Improving the Fanger Model's Thermal Comfort Predictions for Naturally Ventilated Spaces

by

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ABSTRACT

The Fanger model is the official thermal comfort model in U.S. and international standards and is based on the heat balance of the human body with the environment. This investigation focuses on re-specifying the parameters in Fanger's model, the majority of which are empirically-derived coefficients, to improve its thermal comfort predictions for naturally ventilated spaces. A sensitivity analysis revealed that the comfort temperature prediction is by far most sensitive to the comfort value of mean skin temperature. Furthermore, the sensitivity analysis also indicated that for the Fanger model to produce better comfort temperature predictions for naturally ventilated buildings, the comfort mean skin temperature needs to be correlated to an outdoor climate variable, thereby accounting for the psychological adaptations of occupants of naturally ventilated buildings that were largely ignored in the original climate chamber derivation of this parameter. A modified comfort mean skin temperature, that is a function of both metabolic rate and outdoor effective temperature and is applicable to naturally ventilated environments only, produces comfort temperature predictions that agree well with field study data. The thermal sensation transfer coefficient was also updated based on a weighted multiple linear regression of field study data. The results suggest that a Fanger model with a modified comfort mean skin temperature and modified thermal sensation transfer coefficient can significantly improve the thermal comfort predictions for naturally ventilated spaces. However, experiments need to be conducted to determine the true functional forms of both parameters.

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Dedicated to Fred, Ipo, and Leaf.

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1. Introduction

Thermal comfort is an important consideration in building design. Design decisions that do not take into account occupants' thermal comfort preferences can affect the productivity, health, and well-being of occupants [1-4], and can also lead to an over-cooling or over-heating of spaces amounting to needless energy consumption. Particularly, in regards to naturally ventilated (NV) buildings, research [5-8] has shown that differences exist in the thermal comfort requirements of these occupants and those of occupants in buildings with centrally-controlled heating, ventilating, and air-conditioning systems (HVAC). The official thermal comfort model in ASHRAE Standard 55 and International Standard ISO 7730, the Fanger heat balance model, fares much better at predicting the temperatures at which occupants would feel comfortable for HVAC buildings than for NV buildings [7, 9-15]. However, since natural ventilation is becoming a popular energy-saving alternative for the cooling of buildings, it is critical that a comprehensive thermal comfort model is available to aid in the design of NV spaces. The focus of this work is to suggest reasonable modifications to the Fanger model as a first step in the development of such a model.

2. Background

2.1. Static vs. adaptive thermal comfort models

ASHRAE Standard 55 [16] defines thermal comfort as “that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation.” Over the past forty years, two main schools of thought have developed in regards to what factors influence that condition of mind. On the one side, there is the static heat balance hypothesis; on the other, the adaptive hypothesis. Adherents of static heat balance models view “the person as a passive recipient of thermal stimuli” [7] and support the idea that the physical processes of heat and mass transfer are sufficient in characterizing the thermal comfort response. In particular, it is believed that temperature and moisture sensation from the skin, internal body temperature, and the regulatory efforts necessary to maintain a near constant internal body temperature (homeostasis) are the primary agents influencing the condition of mind that expresses thermal satisfaction. The regulatory efforts encompass the regulation of blood flow, also known as vasodilation and vasoconstriction, and sweat secretion and shivering under more extreme environmental conditions. When these regulatory efforts are minimized, as determined by mean skin temperature and evaporative heat loss due to sweating, a person will feel thermally comfortable. The governing equation in static heat balance models is the energy balance of the human body with the surrounding environment [7, 17, 18]:

$$H = M - W = (C + R + E_{sk}) + (C_{res} + E_{res}) + (S_{sk} + S_{cr}) \tag{1}$$

H = rate of internal heat production, W/m^2
M = rate of metabolic heat production, W/m^2
W = rate of mechanical work accomplished, W/m^2
$C + R$ = sensible heat loss from skin, W/m^2
E_{sk} = total rate of evaporative heat loss from skin, W/m^2
C_{res} = rate of convective heat loss from respiration, W/m^2
E_{res} = rate of evaporative heat loss from respiration, W/m^2
S_{sk} = rate of heat storage in skin compartment, W/m^2
S_{cr} = rate of heat storage in core compartment, W/m^2

Supporters of the adaptive school of thought, on the other hand, believe that factors beyond physics and physiology can influence the condition of mind that expresses thermal satisfaction. Adaptive models are based on the idea that occupants "play an instrumental role in creating their own thermal preferences": they will behaviorally and psychologically adapt to make themselves feel more comfortable. The behavioral adaptations take the form of clothing and airspeed adjustments, while psychological adaptations consist mainly of attenuated thermal perceptions and expectations due to past thermal experiences and greater levels of personal control. The effect of both is to widen the temperature range at which occupants feel comfortable. These adaptations have been observed in NV environments where occupants have access to operable windows and are more likely to expect the indoor thermal environment to fluctuate with the outdoor climate. For this reason, models based on the adaptive hypothesis tend to correlate comfort predictions, and hence the magnitudes of the behavioral and psychological adaptations that influence these comfort predictions, to a climate variable such as outdoor temperature [7].

The two schools of thought have led to two distinct thermal comfort models within ASHRAE Std. 55-2004 [16]: the Fanger heat balance model and the adaptive model for NV spaces. In the ASHRAE standard, the Fanger model is described as "the methodology that shall be used for most applications," while the adaptive model "may, *as an option*, be applied to spaces that meet [certain] criteria."

2.2. The Fanger heat balance model

The Fanger heat balance model, also widely known as the PMV model, was developed by P.O. Fanger in the late 1960s primarily based on laboratory and climate chamber research. While the general form of the human body energy balance (Eqn. 1) can be applied to both steady state and transient situations, the Fanger model assumes steady state conditions so that the internal heat production always equals the heat dissipation with no significant heat storage [19]. The model uses inputs to four environmental variables (air temperature, mean radiant temperature, air speed, and humidity) and two personal variables (metabolic rate and clothing insulation) to evaluate the steady state heat balance of the human body with the surrounding environment. The model's main equation calculates the difference between the internal heat production and the sum of the heat losses to the environment for a human being *hypothetically* kept at the comfort level of mean skin temperature (T_{skin}^{comf}) and the comfort level of evaporative heat loss due to sweating (E_{sw}^{comf}) for the actual metabolic rate. This difference is termed the thermal load *(L)*, and the equation described is the thermal load equation:

$$H - \sum Q_{loss}^{\boldsymbol{comf}} = L \tag{2}$$

H = rate of internal heat production, W/m^2

$\sum Q_{Loss}^{\boldsymbol{comf}}$ = total rate of heat loss to the environment for a human being kept at the *comfort* values of T_{skin} and E_{sw}, W/m^2

L = thermal load, W/m^2

The formulation of the thermal load equation is based on Fanger's assumptions that, under steady state conditions, for a human being to be at thermal comfort, three conditions must be met: 1) Heat balance must be maintained, 2) T_{skin} needs to be within a narrow range of values, and 3) E_{sw} needs to be within a narrow range of values. The first condition states that the internal heat production has to be balanced by the heat losses to the environment. Under steady state conditions, this is possible since the human thermoregulatory system will rely on its effector mechanisms, the regulatory efforts described in Section 2.1, to maintain homeostasis under a wide range of environmental conditions [19]. However, within this wide range of environmental conditions, previous research [20-24] has shown that there exists only a narrow interval within which human beings actually feel comfortable. This narrow interval corresponds to a limited range of values for T_{skin}^{comf} and E_{sw}^{comf}, which represent Fanger's second and third conditions for thermal comfort [19].

Since the thermal load equation models a human being hypothetically kept at the comfort values of T_{skin} and E_{sw}, L quantifies the deviation away from comfort and, according to Fanger [19], is a measure of the physiological strain upon the effector mechanisms. Under comfort conditions, the thermal load equation yields zero and L is zero. For all other conditions, L is non-zero and physiological strain upon the effector mechanisms is present. Under all conditions, the steady state heat balance is maintained.

It is important to keep in mind that the Fanger model does not actually model the change in T_{skin} or E_{sw} that one would actually experience under conditions away from comfort (Eqn. 3). The only T_{skin} and E_{sw} occurrences within the model are those at comfort. Changes to these physiological parameters under off-comfort conditions are accounted for within L (Eqns. 4, 5):

$$H - \sum Q_{loss} = 0 \tag{3}$$

$$H - \sum Q_{loss}^{\boldsymbol{comf}} - L = 0 \tag{4}$$

$$\sum Q_{loss} = \sum Q_{loss}^{\boldsymbol{comf}} - L \tag{5}$$

H =	rate of internal heat production, W/m^2
$\sum Q_{loss}$ =	total rate of heat loss to the environment for a human being kept at the *actual* values of T_{skin} and E_{sw}, W/m^2
$\sum Q_{Loss}^{\boldsymbol{comf}}$ =	total rate of heat loss to the environment for a human being kept at the *comfort* values of T_{skin} and E_{sw}, W/m^2
L =	thermal load, W/m^2

By doing this, Fanger was able to greatly simplify his model and also extract a measure for thermal load that could subsequently be correlated to thermal sensation vote, something which would not have been possible if the model had incorporated the dynamics of T_{skin} and E_{sw}.

An empirically-derived thermal sensation transfer coefficient (TS) multiplies L to yield the "Predicted Mean Vote" (PMV), the mean thermal sensation vote of a large group of people exposed to a particular environment [19]. This thermal sensation vote is measured on the ASHRAE seven-point thermal sensation scale [16]:

+3 hot
+2 warm
+1 slightly warm
0 neutral
-1 slightly cool
-2 cool
-3 cold

PMV is an estimate of the *mean* thermal sensation vote of a large group of people. Using an empirically-derived correlation, the PMV can also be transformed to the "Predicted Percentage of Dissatisfied" (PPD), which accounts for the variability in thermal sensation within a large group of people. Fanger defines PPD as the percentage of persons who are decidedly thermally dissatisfied, that is, those voting outside of -1 to +1 on the thermal sensation scale [19].

One of the main strengths of Fanger's model is that it accounts for the major physical variables influencing the human heat balance, and thus the relative effect of each of the variables on thermal comfort can be studied. Furthermore, the model has a physical basis, derived primarily from heat and mass transfer principles. Its major shortcoming is that, in its current form, it does not seem to be able to accurately predict comfort temperatures for NV environments, with some studies indicating discrepancies of up to 1.5 K [7, 9-12, 14, 15].

2.3. The adaptive model

The adaptive model was proposed by de Dear and Brager in the 1990s based on a statistical analysis of field study data taken in NV buildings. It is applicable exclusively to NV spaces in which operable windows adjustable by occupants serve as the "primary means of regulating the thermal conditions of the space." There must be no mechanical cooling system in the space, and the adaptive method does not apply when a heating system is in operation. Furthermore, occupants also need to be able to "freely adapt their clothing to the indoor and/or outdoor thermal conditions." The model is a simple linear regression that predicts the indoor operative temperature (T_{in}^{op}) necessary for comfort based on the mean monthly outdoor air temperature. It can only be applied to occupants at near sedentary activity levels and is valid within the mean monthly outdoor air temperature range of 10-33°C [16].

