Analysis of Buoyancy Driven
Airflow Patterns in a Model of a
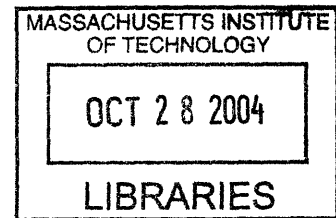Naturally Ventilated Building

By

Melissa Cain

Submitted to the Department of Mechanical
Engineering in Partial Fulfillment of the Requirements
for the Degree of

Bachelor of Science

at the

Massachusetts Institute of Technology

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Abstract

Models can help us understand the climate conditions inside naturally ventilated buildings in order to improve the efficiency of the design. Naturally ventilated buildings use temperature gradients to create buoyancy forces in the space and drive the airflow pathways in the space. One architectural design feature that facilitates natural ventilation is the presence of stack ventilation in the roof of the building, which facilitates the expulsion of heated air from the space. An architectural feature that changes the airflow pathways is the presence of railing on the upper floors where there is a danger of falling into the atrium. Using the model of a naturally ventilated building located in the Building Technology Department at MIT airflow visualization studies were carried out using incense to view the airflow patterns in the model. The variables of temperature, size of stack ventilation opening, and whether there were railings in the building or not were varied to determine their effects on the airflow. Temperature had the effect of increasing the velocity of the airflow, but did not significantly change the overall airflow profile. The size of the stack vent opening changed the airflow pathways significantly as did adding railings into the model. Comparing the results with a computational fluid dynamics model shows that there are some discrepancies.

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Introduction

Modeling a naturally ventilated building is complicated because it involves incorporating many complex design specifications into the model. A standard architectural model is usually made of simple materials, which makes it difficult to simulate the way a space deals with heat and airflow. This project uses a model of a naturally ventilated building to examine the pathways of air due to buoyancy driven airflow and compares those pathways to a computer model of the airflow in the building.

Natural Ventilation

Natural ventilation is the process of supplying fresh air to and removing ventilated air from a space by means of purpose-provided aperture (such as operable windows, ventilators and shafts) and the natural forces of wind and temperature-difference pressures. The primary aim of ventilation is to preserve the quality of air. Ventilation may also be used to lower the temperature inside an occupied area.

Natural ventilation systems rely on pressure differences to move fresh air through buildings. Pressure differences can be caused by wind or the buoyancy effect created by temperature differences or differences in humidity.

Natural ventilation is important because it enormously reduces the need for mechanically controlled ventilation systems, which tend to use a lot of energy and often

account for the majority of expenses in maintaining a building. Naturally ventilated buildings use less energy and therefore cost less to operate over a long period of time.

There are two ways that a naturally ventilated system is driven. One way is by wind, which enters through windows in the building and forces circulation throughout the space. The second form of natural ventilation called buoyancy occurs when there is no wind driving the airflow and the air circulation is only due to temperature, humidity, and pressure differences within the space.

This paper will focus on the effects of buoyancy driven airflow in a naturally ventilated building when all the windows of the building are open.

The Building

The building that was analyzed for this paper is a naturally ventilated building in Luton, England and thus has many architectural characteristics designed to make the building as a whole more energy efficient. A picture of the building and a model of the windows are attached.

The location of the building (in Southern England) ensures that during almost all of the summer days the outside temperature will be lower than the inside temperature so there are substantial pressure differences to insure that buoyancy driven flow occurs.

However, this location also ensures that there are few extremes in heat or cold so it is easier to ventilate the building to the point where people feel comfortable. In addition, the building is located on a hill, so there are no buildings and few trees to block the wind flow to the building.

The building plan is very open to allow maximum airflow through the space. The occupants sit in the large open space at desks with low dividers between each worker's areas. This arrangement allows for cross ventilation to occur across the building by allowing the free flow of air throughout the space. Specifically, what is important for natural ventilation is that air is able to travel from the windows through the working space and to the atrium of the building and out the vents at the top of the atrium.

The windows of the building are oriented in the North South direction with few windows on the East and West Sides of the building. This allows for maximum wind-induced ventilation because the building is oriented with respect to the prevailing summer wind. North-South windows are also best for maximizing shade in the summer and minimizing shade in the winter to help control the amount of heat that the thermal mass receives.

The building includes a large central atrium, which allows the air to mix from floor to floor. This provides higher air velocities in the buoyancy driven case, but usually means that heated air from the lower floors will rise and flow to the upper floors causing them to be hotter. One of the major reasons for the atrium is that air can be released

through the large stack vents at the top of the atrium. When the vents are open, the air that has been heated due to mechanical and human heat loads in the building rises and is released through the top of the atrium.

Every window in the building contains a smaller vent immediately above it (as you can see in the design of the model that is attached). The vents release the heated air that rises to the ceiling of each floor. These vents allow the heated air to easily escape without first flowing to the atrium. While most of the heated air can be released through the stack vents, the vents above the windows are crucial for releasing air that is far away from the atrium so the air for each floor does not become stagnant.

The building has a concrete structure, which acts as a large thermal mass to help create airflow in the space. The concrete is heated by the sun and then circulates the air through convection.

The roof of the building is uneven as is apparent in the section of the building seen in Appendix B. There is an additional floor on the North side of the building. This design allows the southern rays of the sun to shine into the atrium of the building and heat the top floor on the North side of the building. In the middle of the day, the sun can penetrate all the way to the second floor on the North side as well. This is important in the winter because it allows for more of the building to act as a thermal mass. In the summer, the penetration of sunlight means that sometimes the heat in the building reaches uncomfortable levels.

The Model

This experiment was performed on a model of the building built by MIT's Building Technology Program. The model only includes a portion of the building as shown in the picture below. The envelope of the model is made of hardboard except on the Western side of the atrium and a five-inch spread on the Western side of the northwest corner of the building. Here, the hard board has been replaced by plexiglass to allow visual access to the inside of the building. Insulation was added to the outside of the hard board to reduce heat losses due to radiation. The floors are constructed of luan supported by basswood columns. The top of the atrium is made of foamcore and includes three holes to simulate the stack vents, each of which can be covered to varying amounts.

The model includes heaters that simulate the actual heat loads experienced by the buildings. The model is 1:10 scale so the heat loads are also scaled in the model to induce similar airflow patterns to the actual building. The heaters attempt to simulate the heat given off by the people in the building as well as any electronic equipment such as computers. The model does not take into account the sun and the heat loads that it provides.

