	0.003496
dYr4T	0.028125	0.028125	0.028125	0.028125	0.028575	0.028125	0.028125	0.028125	0.028125	0.027706
SUMS dXr4T	#########	#########	#########	#########	##########	##########	##########	##########	#########	-0.015996
dXr4L-R4x	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	>X1	<X1 ##
dXr4T	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X	<X1-r4X
RAY 4 Bounce 1	out	out	out	out	out	out	out	out	out	hit
Ray 4 Lit or unlit	lit	lit	lit	lit	lit	lit	lit	lit	lit	lit
RESULT Ray 3	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-out	lit-hit
Hit-hit condition?	no	no	no	no	no	no	no	no	no	no
lit-out	4	4	4	4	4	4	4	4	4	2
lit-hit	0	0	0	0	0	0	0	0	0	2
lit-in	0	0	0	0	0	0	0	0	0	0
hit-hit	0	0	0	0	0	0	0	0	0	0

ReflectionTotal Table:	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Rho4,s	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Rho4,d	0.15	0.15	0.15	0.15	0.15	0.3	0.15	0.15	0.15	0.1
abs of blind, alpha4	0.75	0.75	0.75	0.75	0.75	0.6	0.75	0.75	0.75	0.6
1/4 sum of "lit-out"	1	1	1	1	1	1	1	1	1	1
1/4 sum of "lit-hit"	0	0	0	0	0	0	0	0	0	1
1/4 sum of "lit-in"	0	0	0	0	0	0	0	0	0	0
1/4 sum of "hit-hit"	0	0	0	0	0	0	0	0	0	0
F4U4L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
F4U6	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
F4U2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
F4L4U	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
F4L6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
F4L2	1.00	1.00	1.00	0.92	0.99	1.00	1.00	1.00	1.00	0.74
Rho 4, tot-out	0.2497	0.2499	0.2499	0.2387	0.2487	0.3995	0.2497	0.2497	0.2497	0.1243
Alpha 4 tot	0.7500	0.7500	0.7500	0.7500	0.7500	0.6000	0.7500	0.7500	0.7500	0.6441
Rho 4, tot-in	-0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0167
	0.9997	0.9999	0.9999	0.9887	0.9987	0.9995	0.9997	0.9997	0.9997	0.7851
							1.00			

Buoyancy forces in Air
Calculations

Laminar Case

Ambient conditions:

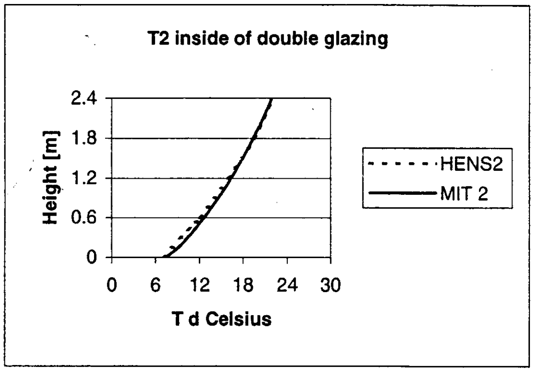
temp of inside air	0 deg C
temp of outside air	0 deg C
density of inside air	1.290627455 kg/m3
density of outside air	1.290627455 kg/m3

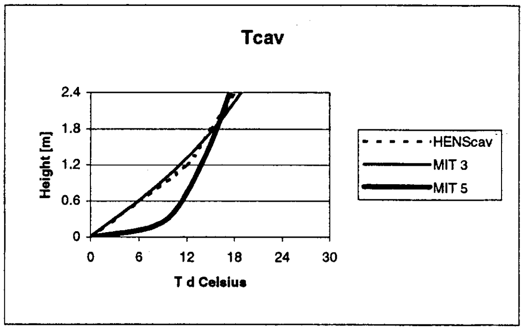
RELATES TO D1: **outer**		RELATES TO D2: **inner**	
Outer Cavity		**Inner Cavity**	
Average Temp	10.96 deg C	Average Temp	13.54 deg C
Average Density	1.240620755 kg/m3	Average Density	1.229362068 kg/m3
Choose Rho infinity	**1.290627455** kg/m3	Choose Rho infinity	**1.290627455** kg/m3
Ave viscosity ,mu	0.00001774	Ave viscosity ,mu	0.00001786
gravity, g	9.81 m/s2		
Height, H	2.4 m		
Area Cross Sec,Acs	0.1 m2	Area Cross Sec,Acs	0.045 m2
delta P Net	**0.117735773**	**delta P Net**	**0.064909452**
neglecting entrance and exit effects			
Ave Velocity, Vave	**2.3044 m/s**	**Ave Velocity, Vave**	**0.2555 m/s**
Dh	0.20	Dh	0.09
Reynolds, Re	32231.2954 **LAMINAR**	Reynolds, Re	1583.069177 **LAMINAR**