Some of the advantages of the adaptive model are its simplicity, making it easy for designers to use, and its ability to provide more accurate comfort temperature predictions for NV spaces than the current Fanger model can. One of its main weaknesses is that it does not include inputs for all of the six physical variables that are known to be important for determining thermal comfort.

2.4. Statement of problem

The Fanger model is currently the official model in ASHRAE Std. 55, while the adaptive model is an optional rather than required method for those spaces that meet the criteria of Section 2.3. Since it seems that the form of the Fanger model is preferred, it would be worth investigating if this type of model could be modified and improved to be applicable to NV buildings. There are several advantages to having such a model. A thermal comfort model that incorporates all six physical variables and that can be applied to NV spaces would allow designers to study the effect of each variable on the thermal comfort predictions in these spaces. For example, many work places enforce dress codes, and while this undoubtedly reduces the range of behavioral adaptation for occupants of NV buildings, there presumably would still be a certain amount of psychological adaptation due to lowered thermal expectations that could lead to a wider range of comfort temperatures. Yet such a scenario cannot be modeled using the adaptive model since clothing is defined as being adjustable and not as an input, so presently one would have to revert to the Fanger model which, however, has been shown to not work well in NV cases [7, 9-12, 14, 15].

In support of the adaptive model, De Dear [25, 26] has mentioned that providing accurate values for clothing insulation is difficult; while this may be true, a thermal comfort model for NV buildings that includes clothing as an input would at least allow one to study the uncertainty associated with this estimation; that is, one could input a range of clothing values that could serve as bounds to the thermal comfort prediction. Additionally, having a model for NV spaces that resembles in form the model currently used for HVAC spaces would facilitate the development of a thermal comfort model for spaces with hybrid ventilation.

Ultimately, however, the intention of this investigation is not to prove one model better than another, but rather to take a closer look at some of Fanger's assumptions and to offer the possibility of an alternative thermal comfort model applicable to NV buildings, one that could explain in more detail how this wider comfort temperature range is made possible. In summary, this research investigates how the Fanger model could be modified to apply to NV spaces, by first conducting a sensitivity analysis on the model's parameters using field study data from NV buildings and then proposing reasonable re-specifications of the most important parameters involved.

3. Methods

3.1. Data preparation

The data used in this analysis was obtained from the ASHRAE RP-884 project database [27] that is available to the public online. This database consists of thermal comfort field studies collected from both HVAC and NV buildings, altogether representing four continents and a wide spectrum of climate zones. The database includes comprehensive physical measurements of the local thermal environment, clothing insulation and metabolic rate estimates, outdoor meteorological recordings, and occupants' subjective ratings of thermal comfort including thermal sensation vote. Only those observations that had values for all the relevant physical variables (metabolic rate, clothing plus upholstery insulation level, indoor air and mean radiant temperature, air speed, relative humidity, and outdoor effective temperature) and a recording of the thermal sensation vote were included in the analysis. Additionally, observations with metabolic rates below 1.0 met or above 2.0 met and observations with insulation levels above 1.5 clo were discarded since the calculation of PMV using the ASHRAE computer model method [16] precludes such values. The database was thus reduced from 25,000 observations to roughly 16,000, 45% of which were recorded in 42 NV buildings and 55% in 133 HVAC buildings.

3.2. Data representation

The field study data was used to evaluate the accuracy of the Fanger model's comfort temperature predictions. This section describes the calculation of comfort temperatures

(T_{comf})[1] and the representation of the data in terms of mean outdoor effective temperature (ET^*_{out}), which is the temperature at 50% relative humidity that results in the same total heat loss from the skin as in the actual environment [17]. The methodology that was used in the development of the adaptive model [7] is followed quite closely. First, the building level was used as the statistical unit of analysis. Any linear regression fitted to a dataset of mean building values was weighted by the number of observations taken within each building. Since the field study experiments did not necessarily sample a thermal environment in which the majority of occupants of a particular building voted zero, the *observed* T_{comf} for each building was obtained by regressing the thermal sensation votes of that particular building against the corresponding T_{in}^{op} and solving the regression equation for neutral thermal sensation. Only the T_{comf} of those buildings with statistically significant regressions ($P < 0.05$) were retained. The *predicted* T_{comf} for these buildings were determined by inputting the mean value of metabolic rate, clothing insulation, airspeed, and relative humidity for each building into the Fanger model and solving the equation for the T_{in}^{op} (with air temperature equal to mean radiant temperature) at which $PMV = 0$.

[1] While some researchers have made distinctions between "neutral temperatures" and "comfort temperatures", the present investigation will use these terms interchangeably, in both cases meaning the T_{in}^{op} corresponding to a neutral thermal sensation, that is, a thermal sensation vote of zero.

Observed and Fanger model predicted T_{comf} were calculated for HVAC and NV buildings and regressed on ET^*_{out}, as shown in Figure 1.

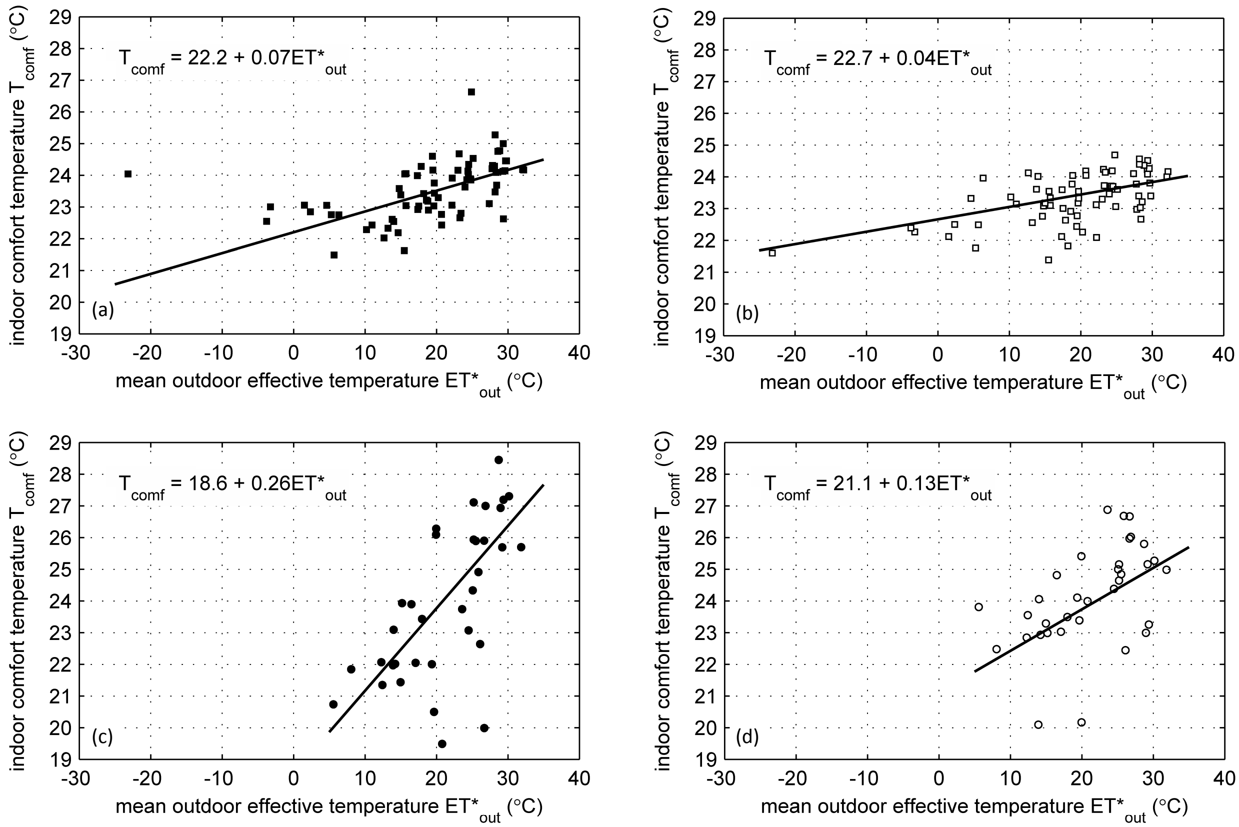

Fig. 1. (a) Observed T_{comf} for HVAC buildings. The weighted linear regression has an R^2 = 0.37 (P < 0.01). (b) Fanger model predicted T_{comf} for HVAC buildings. The weighted linear regression has an R^2 = 0.28 (P < 0.01). (c) Observed T_{comf} for NV buildings. The weighted linear regression has an R^2 = 0.49 (P < 0.01). (d) Fanger model predicted T_{comf} for NV buildings. The weighted linear regression has an R^2 = 0.23 (P < 0.01). Each data point shown represents the mean value for a single building.

The predicted T_{comf} regression lines are compared to observed T_{comf} regression lines in Figure 2. It is evident that the Fanger model's T_{comf} predictions for HVAC buildings are much better than its predictions for NV buildings. The discrepancy between prediction and observation is at most 0.5 K for HVAC buildings compared to about 1.5 K for NV buildings.

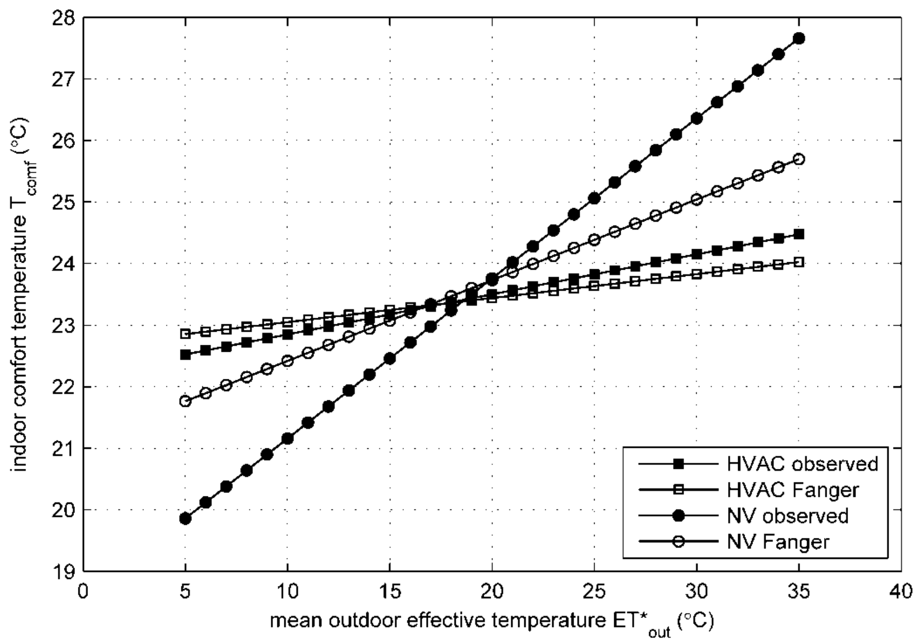

Fig. 2. Observed and Fanger model predicted T_{comf} regression lines for HVAC and NV buildings.