Part of this experiment involves modeling the railings in the building that are present on the First and Second Floors of the building. The railings are located at the

edge of each floor where it leads to the atrium and are significant because they are mostly solid glass so very little airflow can penetrate under them.

The Ground floor on the north side of the building includes several conference rooms and closed offices so this area is climate controlled using a separate HVAC system. Because this area does not use natural ventilation, it is not included in the model.

The Test Chamber

The model is located in a test chamber in the Building Technology Department at MIT. The test chamber is a climate-controlled room and the only supply of air to the room is a diffuser located on the western side of the building. There are no windows in the room and all of the light is fluorescent to reduce the heat loads experienced by the building. This set up allows us to control the conditions of the air surrounding the model.

Buoyancy Airflow

Buoyancy-driven ventilation may be temperature-induced (stack ventilation) or humidity induced (cool tower). For this model, stack ventilation is used to drive the airflow. Buoyancy results from the difference in air density, which depends on temperature. Cool air is heavier than warm air at the same humidity. Within the

building, heat given off by occupants and other internal sources both tend to make air rise. In the case of stack ventilation, the heated air escapes from openings in the roof and cool air is drawn in through lower openings. The cooler air is heated by the space and rises to the roof as the air continues to cycle through the building. The buoyancy forces are strongest when the extremes of temperature in the building are greatest, which usually indicates that the colder the outside air is, the higher the buoyancy force will be within the space because the heat loads within the building stay basically constant day to day.

Airflow Visualization

Airflow visualization is the process of using a buoyancy-neutral material, like smoke, to show the pathways of air through the building. The source of the smoke is placed at specific point in the building and the airflow forces the smoke to move through the space. Airflow visualization shows how the air moves from one part of the building to the other and the general trends of the airflow throughout the space. Airflow visualization can also show the movement of air from floor to floor and through the central atrium. Researchers often use smoke pencils to do airflow visualization. The smoke created is due to a chemical reaction so it is neutrally buoyant and easy to control, however the smoke dissipates quickly and the smoke pencils only produce smoke when manually operated by the user so they do not give off a continuous stream or a steady amount of smoke. For this experiment, incense was used to do the visualization because it has a constant stream of smoke and does not have to be operated by a user so it could

be placed in the model and then the model could be closed and the airflow could be observed from the outside the closed model. The down side of using incense is that the smoke is not initially neutrally buoyant because the incense has to be lit on fire to produce smoke. Recording airflow visualization data can be done with a video camera or by drawing the observed path of the smoke.

Procedure

Airflow and temperature at specific points in the building were taken at frequent intervals using stationary wire temperature censors and anemometers. This data was used to determine when the model had reached equilibrium after each variable was changed in the space. Often the model took several hours to reach full equilibrium, especially in the case of a change in temperature.

For the airflow visualization, burning incense was placed in the model in various locations and the airflow pathways the smoke followed through the building were recorded by drawing pictures of the air pathways. The use of video to record the pathways failed because the model was too dark and the smoke would not show up on the video screen.

There were three variables in the experiment. The first variable was outside temperature. The experiment was run at eight, twelve, and sixteen degrees Celsius to test the effect that outside temperature has on temperature and airflow in the building. As

with the heat loads, the outside temperatures used in the experiment were determined by scaling the values to produce similar airflow states as the actual building.

The second variable was the amount of air that was allowed to escape the building through the holes at the top of the atrium that simulate stack vents. The purpose of testing this variable is to see if the airflow, especially within the atrium, is affected by allowing more air to leave the model. Since buoyancy cooling is based on the heated air leaving the space, the size of the openings and thus the amount of air that leaves the building at any one time should have a large effect on airflow in the space. The experiment was run with the stack vents at the top of the atrium in three different states: fully open, half open, and fully closed. This variable was repeated at all three temperatures.

The entire experiment was then repeated adding railings to the edge of the upper floors where they meet the atrium. The purpose of the railings was to observe the effect the railings had on airflow. This part of the experiment was important because the computer simulation of the airflow through the building does not include railings, but it may be important to add them if including railings significantly alters the path of the airflow.

Results

The temperature change had no noticeable effect on the airflow pathway. As the temperature increased, the air flowed at a slightly higher velocity, but the overall path of the air remained the same. Therefore, the figures comparing airflow at different temperatures are not included in this document. All the data was taken when the heaters were set at 45 degrees Celsius and the supply air temperature to the room was 12 degrees Celsius. The size of the stack vents drastically changed the airflow patterns in the atrium and the railings changed the interaction of the air between floors.

Abbreviations for floors:

South side: Ground Floor (SG)

First Floor (S1)

North side: First Floor (N1)

Second Floor (N2)

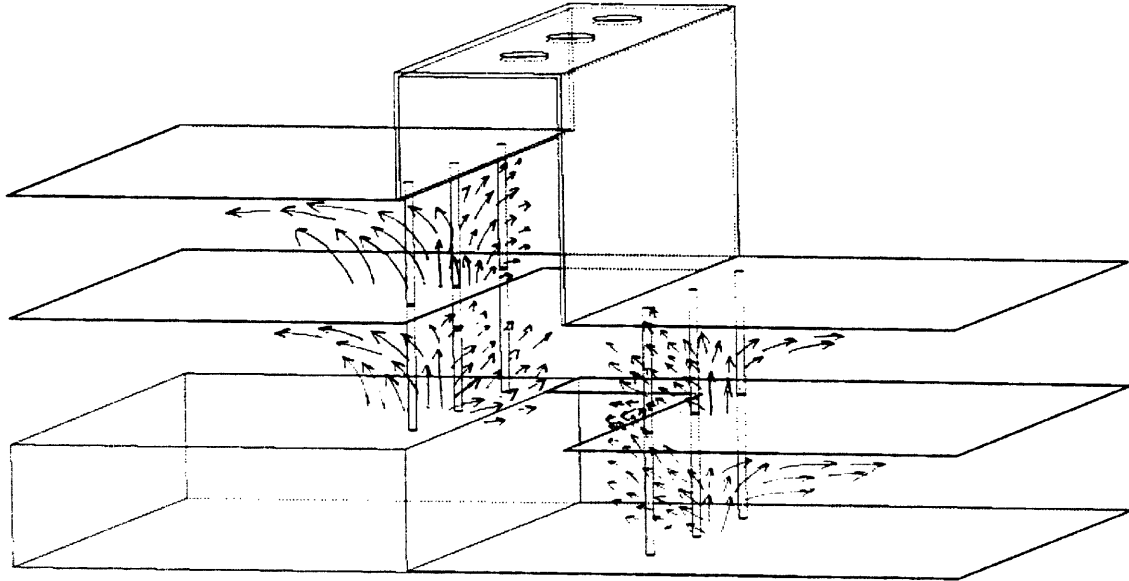**Figure 1: Stacks Fully Closed without Railings**