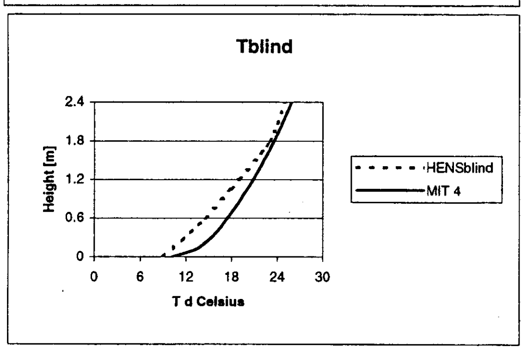
based on a Re, transition # of 1.00E+05

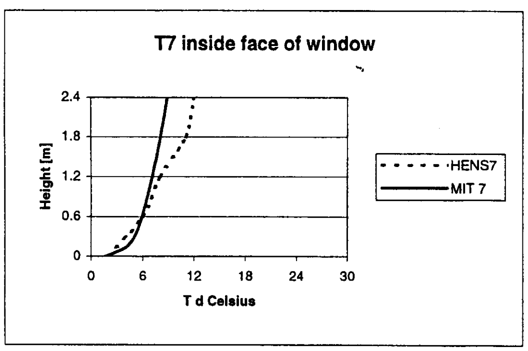
Turbulent Case			
friction factor, f	0.02	friction factor, f	0.050097045
Head loss, lf	0.038299629	Head loss, lf	0.002223156
delta P Net	**0.466125235**	**delta P Net**	**0.026811352**
Ave velocity, Vave	**9.1234 m/s**	**Ave velocity, Vave**	**0.1056 m/s**

RESULTANT VELOCITIES	**2.3044** m/s	**0.2555** m/s

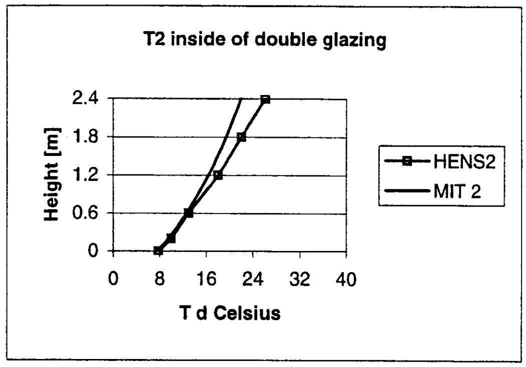


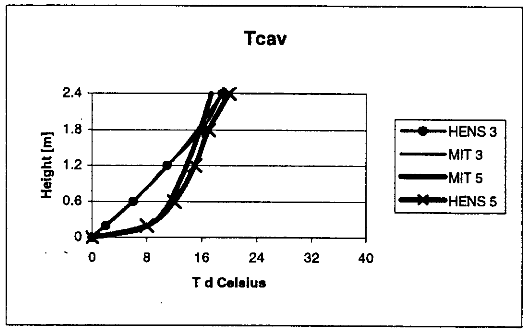


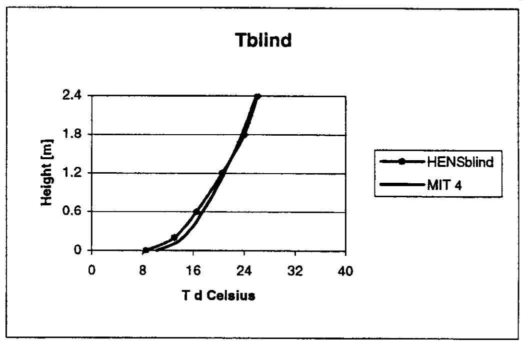


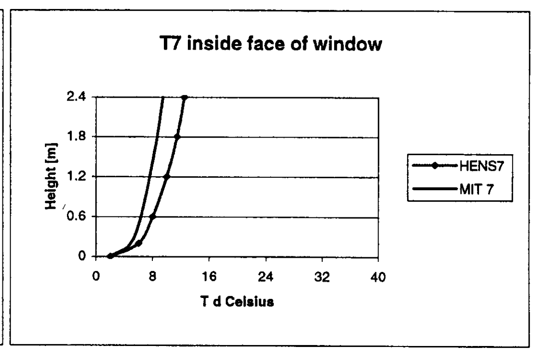


MIT vs. HENS Const. T Model
One cavity balance
Well mixed?