The Fanger model's ability to provide accurate comfort predictions for HVAC buildings has been supported by other studies as well, some of which adopted the semantic artifact hypothesis to match predicted to observed [7, 28].

As explained by Brager and De Dear [7, 28], the discrepancy between the predicted and observed T_{comf} regression lines for NV buildings cannot be attributed to behavioral adjustments since the Fanger model does incorporate clothing insulation and airspeed as inputs. That is, lower clothing levels or higher airspeed levels that are likely to be found in NV buildings are accounted for, so it seems that psychological effects are the only adaptive mechanism left to explain this discrepancy. One of the main questions, then, is how to incorporate the effects of psychological adaptation within the physiology and physics framework of the Fanger model to close this divide between prediction and observation. Since Fanger's model begins at the skin level, the actual psychological mechanisms are not modeled;

rather, any physiological manifestation of these psychological adaptations will serve as the starting point.

3.3. Revision of clothing area factor f_{cl}

To accurately model the heat fluxes in Fanger's model, a correction factor must be applied to the surface area of the nude body to account for the increase in surface area due to clothing. This correction factor is the clothing area factor f_{cl} and is defined as the ratio of clothing surface area to nude body surface area. The best way to determine f_{cl} is from measurements using the photographic silhouette method [17]. At the time of Fanger's derivation of his model in the early 1970s, only a limited number of measurements were available, quite a few of them of clothing ensembles unlikely to be found in workplaces today (>> 1.0 clo). Fanger [29] was still able to correlate f_{cl} to clothing insulation for use in his model but admitted himself that more investigations in this area were needed. This correlation was never updated, despite the fact that McCullough and Jones [30, 31] obtained new f_{cl} measurements in the 1980s from which they derived an updated f_{cl} correlation that can now be found in the 2005 ASHRAE Handbook of Fundamentals [17]. Figure 3 shows the experimental data available at the time Fanger derived his model, Fanger's f_{cl} correlation that is currently in the model, McCullough's newer data, and the updated f_{cl} correlation. Both correlations are plotted for clothing insulation values less than 1.5 clo, since the Fanger model cannot be applied to occupants with higher clothing values.

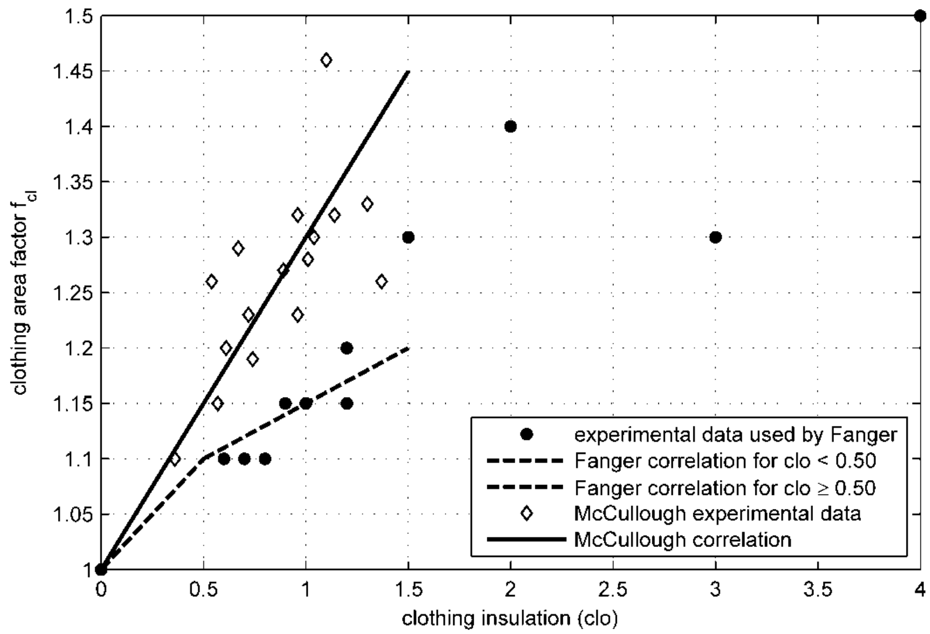

Fig. 3. Comparing Fanger's correlation (1970s) for the clothing area factor f_{cl} to McCullough's correlation (1984). The Fanger correlation for $clo < 0.50$ is $f_{cl} = 1 + 0.20 * clo$, for $clo \geq 0.50$, $f_{cl} = 1.05 + 0.10 * clo$. The McCullough correlation is $f_{cl} = 1 + 0.30 * clo$.

As can be seen, Fanger's f_{cl} relationship significantly underestimates the increase of surface area due to clothing, particularly at higher clothing insulation values. This means that the heat transfer is also underestimated, and the Fanger model would predict higher T_{comf} with the new relationship. Figure 4 shows how the T_{comf} predictions change when the new relationship is used. Since the difference is not entirely insignificant, approaching 0.5 K at low ET^*_{out} for both HVAC and NV regressions, the updated f_{cl} correlation will be used in subsequent analysis. *Any further references to or calculations using the Fanger model will be assumed to include this updated correlation.* Figure 5 shows both the predicted T_{comf} regression lines calculated using the updated f_{cl} correlation and the observed regression lines.

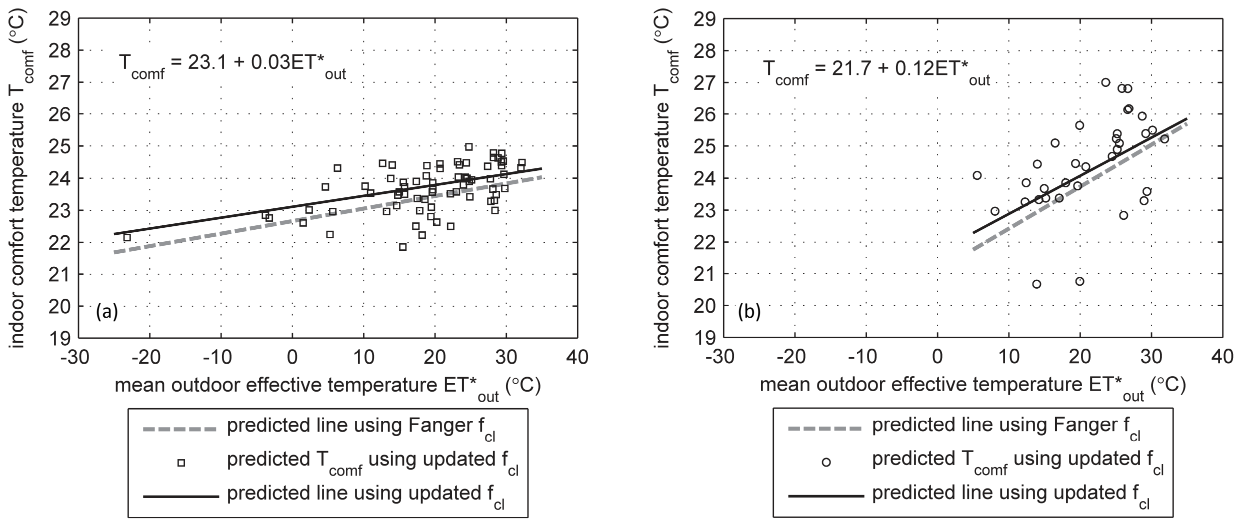

Fig. 4. (a) Predicted T_{comf} for HVAC buildings calculated using Fanger model with updated f_{cl} correlation. The weighted linear regression has an R^2 = 0.24 (P < 0.01). (b) Predicted T_{comf} for NV buildings calculated using Fanger model with updated f_{cl} correlation. The weighted linear regression has an R^2 = 0.22 (P < 0.01). The predicted regression lines calculated using the original Fanger model are also shown.

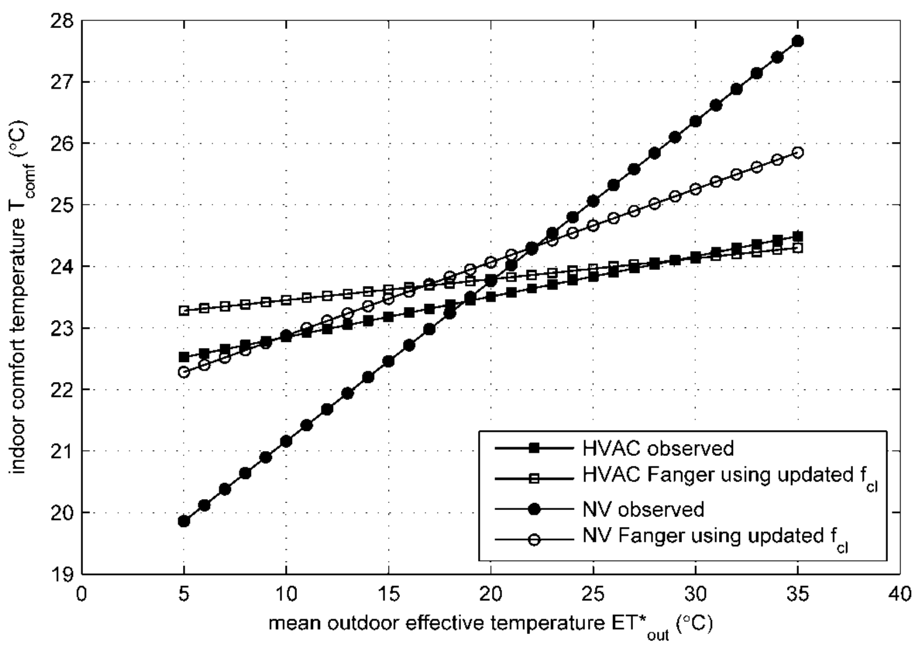

Fig. 5. Observed and Fanger model predicted T_{comf} regression lines for HVAC and NV buildings. Note that the Fanger model used to calculate the predicted regression lines includes the updated f_{cl} correlation.

It is evident that incorporating this new correlation does not really change the relative prediction error, that is, the updated Fanger model still predicts T_{comf} quite well for HVAC buildings but has much weaker predictive power for NV buildings. Hence, the focus of this investigation will be on improving the accuracy of the Fanger model's T_{comf} predictions for NV spaces.

3.4. Approach

Since the publication of ASHRAE RP-884's comprehensive field study database a decade ago, many researchers have made attempts at improving the Fanger model's comfort predictions for NV buildings to obtain better agreement with field study data. Modifications have ranged from improving the accuracy of the heat transfer terms, such as modeling the complex heat paths through multi-layer clothing in cold climates or the vapor permeability of clothing in humid climates, to black box and fuzzy logic models to Fanger's own extension of his model involving a multiplicative expectation factor and a reduction of metabolic rates in warm climates [32-37].