Figure 1 shows that the air from SG tended to flow away from the atrium and towards the windows. Specifically the smoke rose to the ceiling as it moved across the heat source and towards the southern windows. The air from the bottom floors did not rise to the top floors very often because the air in the atrium was mostly stagnant.
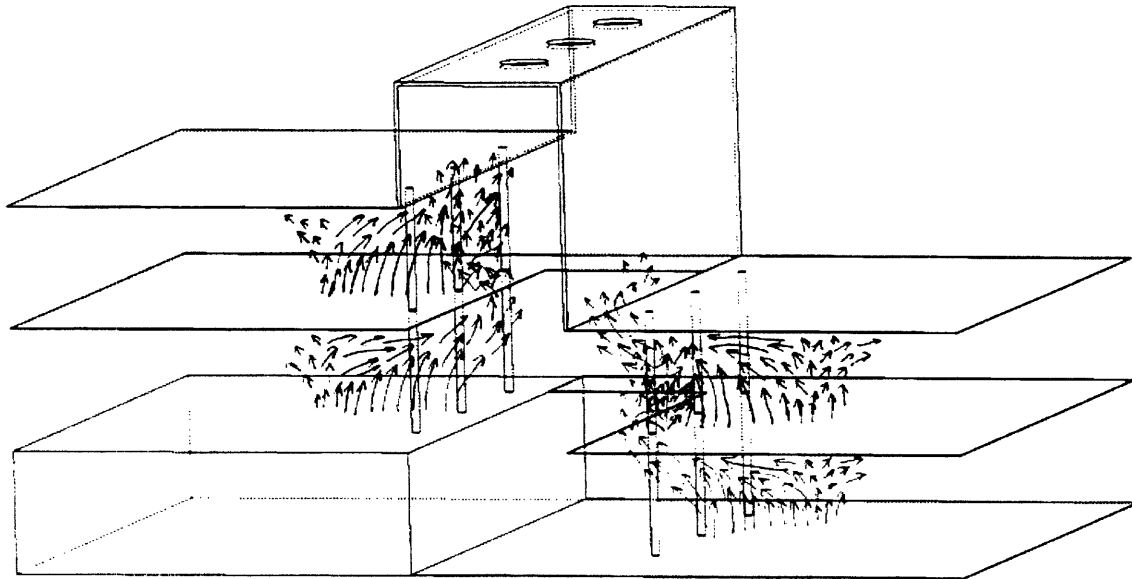
Figure 2: Stacks Half Open without Railings

Figure 2 shows that when the stack vents are half open the airflow profile completely changes. The air from every floor is more likely to flow into the atrium. The air from SG flows to the atrium, but mostly flows onto S1 and becomes part of the S1 airflow pattern just as the smoke from N1 mixes with the N2 smoke. The air leaving the stack vents has a very high velocity.

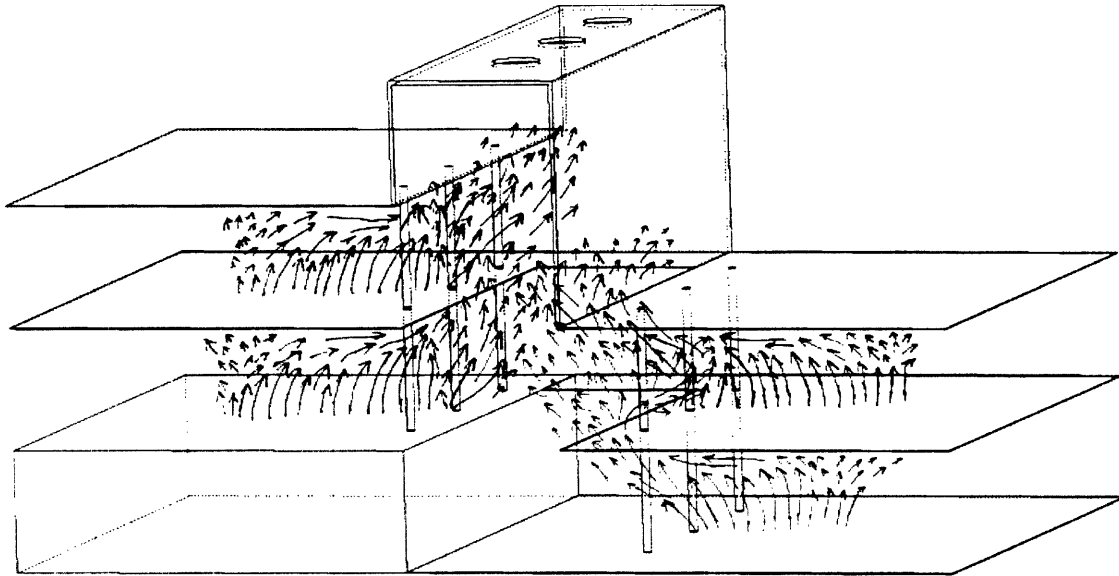**Figure 3: Stacks Fully Open without Railings**

Figure 3 shows that the fully open case acts similarly to the half open case. The airflow

through the vents has a higher velocity that indicates there is a greater airflow out of the

building which is mostly likely due to a higher buoyancy force. A higher buoyancy force

yields more mixing between the floors and more of the air on each floor moves towards

the atrium creating a fully naturally ventilated system.