MIT vs. HENS Double Cav. Model
Airflow in each cavity.
No exchange

Base Case Configurations

Solar Heat Gain Coefficient (SHGC) Determination

file: Calculator.xls

case: 2

Case Parameters

Geometry

Height, H	2.4	m
Num divisions	20	each
delta y	0.12	m
Area,Ady	0.12	m2
d0	15	mm
d1	0.1	m
d2	0.045	m

Design Temps

Tout	0	deg C
Tin	0	deg C
delta T	0	deg C
Tmrt	0	deg C
Tsur	0	deg C

Incident Radiation

qr,incident	500	W/m2

Blinds Properties

emissivity,E4	0.85	nondim
reflectivity, ref_blind	0.25	nondim
Spectral Reflectivity of blind	0.1	nondim
Diffuse Reflectivity of blind	0.15	nondim
Rho 4, tot-out	0.25	nondim
Alpha 4 tot	0.75	nondim
Rho 4, tot-in	7E-16	nondim
absorptivity, abs_blind	0.75	nondim
Length of the blind	0.025	m
Blind Angle from horizontal (Sigma	90	degrees
BlindSpace	0.025	m
F26(IR), geometry factor	9E-15	nondim
F24=1-F(IR), geometry factor	1	nondim
F(sol), geometry factor	0.00	nondim
1-F(sol), geometry factor	1.00	nondim
Area of the blind for convection	0.12	m

Room Properties

emissivity,Ein	0.85	nondim

Heat Transfer, hc

hout=h1	23	nodim
hin=h7	8	nodim

Glass Properties

1/Eeff=1/E12+1/E21-1	6.84		0
Eeff	0.15		0

Glass #1 ID Number	custom	
k,glass1	1	W/(mK)
l,glass1	0.01	mm
abs_front_glass1	0.26	nondim
abs_back_glass1	0.26	nondim
ref_front_glass1	0.19	nondim
ref_back_glass1	0.19	nondim
trans_glass1	0.55	nondim
emissivity_front_glass1	0.85	nondim
emissivity_back_glass1	0.15	nondim

Glass #2 ID Number	custom	
k,glass2	1	W/(mK)
l,glass2	0.006	m
abs_front_glass2	0.12	nodim
abs_back_glass2	0.12	nodim
ref_front_glass2	0.09	nodim
ref_back_glass2	0.09	nodim
trans_glass2	0.79	nodim
emissivity_front_glass2	0.85	nodim
emissivity_back_glass2	0.85	nodim

Glass # ID Number	custom	
k,glass3	1	W/(mK)
l,glass3	0.006	m
abs_front_glass3	0.12	nodim
abs_back_glass3	0.12	nodim
ref_front_glass3	0.09	nodim
ref_back_glass3	0.09	nodim
trans_glass3	0.79	nodim
emissivity_front_glass3	0.85	nodim
emissivity_back_glass3	0.85	nodim

Constants

StefanBoltzman	5.70E-08	W/m2K4

Base Case Configurations

Solar Heat Gain Coefficient (SHGC) Determination

file: Calculator.xls

case: 2

Case Parameters			
Air Properties	d1		d2
Forced Ventilation? (yes/no)	yes	Forced Ventilation? (yes/no)	yes
Inlet Side	in	Inlet Side	in
specific heat Cp	1005.00	specific heat Cp	1005.00
conductivity,k	0.03	conductivity,k	0.03
mass flow rate, m	0.01	mass flow rate, m	0.00
rho, density of air	1.20	rho, density of air	1.20
velocity, V	0.10	velocity, V	0.02
DH	0.20	DH	0.09
Pr	0.69	Pr	0.69
kinematic viscosity,air	0.00	kinematic viscosity,air	0.00
ReD	1264.95	ReD	140.55
Laminar NuDH	9.94	Laminar NuDH	8.34
f	0.06	f	0.19
Turbulent NuDh	1.89	Turbulent NuDh	-25.49
Utilized Nudh	9.94	Utilized Nudh	8.34
hconv	6.20	hconv	5.90