The current investigation assumes that the Fanger model captures the relevant physics, that is, the model's equations account for the dominant heat transfer terms affecting human heat balance. This assumption seems reasonable considering that the model's T_{comf} predictions are quite good for HVAC buildings (Fig. 5). The next step then is to examine the parameters that are contained in the heat transfer terms. Many of these parameters were derived from climate chamber experiments several decades ago, with some experiments conducted at rather small sample sizes, and the model has not been updated since as is evident by the previous section on revising the clothing area factor. This research utilizes sensitivity analysis to first determine the parameters to which the T_{comf} prediction is most sensitive and then explores reasonable re-specifications of these parameters to improve the Fanger model's thermal comfort predictions for NV buildings.

3.5. Overview of sensitivity analysis

The parameters included in the sensitivity analysis are all the coefficients contained in the Fanger model equations, not including those pertaining to the already re-specified f_{cl} correlation nor any physical constants or properties. A full list with descriptions can be found in Table 1. The majority of them are empirically-derived coefficients, and the rest are either approximations or assumptions made by Fanger [19].

Table 1. Fanger model parameters included in sensitivity analysis

Parameter	Value in Fanger model	Units	Derivation
Permeance coefficient of the skin	$1.27 * 10^{-9}$	$\frac{kg}{Pa\,s\,m^2}$	Determined from analysis of empirical data [38]
Constant of T_{skin}^{comf} - M regression equation	35.7	$°C$	Determined from analysis of empirical data [29]
Gradient of T_{skin}^{comf} - M regression equation	-0.028	$\frac{°C\,m^2}{W}$	Determined from analysis of empirical data [29]
Gradient of E_{sw}^{comf} - M regression equation	0.42	[ ]	Determined from analysis of empirical data [29]
M at which there is no sweat secretion at thermal comfort	58.15	$\frac{W}{m^2}$	Assumption made by Fanger [29]
Coefficient correlating pulmonary ventilation to M	$1.43 * 10^{-6}$	$\frac{kg}{J}$	Determined from analysis of empirical data [39]
Coefficient to determine difference in humidity ratio between expired and inspired air	0.0277	[ ]	Determined from analysis of empirical data [40]
Coefficient to determine difference in humidity ratio between expired and inspired air	0.0013	[ ]	Determined from analysis of empirical data [40]
Coefficient to determine difference in humidity ratio between expired and inspired air	-0.80	[ ]	Determined from analysis of empirical data [40]
Temperature of expired air	34	$°C$	Approximation made by Fanger [19]
Constant in heat transfer coefficient equation for natural convection	2.38	$\frac{J}{s\,m^2\,°C^{5/4}}$	Determined from analysis of empirical data [41]
Constant in heat transfer coefficient equation for forced convection	12.1	$\frac{J}{s^{1/2}\,m^{5/2}\,°C}$	Determined from analysis of empirical data [42]
Ratio of effective radiation area to surface area of clothed body	0.71	[ ]	Determined from analysis of empirical data [19]
Emittance of outer surface of clothed body	0.97	[ ]	Approximation made by Fanger [19]

Each parameter was varied from -10% to +10% of its original value with the other parameters held constant at their original values. At each 1% increment, the predicted T_{comf} regression line was calculated using the field study data for NV buildings and plotted. The next section will present and discuss the results of the sensitivity analysis.

4. Results

The results of the sensitivity analysis are shown in Figures 6 and 7. For brevity, only a few sensitivity plots are shown in Figure 6; these are representative of the behavior of the majority of the parameters included in the analysis. Figure 7a clearly shows the predicted T_{comf} regression lines plotted at each 1% change in parameter value as well as the original prediction line obtained using Fanger's values for all the parameters.

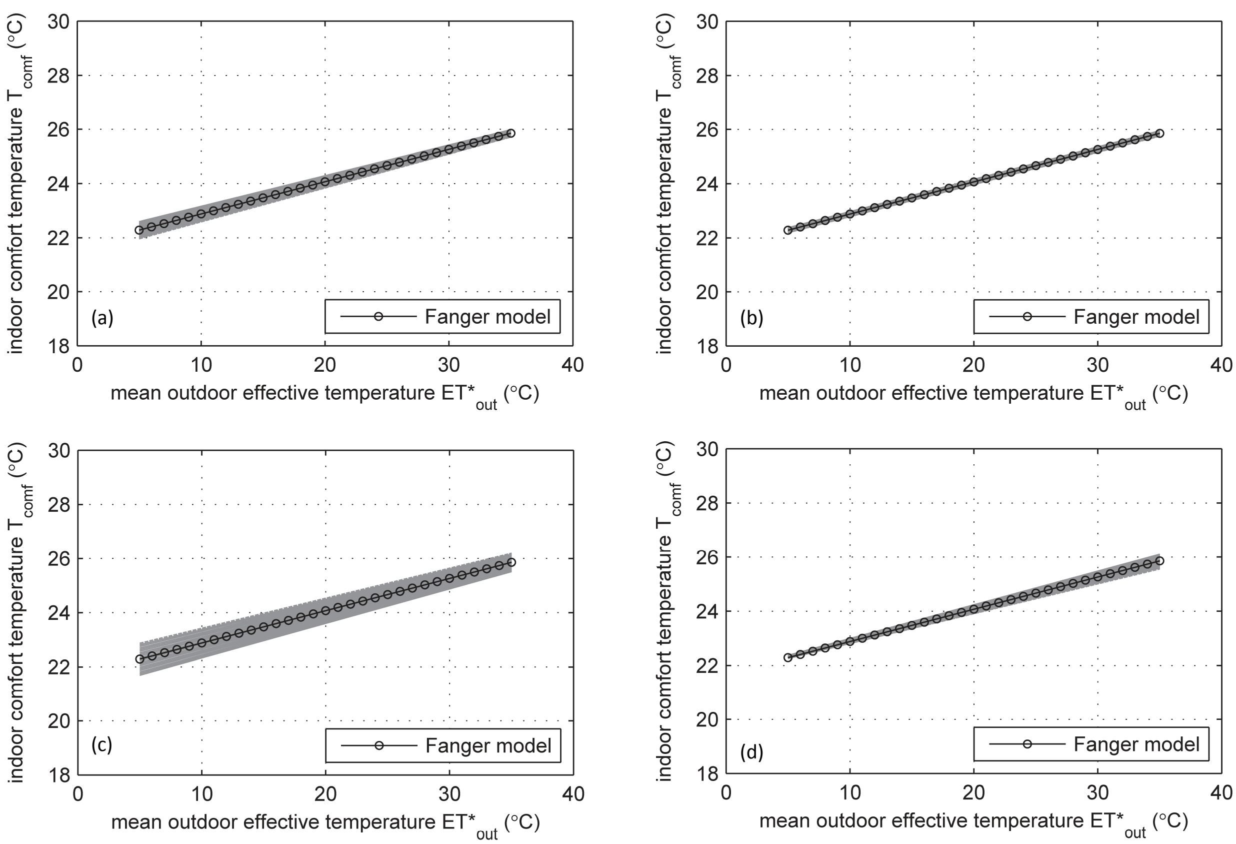

Fig. 6. Sensitivity plots of a representative set of parameters. (a) Permeance coefficient of the skin. (b) Gradient of E_{sw}^{comf} - M regression equation. (c) M at which there is no sweat secretion at thermal comfort. (d) Constant in heat transfer coefficient equation for forced convection. Each parameter's value was changed from -10% to +10% of its original value, and the predicted T_{comf} regression line was calculated and plotted at 1% increments. The original prediction line, calculated using Fanger's values for all the parameters, is also shown. The T_{comf} regression line's low sensitivity to these parameters results in tight gray bands centered on the original prediction line, as shown.

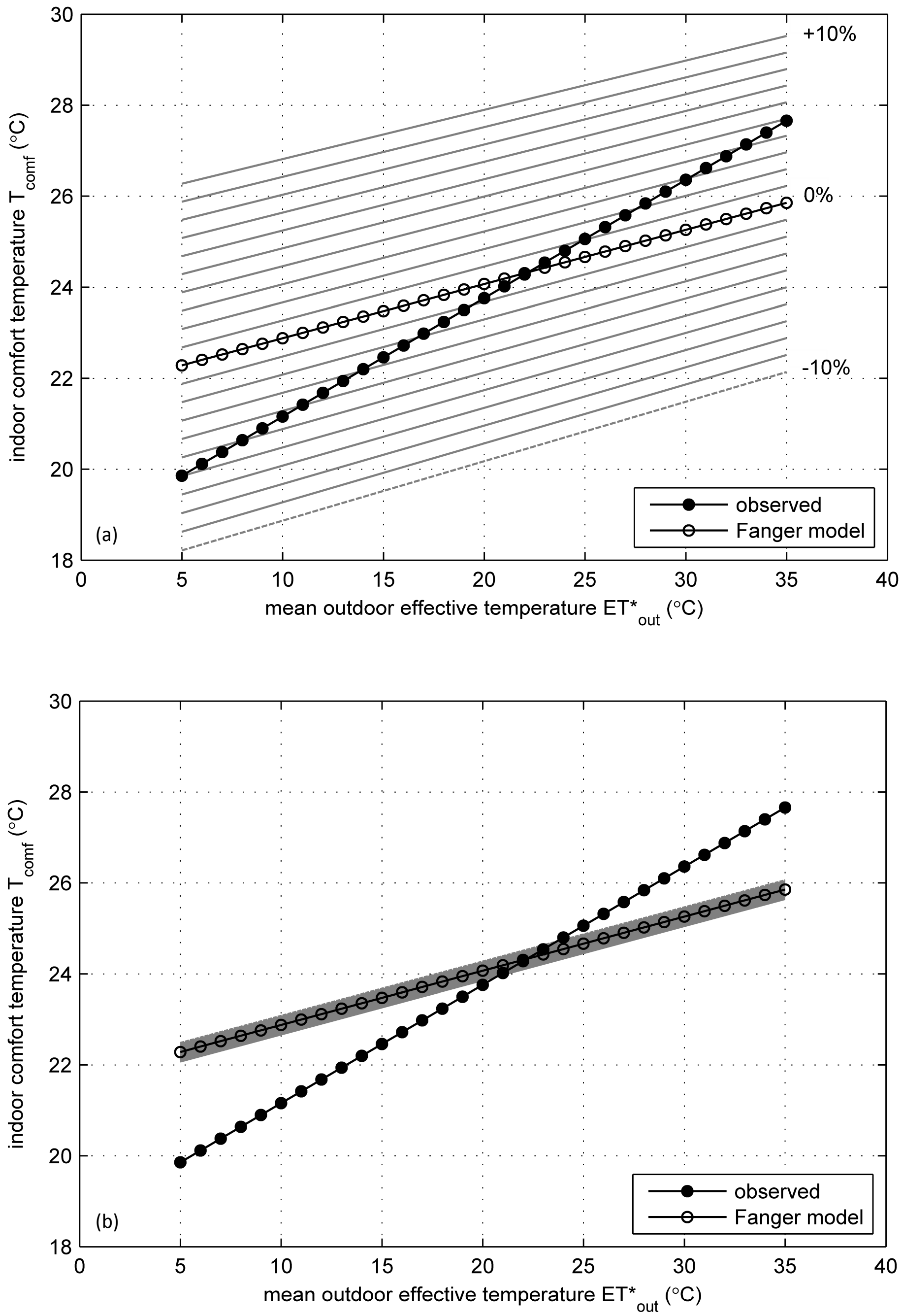

Fig. 7. Sensitivity plots of parameters in T_{skin}^{comf} correlation. (a) Constant of T_{skin}^{comf} - M regression equation. (b) Gradient of T_{skin}^{comf} - M regression equation. Each parameter's value was changed from -10% to +10% of its original value, and the predicted T_{comf} regression line was calculated and plotted at 1% increments. The original prediction line, calculated using Fanger's values for all the parameters, as well as the observed T_{comf} regression line are also shown.