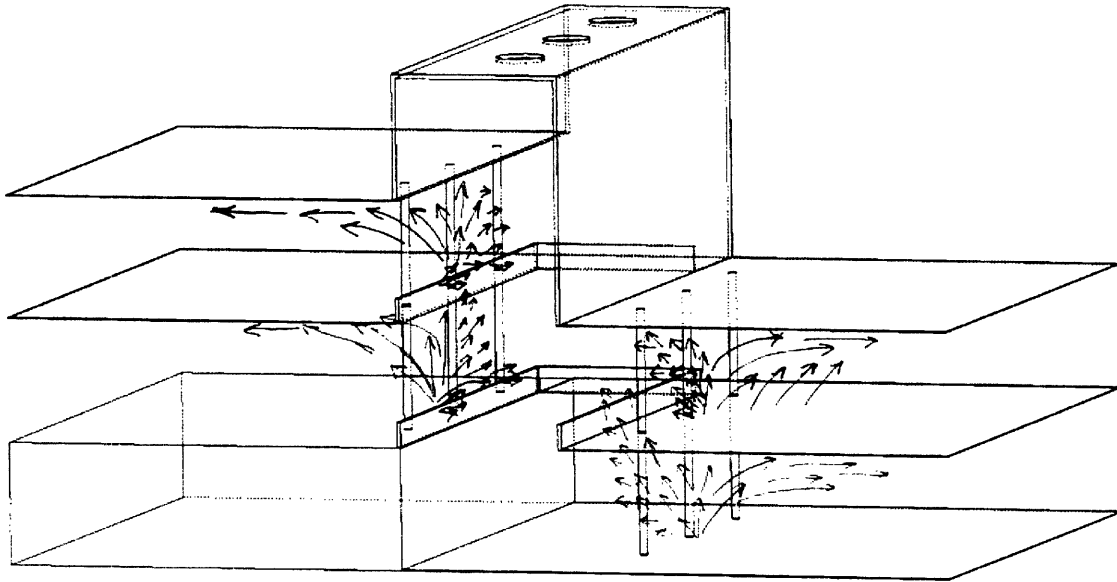**Figure 4: Stacks Fully Closed with Railings**

Figure 4 shows that the air profile for the closed vent case changes little when railings are added because most of the airflow is away from the atrium. The railings may limit some mixing of air, but it was hard to definitely say that because so little air moved towards the direction of the atrium and railings.
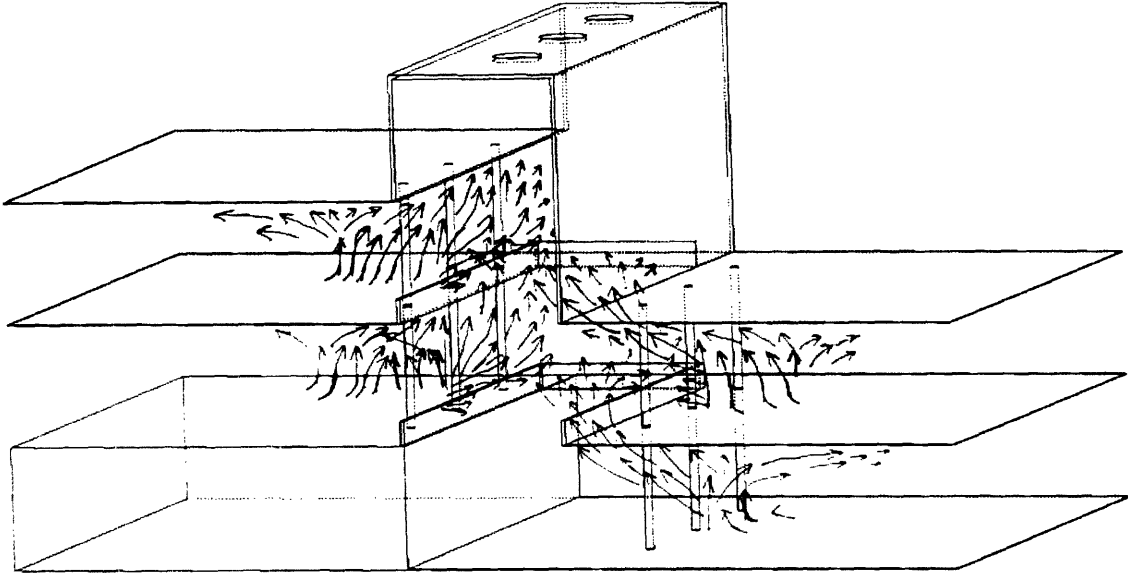
Figure 5: Stacks Half Open with Railings

Figure 5 shows that the railings block the air moving between floors and cause there to be less airflow interaction between floors which means that more air from lower floors is released through the vents and the flow on floors that contain railings is altered slightly to move around and over the railing.

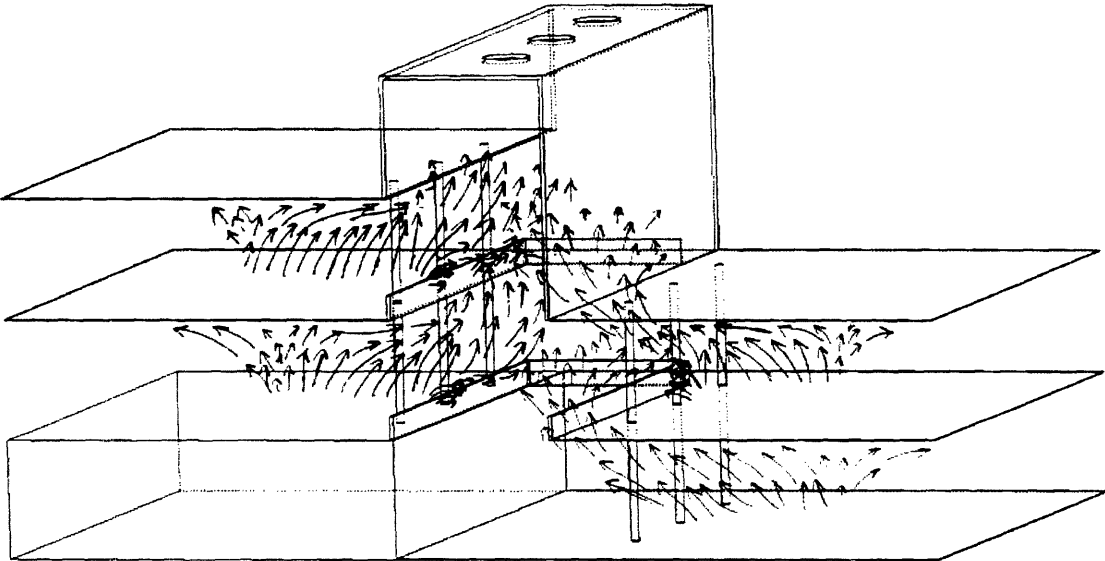**Figure 6: Stacks Fully Open with Railings**

Figure 6 shows that the railings hinder the mixing of air from one floor to the other and therefore have large effect on the equilibrium of the building.