#
0
0
0
0
0
0
0
0
0
0

Base Case Configurations

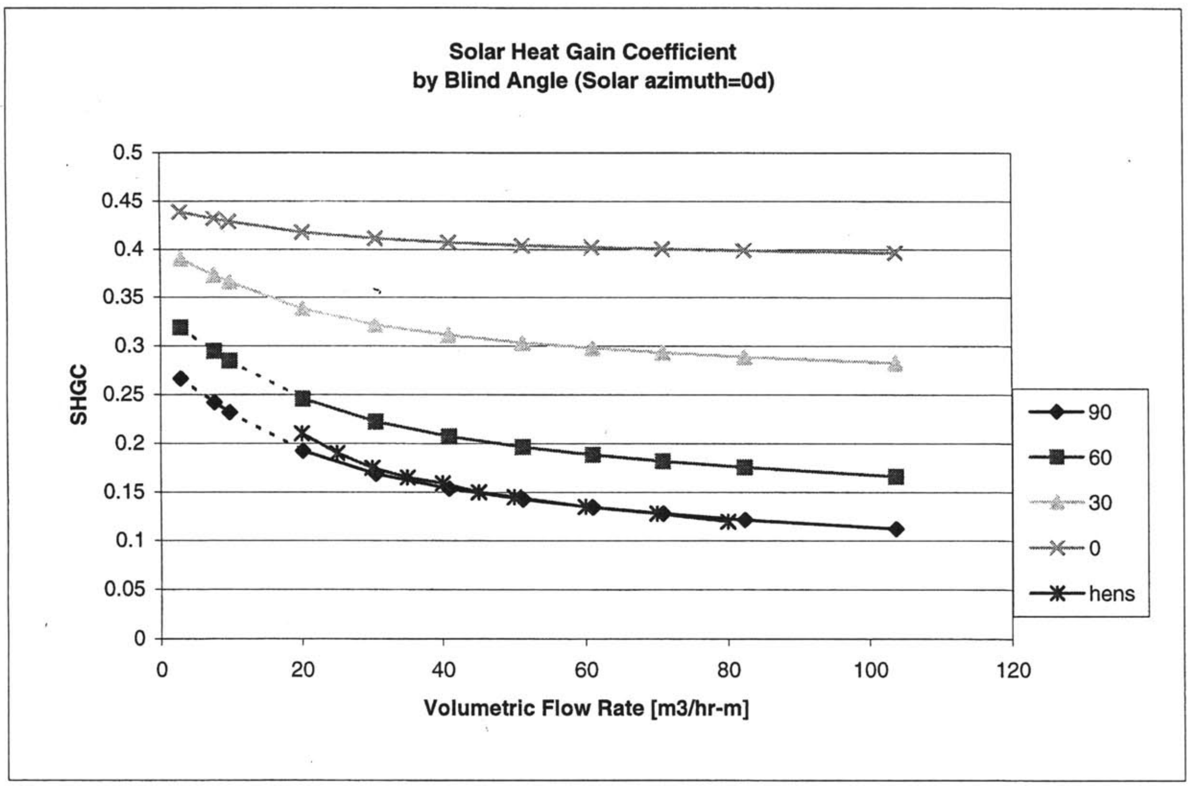
Solar Heat Gain Coefficient (SHGC) Determination

file: Calculator.xls

case: 2 HENS hH=2.4 m=0.8

Solar Angle Sensitivity

m/s	m3/hm	kg/s	Blind Angle				hens	
	2 cavities	0.00	90	60	30	0		
0.005556	2.860169	0.000469	0.266393	0.318798	0.39037	0.438675	20	0.21
0.014816	7.627119	0.00125	0.241976	0.29485	0.373306	0.431789	25	0.19
0.018964	9.762712	0.0016	0.231737	0.284779	0.366136	0.428898	30	0.175
0.039113	20.13559	0.0033	0.19225	0.245773	0.338391	0.417675	35	0.165
0.059263	30.50847	0.005	0.168729	0.222391	0.321883	0.411233	40	0.159
0.079412	40.88136	0.0067	0.153427	0.207156	0.311155	0.407094	45	0.15
0.099561	51.25424	0.0084	0.142477	0.196249	0.303497	0.404173	50	0.145
0.118526	61.01695	0.01	0.134519	0.188328	0.297949	0.40208	60	0.135
0.13749	70.77966	0.0116	0.128033	0.181876	0.293441	0.400397	70	0.128
0.160009	82.37288	0.0135	0.121626	0.175509	0.289004	0.398758	80	0.12
0.201493	103.7288	0.017	0.112203	0.16616	0.282512	0.396394		



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