4.1. Importance of mean skin temperature

The sensitivity analysis revealed that there indeed is a parameter to which the T_{comf} prediction happens to be much more sensitive to than all other parameters -- this parameter is the regression constant of the correlation between T_{skin} and metabolic rate (M) that Fanger [19] obtained from climate chamber experiments *under comfort conditions*:

$$T_{skin}^{comf} = 35.7 - 0.028M \tag{6}$$

where T_{skin}^{comf} is in °C and M has units of W/m^2. The original data and regression are shown in Figure 8. Since these experiments were conducted under comfort conditions, the ambient temperature was lowered as M increased. All other experimental conditions were held constant, so lower ambient temperatures also yielded lower T_{skin}. Hence, the gradient of the regression line is negative.

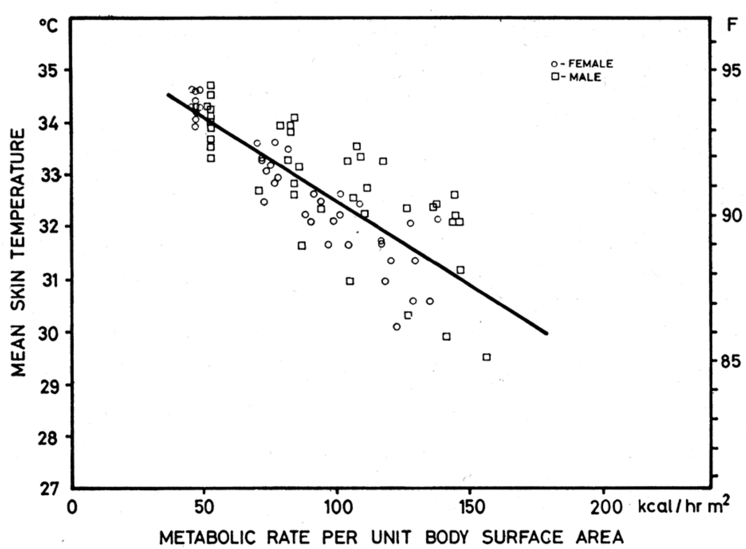

Fig. 8. Fanger's T_{skin}^{comf} to M correlation obtained from climate chamber experiments. Note that these experiments were conducted *under comfort conditions*, that is, the ambient temperature was lowered as M increased [19].

Figure 7a shows the sensitivity analysis for Fanger's T_{skin}^{comf} - M regression constant. Comparing the plots of Figures 6 and 7, the difference in sensitivities can be deduced qualitatively immediately. A 3% change in the value of the regression constant alters T_{comf} by 1 K (Fig. 7a), while a 10% change in any one of the other parameters does not produce nearly such a substantial shift (Figs. 6, 7b). Since the T_{comf} predictions are highly sensitive to the T_{skin}^{comf} - M regression constant and largely insensitive to the other parameters, a reasonable first step would be to consider whether this parameter, or more generally T_{skin}^{comf}, needs to be re-specified. The following section presents the rationale behind the proposed re-specification of T_{skin}^{comf}.

5. Discussion

5.1. Accounting for sampling error in Fanger's T_{skin}^{comf} specification

A first step in re-specifying T_{skin}^{comf} to improve the Fanger model's comfort predictions for NV buildings might be to address the sampling error in Fanger's T_{skin}^{comf} - M regression. Looking at Figure 8, the data does exhibit quite a bit of scatter; this particular experiment included a mere twenty test subjects [29], a very small sample size for trying to determine a parameter to which the model happens to be highly sensitive. Consequently, large sampling error leading to large confidence intervals for the regression constant and coefficient is likely [43], so the true regression between M and T_{skin}^{comf} might be quite different from what Fanger obtained.

This can be investigated using the sensitivity plots of the T_{skin}^{comf} - M regression constant and coefficient, shown in Figures 7a and b with the observed T_{comf} regression lines also plotted. Looking at these, it is evident that any change in the constant or any change in the gradient, basically *any* other T_{skin}^{comf} - M regression line, will only shift the prediction line up and down, but is not capable of rotating it to better match the observed line. This is key: for Fanger's prediction to match up with observation, the prediction line needs to rotate. Figure 9 illustrates how changing the value of either or both of these two regression parameters does not produce a rotation. So accounting for sampling error in the T_{skin}^{comf} - M regression by considering regression lines other than the one Fanger obtained does not actually improve the model's predictive power for NV buildings.

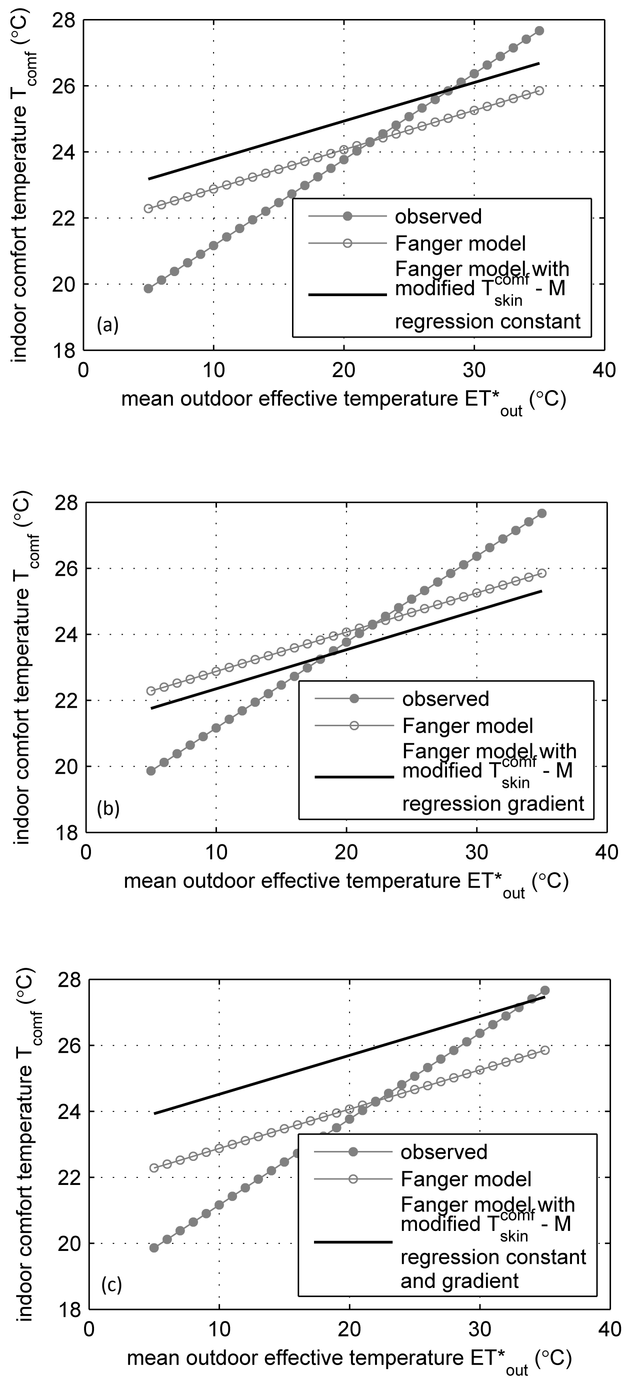

Fig. 9. Predicted T_{comf} regression lines for NV buildings calculated using a Fanger model with modified T_{skin}^{comf}. (a) Changing the value of the T_{skin}^{comf} - M regression constant from 35.7 to 36.5. (b) Changing the value of the T_{skin}^{comf} - M regression coefficient from -0.0280 to -0.0350. (c) Changing the value of the T_{skin}^{comf} - M regression constant and coefficient from 35.7 to 36.3 and -0.0280 to -0.0150, respectively. The observed regression line and the predicted regression line calculated using the original Fanger model are also shown.

Furthermore, such a re-parameterization would affect the Fanger model's T_{comf} predictions not only for NV buildings but also for HVAC buildings, since a re-specification of T_{skin}^{comf} based on sampling errors does not distinguish between the two ventilation strategies. As demonstrated in Section 3.2, the Fanger model's predictions for HVAC buildings already agree with field study results quite well, so any re-specification of T_{skin}^{comf} is likely to adversely affect the accuracy of these predictions even while improving the model's accuracy for NV buildings. The prediction error for HVAC buildings is not of the same order as the prediction error for NV buildings. So revising T_{skin}^{comf} based on sampling errors would lead to a single model that cannot provide accurate predictions for *both* HVAC and NV environments.

5.2. Re-specifying T_{skin}^{comf} exclusively for occupants of NV spaces

To preserve the Fanger model's predictive power for HVAC spaces, could T_{skin}^{comf} be re-specified solely for occupants of NV spaces? Fanger [19] obtained the T_{skin} measurements shown in Figure 8 from climate chamber experiments conducted under comfort conditions, meaning the T_{in}^{op} was set to levels at which the test subjects subjectively expressed thermal comfort. But if there exist differences in the conditions climate chamber test subjects and occupants of NV spaces find comfortable (or even in the conditions climate chamber test subjects and occupants of HVAC spaces find comfortable), then the experiments would need to be repeated for the other comfort conditions. And if the experiments show that the different comfort conditions indeed correlate to different T_{skin}^{comf} measurements, then the Fanger model would *not* be applicable to these other environments since it is the *climate chamber definition* *of* T_{skin}^{comf} that is embedded in Fanger's parameterization.   Fortunately, as shown in Section 3.2 and other studies [7, 9, 13], the Fanger model has good predictive power for HVAC spaces, so it seems that climate chamber test subjects and occupants of HVAC spaces prefer similar conditions at comfort. Consequently, the T_{skin}^{comf} measurements that were obtained at the comfort conditions of climate chamber test subjects are likely to apply to occupants of HVAC spaces as well. However, the same might not be true of occupants in NV spaces. In warm climates, it has been observed that these occupants express thermal comfort at T_{in}^{op} that are higher than those found in HVAC buildings at comfort (Fig. 5) and hence also higher than those found in climate chambers at comfort. This means that the comfort conditions of occupants of NV buildings are not the same as those at which the Fanger experiments were conducted, and one might hypothesize then that their corresponding T_{skin}^{comf} might also be different, all other experimental conditions held constant. If this was true, then the T_{skin}^{comf} specification in the Fanger model could be modified exclusively for occupants of NV buildings, and Fanger's definition [19] of a single T_{skin}^{comf} per M would be incorrect.