Figure 7&8: Close-up of Edge of Floor without Railings and with Railings

Figure 7 & 8 more clearly show the effect railings have on the airflow from a lower to an upper floor. The figure on the left shows that without railings, the air freely moves over the edge of the floor and mixes with the air on the upper floor. The figure on the right shows that the air movement is impeded by the railing and therefore there is very little mixing between the upper and lower floors.

Airflow Visualization versus CFD

One of the main purposes of the experiment is to compare the airflow visualization of the physical model to the computational fluid dynamic (CFD) computer model being developed of the airflow patterns in the building.

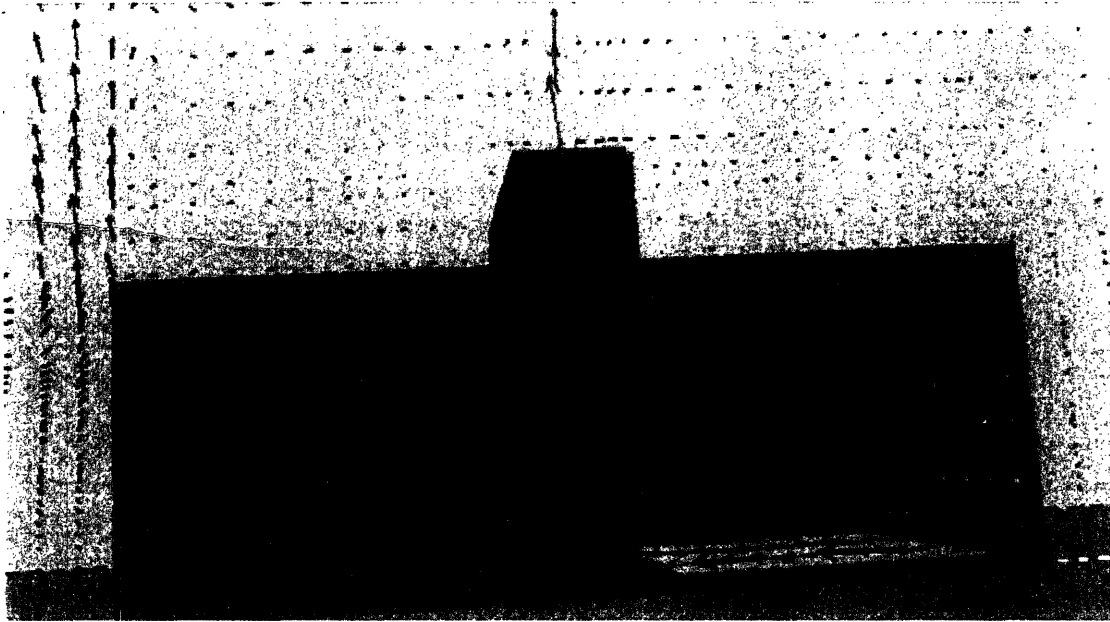**Figure 8. Computational Fluid Dynamic Model of Airflow in the model**

Figure 8 can be compared with the airflow visualization of the model that has open vents

and no railing. You can see that the CFD model has some intricacies not detectable in the

airflow visualization experiment. The CFD models the air flow through the whole floor,

but due to the nature of the incense and the heater placement in the model it was difficult

to get readings for the areas close to the floor. Because the incense smoke was not

neutrally buoyant, it always rose initially and then continued to follow the airflow which

indicates that it may initially have been hotter and therefore lighter than the surrounding

air.

Limitations

The smoke from the incense dissipated slower than the smoke from the smoke pencils, but it did not last long enough to trace the complete pathway of smoke throughout the length of half of the floor. The incense had to be within eight inches of the atrium to see the path the smoke took through the atrium. The model also only allows clear views to the atrium and near the north side windows.

Incense, while not producing much heat, could have an effect on the heat loads in the building. The air directly above the lighted incense was probably hotter than the surrounding air and could have altered the airflow in that area. The experiment showed that smoke tended to rise directly up first from the incense and then spread out, which may be due to the heat coming from the burning incense.

Conclusion

The airflow visualization yielded mostly expected results. It was presumed that the airflow pattern would be similar to the CFD model and that there would be more air movement when the vents were fully open. The pattern of airflow seen in the CFD model towards the floor of each floor did not exactly fit the model, but that probably has more to do with use of incense to visualize the air. The railings had the effect of decreasing the amount of air that is passed from a lower floor to a higher floor. The

railings could therefore have a substantial impact on the equilibrium of the building and should be included in the CFD and the scale model.

The airflow and the mixing of air from floor to floor increased as the opening for the stack vent increased, which is consistent with the theory behind buoyancy driven airflow. It would be interesting to actually use stack vents that included fans to drive the air out of the building when the temperatures are extremely high. That way the air would never remain stagnant.

One interesting finding was how strong the airflow towards the windows was when the vents were closed. The airflow seemed almost as strong that way as it was towards the atrium when the vents were open. There were some air leaks in the model so it is possible that affected the airflow especially when the vents were closed, but it was still very significant.
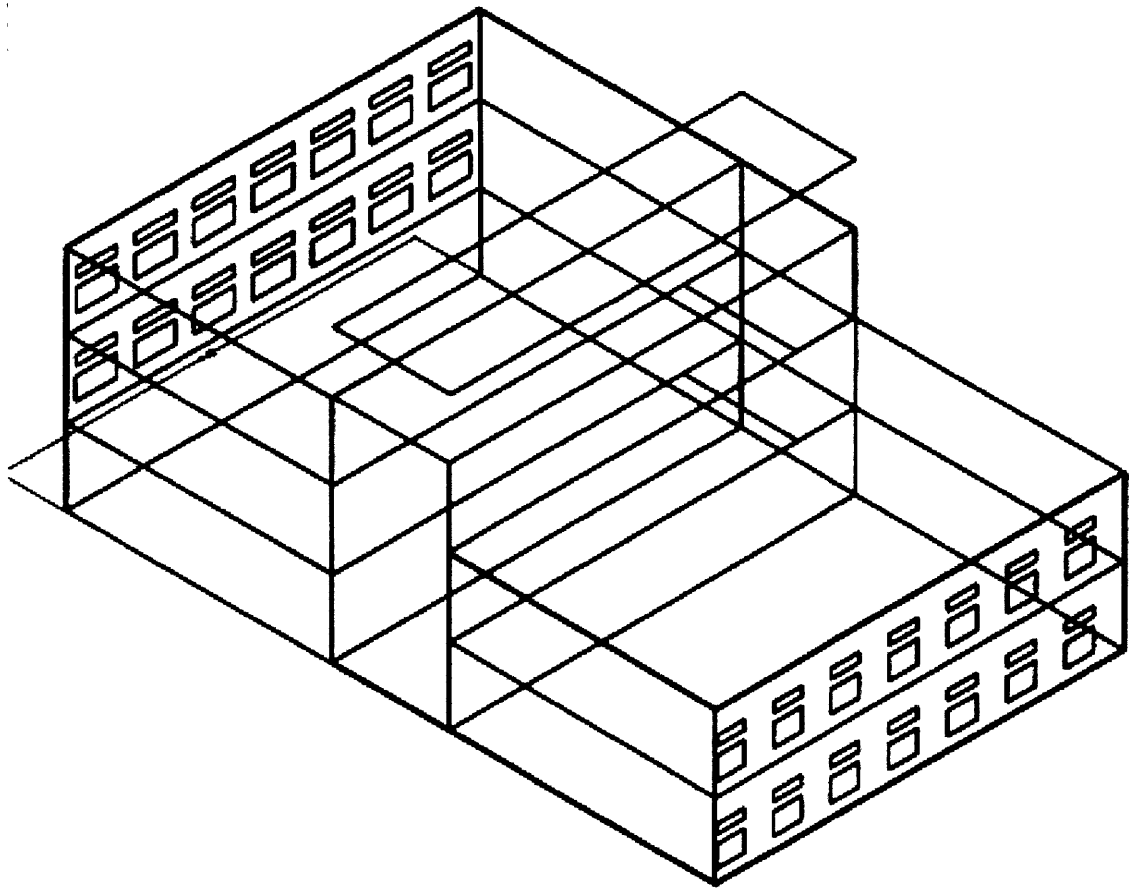
References

Tan, Gang. Unpublished thesis work on computational fluid dynamics model of the naturally ventilated building in Luton, England.
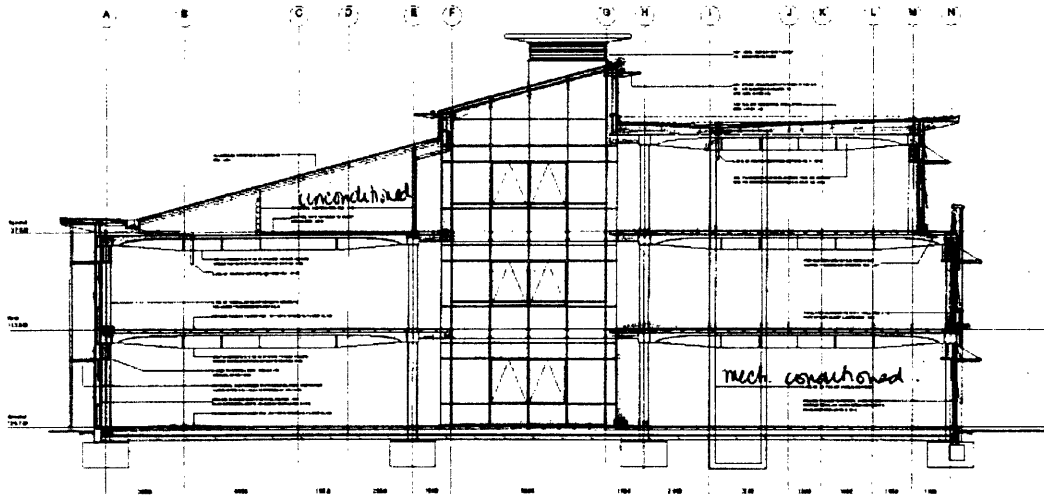
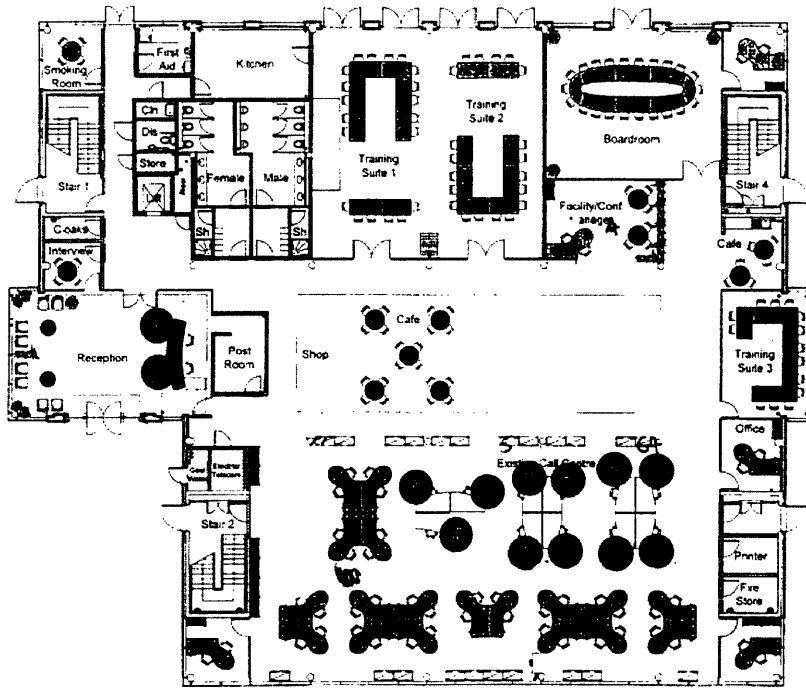# Appendix 1: Pictures and Drawings of Building in Luton, England
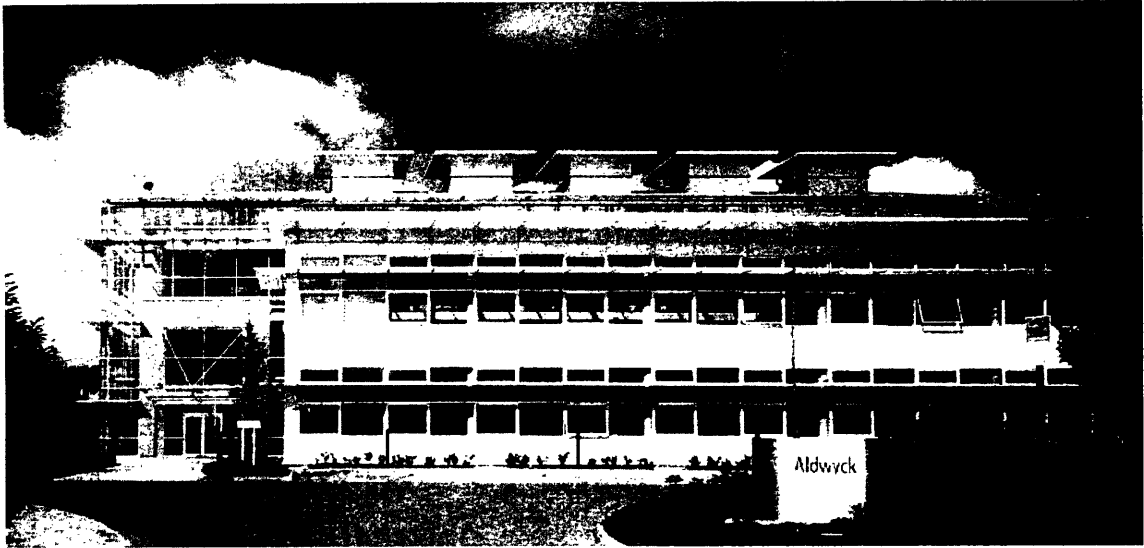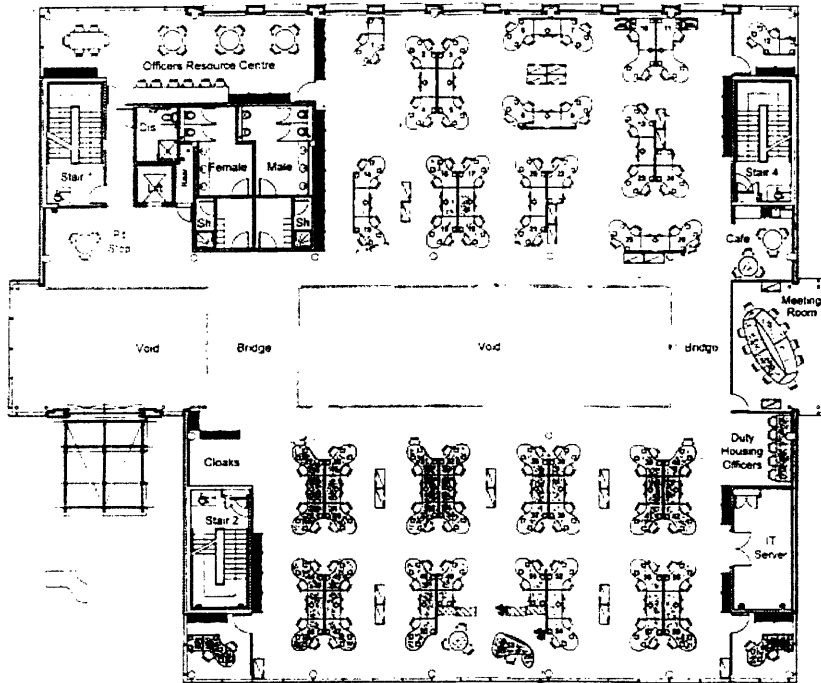