Using Fanger's thermal load equation and his assumption that comfort is the condition of zero thermal load, it can be shown that higher T_{skin}^{comf} do necessitate higher T_{in}^{op} at comfort. For a given metabolic heat generation, if T_{skin}^{comf} is higher, T_{in}^{op} also needs to be higher at comfort to maintain the temperature gradient of skin to environment and thus the magnitude of the heat loss that yields the zero thermal load required for comfort. The question it comes down to, then, is *how* occupants of NV spaces in warm climates could tolerate T_{skin}^{comf} that are higher than the values Fanger determined from his climate chamber studies. As discussed in

Section 3.2, psychological adaptation plays an essential role in widening the T_{comf} range for occupants of NV buildings, and hence the question of how to incorporate the effects of this psychological adaptation within the Fanger model is key to improving the accuracy of its predictions for NV buildings. Current adaptive theory does not provide a relationship between psychological adaptation and the physiological requirements of thermal comfort. However, based on the current discussion, it seems reasonable to hypothesize that psychological adaptations such as lowered thermal expectations could be allowing occupants of NV buildings in warm climates to feel comfortable at the higher T_{skin} needed to maintain zero thermal load at the higher T_{in}^{op}. So what has been observed in the field, that T_{comf} are higher in warm climates for occupants of NV buildings than occupants of HVAC buildings, could also be explained by the influence of psychological adaptation on the physiological requirements of thermal comfort.

It is important to point out that suggesting to improve the T_{skin}^{comf} model to account for the thermal comfort preferences of occupants of NV buildings is merely an extension of what Fanger has done already. In his experimental studies [19], Fanger sampled the subjective thermal comfort preferences and consequently the psychological state of climate chamber subjects only; these results happened to match those of occupants of HVAC buildings fairly closely. Fanger thus seeded his model with a certain definition of T_{skin}^{comf}; if there exists a different definition of T_{skin}^{comf} for occupants of NV buildings because of psychological adaptation, then this would yield different T_{comf} to maintain zero thermal load. It is then perfectly reasonable to suggest that the experiments to determine T_{skin}^{comf} should be repeated in the field for occupants of NV buildings, since their thermal comfort preferences and psychological state hold a different but equally valid position in the construction of thermal comfort models.

5.3. Shifts vs. rotations of the predicted T_{comf} regression line

Prior to doing the actual experiments, it is possible to consider how T_{skin}^{comf} could be re-specified to yield improved T_{comf} predictions for NV buildings. Section 5.1 demonstrated how modifying the T_{skin}^{comf} - M regression equation by changing the value of its constant and/or gradient term only shifts the prediction line up and down, while what is really needed is a rotation for predicted T_{comf} to better agree with observed. The reason for shifts, rather than rotations, is that Fanger defined T_{skin}^{comf} in terms of only one variable, M. For any T_{skin}^{comf} - M regression line one can imagine, T_{skin}^{comf} is still only *one value* per M. If one accepts that M does not depend on climate [28], then occupants with similar M should be found in regions where ET_{out}^{*} is low as where ET_{out}^{*} is high. If this is the case, then if a higher T_{skin}^{comf} value for a given M is considered (if, for example, the true T_{skin}^{comf} happens to be higher than what Fanger originally determined), T_{skin}^{comf} would increase for any data points that have that particular M, and since such data points are randomly distributed within the range of ET_{out}^{*}, the predicted T_{comf} regression line would shift straight up with no rotation (such as in Fig. 9a). For the prediction line to rotate and match observed, T_{skin}^{comf} needs to take on a specific *range of values* for a given M, that is a higher value at high ET_{out}^{*} and a lower value at low ET_{out}^{*} for the same M. Because of this specific requirement, incorporating the variability in T_{skin}^{comf} estimates due to factors such as individual or gender differences, the effect of circadian rhythm, and different measurement and weighting techniques for determining mean skin temperature [44-47], would also not rotate the T_{comf} prediction line since any errors due to variability are randomly distributed and not systematically a function of ET^{*}_{out}.

5.4. Re-specifying T_{skin}^{comf} by correlating it to an outdoor climate variable

If the sensitivity analysis had shown that as the T_{skin}^{comf} - M regression constant is changed, the gradient of the predicted T_{comf} regression line changes, or if it had shown that some of the other parameters could influence the gradient significantly, then one could argue that adjusting the numerical values of the most sensitive parameters might be sufficient in aligning the Fanger model's predictions with field study results for NV buildings. Since the sensitivity analysis did not show this, it seems that the most sensitive parameters need to be re-specified in ways beyond simple changes to their numerical values. As presented in Section 5.3, for prediction to better match observation, T_{skin}^{comf} needs to be higher at high ET^{*}_{out} and lower at low ET^{*}_{out} for a given M. So a reasonable modification would involve changing T_{skin}^{comf} from a fixed value per M to a range of values per M that depends on ET^{*}_{out}, which would mean that the most sensitive parameter, the T_{skin}^{comf} - M regression constant, is re-specified to be a function of ET^{*}_{out}. Similar to the adaptive model, an outdoor climate variable is used to quantify the magnitude of the psychological adaptation; however, the distinction is that here the psychological adaptation is hypothesized to extend the range of T_{skin} at which occupants of NV buildings feel comfortable.

What might this relationship between T_{skin}^{comf} and ET_{out}^{*} look like? A first guess might be a simple linear relationship. A first order estimate of 33.1 - 35.1°C is used as a plausible range of T_{skin} within which psychological adaptation would allow near sedentary occupants of NV spaces to still vote neutral and express thermal comfort. These values, amounting to a mere 1°C bound on Fanger's original T_{skin}^{comf} value of 34.1°C for near sedentary activity level, are physiologically possible values for T_{skin}^{comf}, as can be seen by Fanger's own experimental data (Fig. 8). Figure 7a, which is the sensitivity plot for the T_{skin}^{comf} - M regression constant, can be used to approximate what ET_{out}^{*} these T_{skin}^{comf} values need to correspond to for the prediction line to match up with observation (the mean M of the dataset that was used to generate this plot is also near sedentary). This yields T_{skin}^{comf} = 33.1°C at ET_{out}^{*} = 13.8°C and T_{skin}^{comf} = 35.1°C at ET_{out}^{*} = 30°C. This means that in NV spaces, because of psychological adaptations, at an ET_{out}^{*} ≈ 14°C most sedentary occupants will vote neutral if their T_{skin} ≈ 33°C, and at an ET_{out}^{*} ≈ 30°C most sedentary occupants will vote neutral if their T_{skin} ≈ 35°C. In comparison, the original specification by Fanger [19] states that most sedentary occupants will vote neutral at a T_{skin} ≈ 34°C, regardless of what the ET_{out}^{*} is. With this pair of ET_{out}^{*} - T_{skin}^{comf} coordinates, the line that predicts T_{skin}^{comf} for any ET_{out}^{*} can be determined. Appending this to Fanger's T_{skin}^{comf} - M regression equation, hence effectively changing the value of the regression constant, a function that linearly relates T_{skin}^{comf} to not only M, but also to ET_{out}^{*} is obtained:

$$T_{skin}^{comf} = (0.124ET_{out}^{*} - 2.704) + (35.7 - 0.028M) \tag{7}$$

where T_{skin}^{comf} is in °C, and M has units of W/m^2. Figure 10 shows the predicted T_{comf} for NV buildings calculated using this new T_{skin}^{comf} model. The Fanger model predictions are also plotted for comparison. The new prediction line is compared to the observed line in Figure 11. As can be seen, a Fanger model with a T_{skin}^{comf} - ET_{out}^{*} correlation can yield a predicted T_{comf} regression line that is a near perfect match to the observed line for NV buildings.

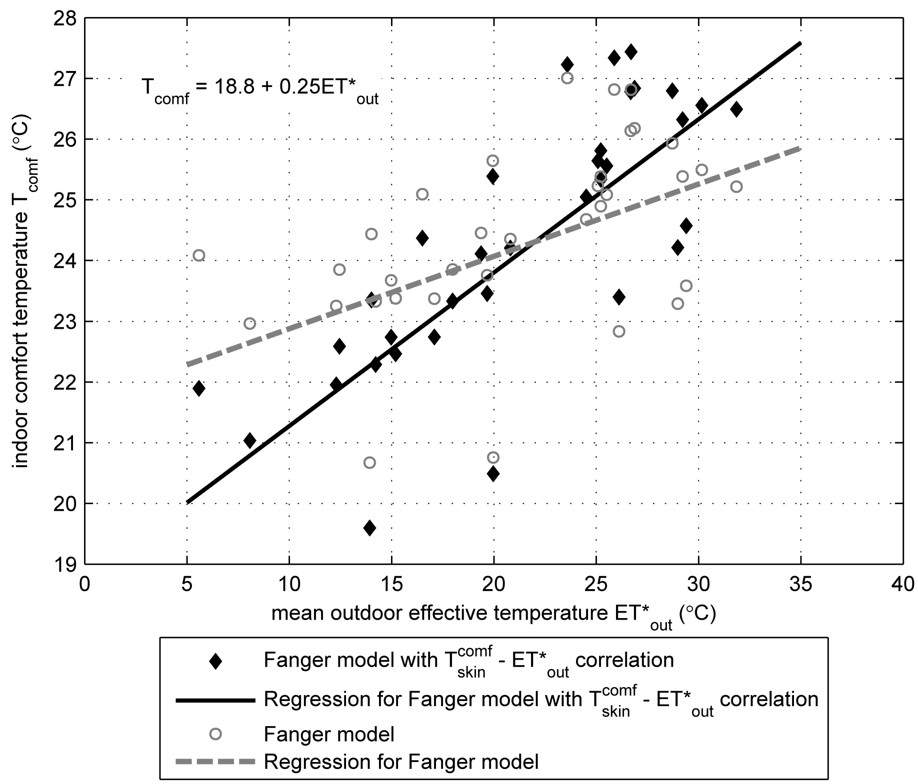

Fig. 10. Predicted T_{comf} for NV buildings calculated using a Fanger model with a T_{skin}^{comf} - ET_{out}^{*} correlation. The weighted linear regression has an R^2 = 0.57 (P < 0.01). The original Fanger model predicted T_{comf} and regression line are also shown.

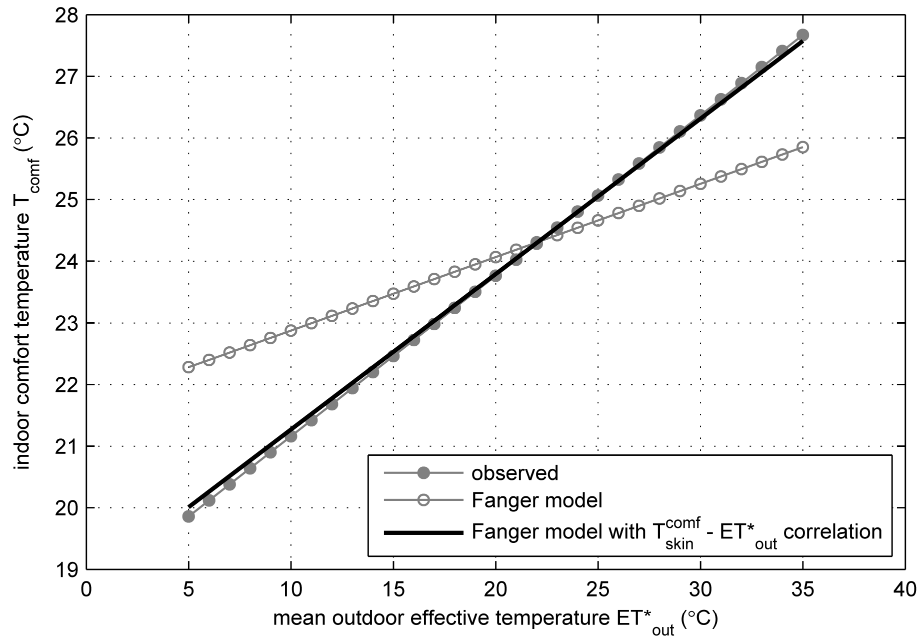

Fig. 11. Predicted T_{comf} regression line for NV buildings calculated using a Fanger model with a T_{skin}^{comf} - ET_{out}^{*} correlation. The observed regression line and the predicted regression line calculated using the original Fanger model are also shown.

In regards to Fanger's assumption that comfort is the condition at zero thermal load (Section 2.2), the above numerical values also make sense. At an ET_{out}^{*} of 30°C, the observed T_{comf} for NV buildings is about 1°C higher than Fanger's prediction for the same values of clothing, metabolic rate, airspeed, and relative humidity (Fig. 5). A T_{skin}^{comf} estimate of 35.1°C at this ET_{out}^{*} is exactly a 1°C increase in T_{skin}^{comf} from Fanger's original value of 34.1°C. Hence, for a given M, a 1°C increase in T_{skin}^{comf} yields a 1°C increase in T_{comf}, so the requirement of zero thermal load at comfort is maintained.

Naturally, one might assert that referencing the sensitivity plot to determine the exact T_{skin}^{comf} - ET_{out}^{*} functional relationship would undoubtedly result in a near perfect fit to observed, and that is true. The intention of the current investigation is not to deliver the exact functional form for a new thermal comfort model but rather to illustrate that a rotation in the prediction line is necessary and that such can be accomplished if T_{skin}^{comf} is correlated to ET_{out}^{*} in addition to M. The values used to determine this correlation, while probably not precise, are reasonable first order estimates to highlight a point. The present analysis offers a plausible hypothesis for improving the Fanger model's predictions for NV buildings, and to obtain the actual functional form of T_{skin}^{comf}, focused experiments in HVAC, NV, and mixed-mode buildings are needed. These field study experiments might show that accommodating for ET_{out}^{*} improves the prediction but some of the other, less sensitive parameters need to change also, or that the missing variable does not have to be ET_{out}^{*} but can be another climate variable to which T_{skin}^{comf} correlates, or maybe even that occupants' T_{skin}^{comf} are really invariant to the different ventilation strategies, in which case improving the Fanger model's thermal comfort predictions for NV buildings might require more invasive modifications beyond the sole re-specification of parameters.

5.5. From T_{comf} to PMV predictions

The present investigation so far has only focused on modifying Fanger's thermal load equation to yield better temperature predictions for the comfort condition, that is, the condition of zero thermal load and at which occupants vote neutral. The Fanger model is widely known as the PMV model, which refers to its ability to analyze conditions away from neutral using the PMV index on the ASHRAE seven point scale of thermal sensation. The thermal load obtained from the heat balance equation is transformed to a PMV via a multiplicative thermal sensation transfer coefficient that Fanger [19] derived from climate chamber experimental studies involving a large number of subjects. Since these experiments were conducted in climate chambers, and the subjective thermal comfort preferences and hence the psychological state of only climate chamber test subjects were recorded, it is likely that the TS takes on a different value for occupants of NV buildings, similar to how the T_{skin}^{comf} specification needed to be reconsidered. This section discusses how the TS might be modified, and how the PMVs of a Fanger model with a modified T_{skin}^{comf} and TS compare to observed votes for NV buildings.

Figure 12 shows the observed and original Fanger model predicted thermal sensation votes for the NV buildings in the field study.

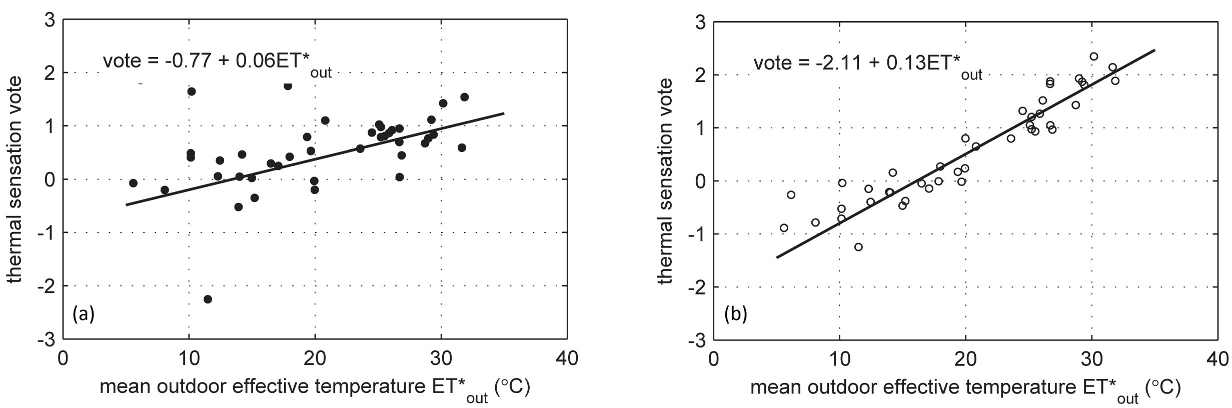

Fig. 12. (a) Observed thermal sensation votes for NV buildings. The weighted linear regression has an R^2 = 0.40 (P < 0.01). (b) Fanger model predicted thermal sensation votes for NV buildings. The weighted linear regression has an R^2 = 0.90 (P < 0.01). Note that all buildings, not just those with statistically significant regressions, are included here, since the calculation of thermal sensation votes did not require interpolation of building-level regressions as was done for the calculation of T_{comf}.

The predicted vote regression line calculated using a Fanger model that contains the T_{skin}^{comf}-ET_{out}^{*} correlation derived in the last section is compared to the original Fanger model prediction line and the observed line in Figure 13. It is evident that the new model can reduce the error between Fanger's predictions and the observed votes by almost half; however, the new model still under- or over-estimates by more than 0.5 vote units in the extremes of the

ET^*_{out} range. If the TS can be modified to account for the psychological adaptation that influences the thermal comfort preferences of occupants of NV buildings, this error might be greatly reduced.

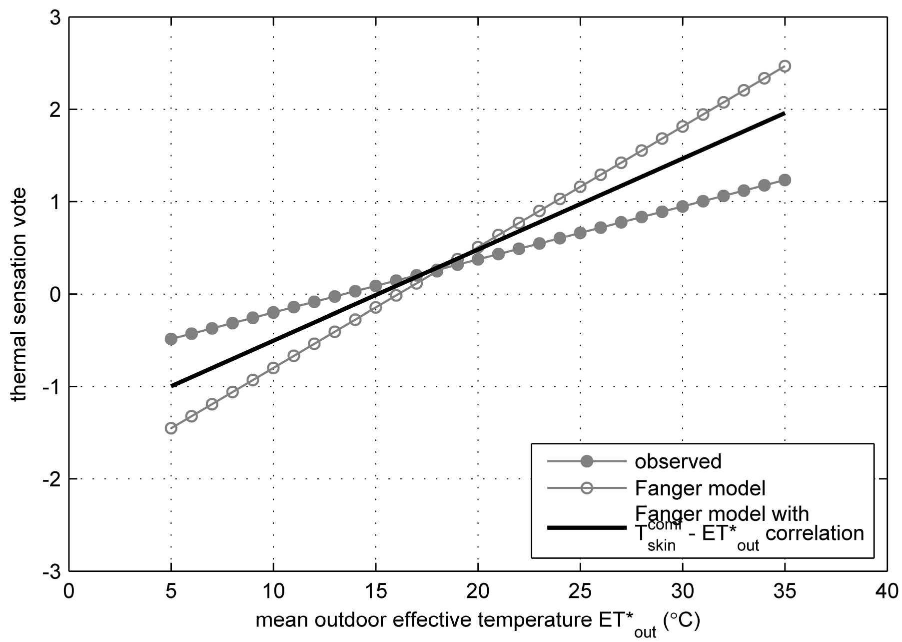

Fig. 13. Predicted thermal sensation vote regression line for NV buildings calculated using a Fanger model with a T^{comf}_{skin} - ET^*_{out} correlation. The observed vote regression line and the predicted vote regression line calculated using the original Fanger model are also shown.

As a first estimate, it is possible to test this hypothesis prior to conducting actual experiments by relying on a regression analysis of the field study data and a few assumptions. Since the data was obtained from studies in actual NV buildings, the thermal comfort preferences and psychological state of the occupants were captured. Following is a summary of the procedure Fanger used in deriving his TS as well as the author's slightly modified procedure used in deriving a new TS applicable to NV buildings only. Please keep in mind that Section 5.5.2 is intended merely to illustrate an idea and that the derived TS is not meant to be definitive -- experiments clearly need to be conducted to determine the true functional form of the TS.