Exterior

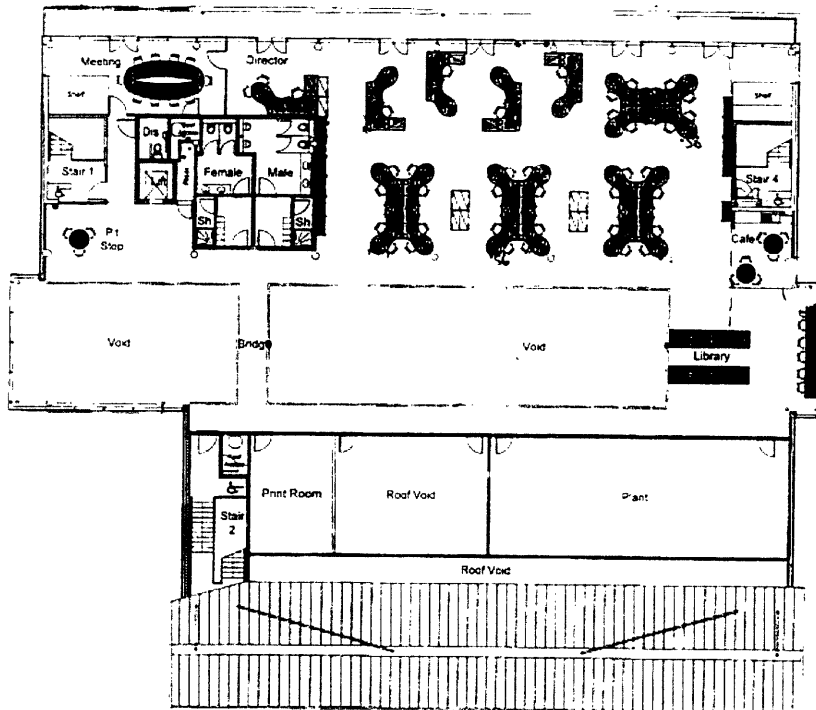Computer sketch showing window openings

Section

Ground Floor Plan

24

First Floor Plan

Second Floor Plan

Appendix 2: Temperature and Air Velocity Distribution in the Model

Chart 1: Temperature in the model at 12° C

		Uncovered	1/2 covered	Fully covered
SouthWest	1	36.35	38.8	39.2
SouthCentral	1	36.75	37.1	41.5
SouthEast	1	36.25	37.4	39.8
NorthEast	1	47.2	48.45	51.75
NorthCentral	1	47.85	51	53.1
NorthWest	1	49.2	49.1	51.3
SouthWest	2	27.7	26.5	27.9
SouthCentral	2	27.95	27.8	27.8
SouthEast	2	28.15	29.2	27.7
NorthEast	2	42.5	43.6	45.5
NorthCentral	2	45.55	44.7	46.3
NorthWest	2	44.6	45.3	47
SouthWest	3	26	26	25.8
SouthCentral	3	27.2	26.9	27.05
SouthEast	3	26.6	26.6	26.6
NorthEast	3	31.85	35.4	36.3
NorthCentral	3	32.05	34.8	36.7
NorthWest	3	32.8	34.8	37.2
SouthWest	4	24.25	25.45	26.25
SouthCentral	4	27.6	26.25	26.7
SouthEast	4	26.8	26.4	27.2
NorthEast	4	26.6	26.4	26.3
NorthCentral	4	27.9	26.85	26.85
NorthWest	4	27.15	27.65	26.2
Top	W	42.9	44.9	
	C	44.15	46.8	
	E	42.5	45.8	

Graph 1: Temperature in the model at 12° C
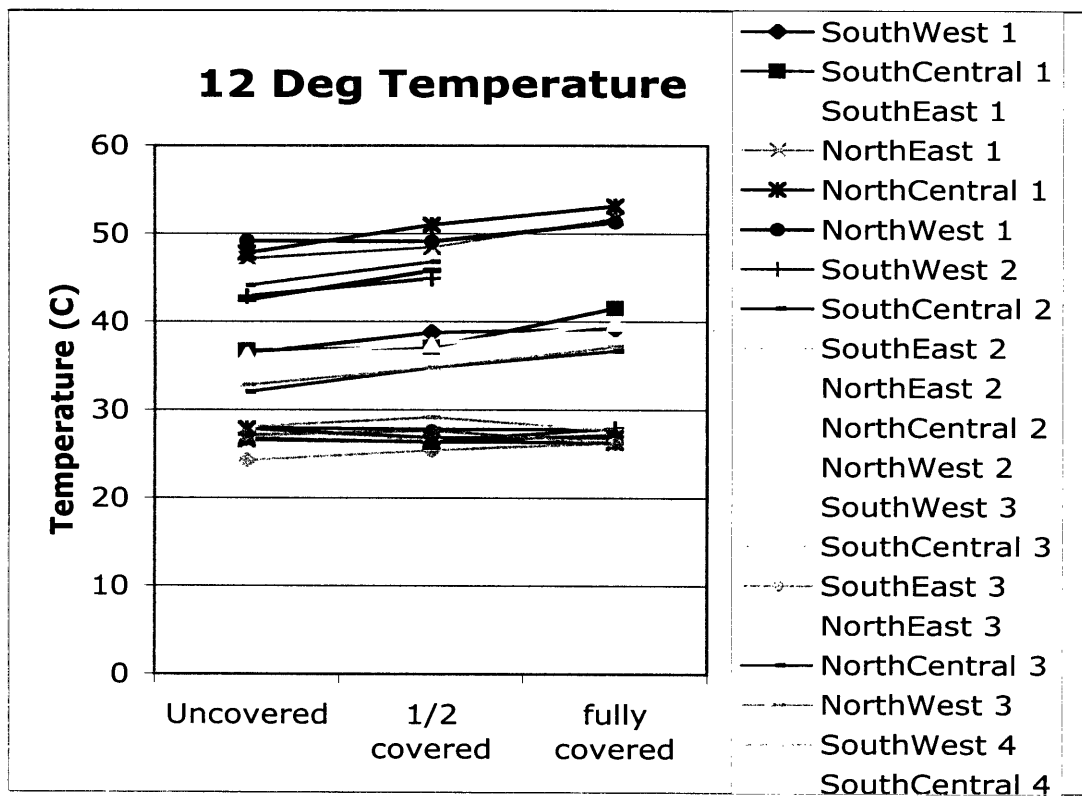
Chart 2: Air Velocity in the model (m/s)

			Uncovered	1/2 covered	Fully Covered
SouthWest		1a	0	0	0
		1b	0	0	0
		1c	0	0	0
		2a	0.2	0.2	0.1
		2b	0.3	0.3	0.3
		2c	0.3	0.3	0.2
		3a	0.3	0.3	0.35
		3b	0.4	0.4	0.4
		3c	0.4	0.4	0.4
		4a	0.4	0.3	0.4
		4b	0.6	0.5	0.5
		4c	0.5	0.6	0.5
SouthCentral		1a	0	0	0
		1b	0	0	0
		1c	0	0	0
		2a	0.2	0.2	0
		2b	0.4	0.3	0.3
		2c	0.2	0.3	0.1
		3a	0.4	0.3	0.4
		3b	0.4	0.5	0.4

	3c	0.4	0.4	0.4
	4a	0.4	0.5	0.5
	4b	0.5	0.5	0.6
	4c	0.6	0.5	0.5
SouthEast	1a	0	0	0
	1b	0	0	0
	1c	0	0	0
	2a	0.2	0.2	0.1
	2b	0.3	0.3	0.2
	2c	0.2	0.1	0.1
	3a	0.3	0.2	0.4
	3b	0.5	0.55	0.45
	3c	0.4	0.2	0.3
	4a	0.5	0.3	0.4
	4b	0.6	0.6	0.45
	4c	0.4	0.4	0.4
NorthEast	1a	0.1	0	0
	1b	0	0	0
	1c	0	0	0
	2a	0.1	0.1	0.1
	2b	0	0	0
	2c	0.1	0.1	0.1
	3a	0.1	0	0
	3b	0.1	0	0.1
	3c	0.1	0	0
	4a	0.2	0.1	0.1
	4b	0.3	0.3	0.2
	4c	0.2	0.1	0
NorthCentral	1a	0	0	0
	1b	0	0.1	0
	1c	0	0	0
	2a	0.1	0.1	0.1
	2b	0	0	0
	2c	0.1	0.1	0.1
	3a	0	0	0
	3b	0	0	0.1
	3c	0	0	0
	4a	0.2	0.1	0.1
	4b	0.3	0.3	0.3
	4c	0.2	0.15	0.1
NorthWest	1a	0	0	0
	1b	0	0	0
	1c	0	0	0
	2a	0.1	0.1	0.1
	2b	0	0	0

		2c	0.1	0	0.1
		3a	0.1	0.1	0
		3b	0	0.1	0
		3c	0	0.1	0
		4a	0.2	0.1	0.1
		4b	0.3	0.1	0.3
		4c	0.1	0.1	0.1
Ceiling Vents		W	0.3	0.4	
		C	0.6	0.6	
		E	0.6	0.6	

Graph 2: Air Velocity in the model (m/s)