5.5.1. Fanger's procedure for deriving his TS

TS is the coefficient that translates thermal load to PMV. That is, $PMV = TS * L$. TS is a function of M. To obtain a value for TS, Fanger needed to relate L to PMV, but since L is not a measurable quantity, he first carried out controlled climate chamber experiments to determine the relationship between T_{in}^{op} and PMV. As T_{in}^{op} was varied and metabolic rate, clothing level, airspeed, and relative humidity were kept constant at their experimental values, test subjects recorded their thermal sensation votes, and a linear equation relating PMV to T_{in}^{op} was obtained. Next, Fanger used the same experimental values as inputs to his thermal load equation to determine the equation relating T_{in}^{op} to L. Both steps were repeated for four different activity levels and combining each set of two equations by substituting for T_{in}^{op} yielded PMV as a function of L for different activity levels, from which TS was readily deduced. In Fanger's model,

$$TS = 0.303e^{-0.036M} + 0.028 \tag{8}$$

where M is in W/m^2 and TS has units of m^2/W [19].

5.5.2. Procedure used in deriving a new TS applicable to occupants of NV spaces

Using the field study data instead of data from controlled experiments, the critical first step in Fanger's TS derivation -- determining the relationship between T_{in}^{op} and PMV -- can still be carried out. First, a weighted multiple linear regression was fitted to the data, that is, observed thermal sensation vote was regressed onto the physical variables that influence thermal comfort: metabolic rate, clothing level, indoor operative temperature, airspeed, and relative humidity. The assumption of normalized residuals underlying linear regression [43] was shown to be valid for the given data. ET^*_{out} was not included as an independent variable in the regression model since ET^*_{out} and T^{op}_{in} are highly correlated with an R^2 = 0.85 (Fig. 14), so including both of these would have lead to spurious regression coefficients [43].

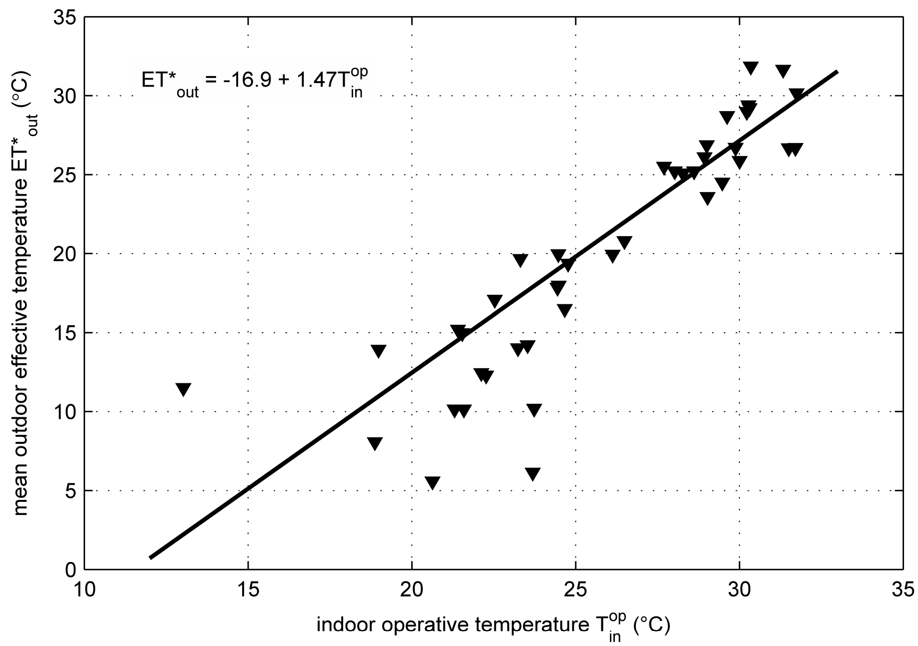

Fig. 14. Correlation of T^{op}_{in} to ET^*_{out} for NV buildings. The weighted linear regression has an R^2 = 0.85 (P < 0.01).

The multiple linear regression equation describes each physical variable's unique effect on PMV, and hence is a statistical method of conducting controlled experiments. To match Fanger's experimental procedure, the next step was to isolate the effect of T^{op}_{in} on PMV, so the regression equation was evaluated at his experimental values for metabolic rate, clothing level, airspeed, and relative humidity, yielding the desired linear equation relating PMV to T^{op}_{in}.

To determine the relationship between T_{in}^{op} and L, the same experimental values were used as inputs to the modified thermal load equation that has T_{skin}^{comf} correlated to ET_{out}^{*}. What values should be used for ET_{out}^{*}? Since T_{in}^{op} and ET_{out}^{*} are highly correlated, it would make sense to define ET_{out}^{*} in terms of T_{in}^{op} for the purposes of this analysis (Fig. 14). Following the substitutions, an equation relating T_{in}^{op} to L was obtained. The steps were repeated for sedentary (58 W/m^2) and low activity level (93 W/m^2) rather than four activity levels as in Fanger's derivation, since the majority of the field study data for NV buildings is comprised of M near sedentary. Again, each set of two equations was combined by substituting for T_{in}^{op}, yielding PMV as a function of L for different activity levels, which was then used to determine TS:

$$TS = -1.003 * 10^{-4} M + 0.039 \tag{9}$$

where again M is in W/m^2 and TS has units of m^2/W. When evaluated for near sedentary activity level, the new TS is approximately half of Fanger's TS value (Eqn. 8) for the same activity level. The implications of this will be discussed in Section 5.6.

5.5.3. Evaluating the new model

The new TS together with the T_{skin}^{comf} - modified thermal load equation were used to calculate thermal sensation votes for the NV buildings. They are shown in Figure 15, plotted alongside the Fanger model predictions. Figure 16 compares this new vote regression line to the original Fanger model prediction line and the observed line. As can be seen, modifying the TS greatly reduced the error between predicted and observed. It seems then that a Fanger model with a modified T_{skin}^{comf} and modified TS specification, both modifications supported by the idea that the psychological adaptations of occupants of NV buildings can be reasonably accounted for within these two important experimentally-derived parameters, could significantly improve the accuracy of the model's comfort predictions for NV environments.

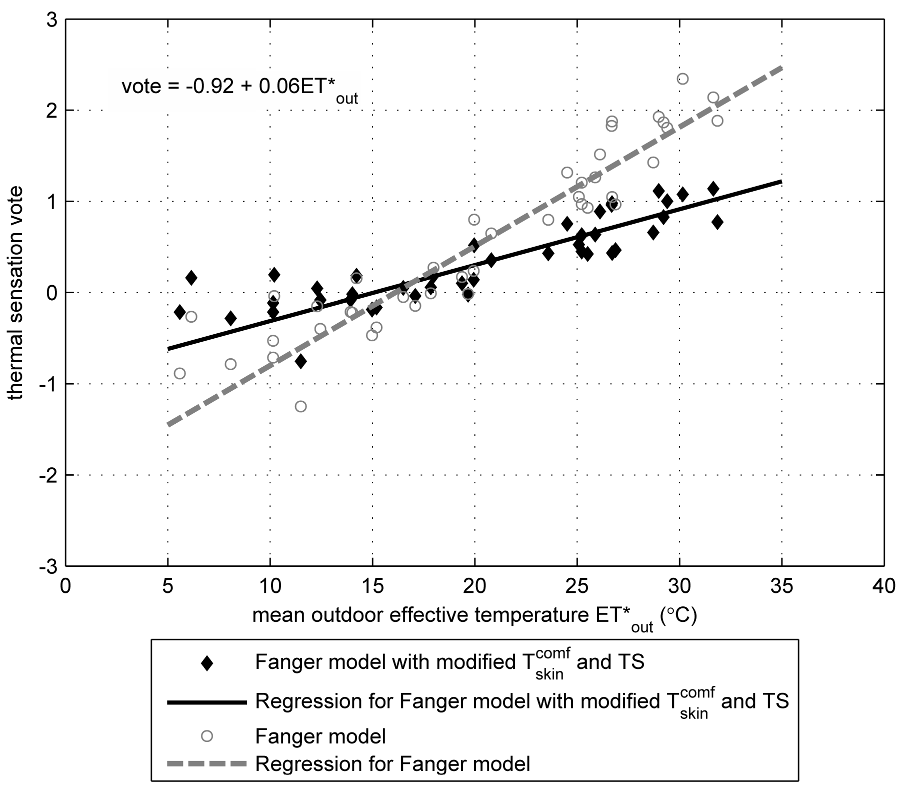

Fig. 15. Predicted thermal sensation votes for NV buildings calculated using a Fanger model with a T_{skin}^{comf} - ET_{out}^{*} correlation and a modified TS. The weighted linear regression has an R^2 = 0.81 (P < 0.01). The original Fanger model predicted votes and regression line are also shown.

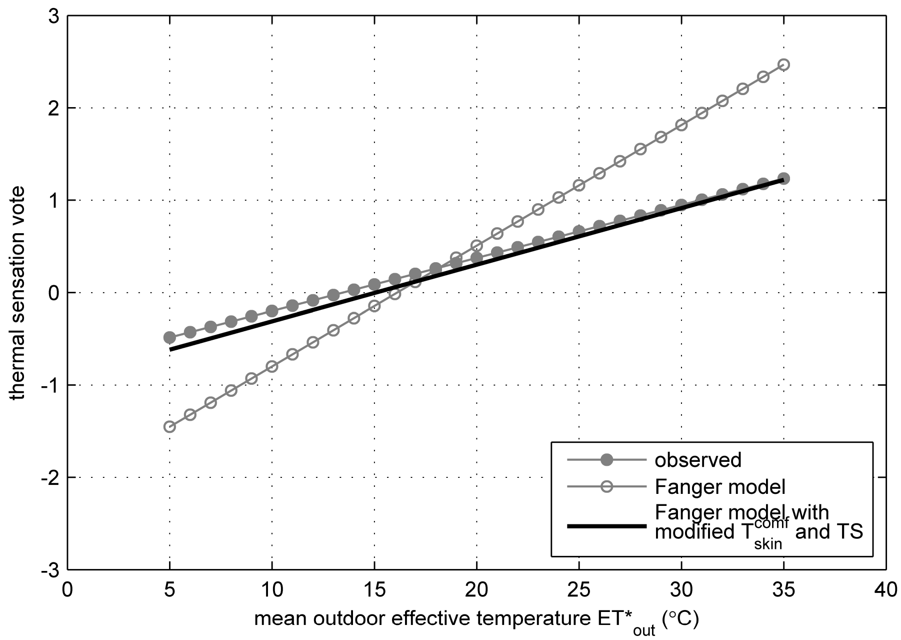

Fig. 16. Predicted thermal sensation vote regression line for NV buildings calculated using a Fanger model with a T_{skin}^{comf} - ET_{out}^{*} correlation and a modified TS. The observed vote regression line and the predicted vote regression line calculated using the original Fanger model are also shown.

5.6. Connection to Fanger's correction factors

The improvements to the Fanger model thus far presented can be examined alongside the modifications Fanger himself proposed to extend the applicability domain of his model to NV buildings. Based on an analysis of a subset of the same ASHRAE RP-884 field study data, Fanger [32] derived two correction factors that would improve the accuracy of the model's comfort predictions for NV buildings in warm climates. The first correction factor reduces the metabolic rate of occupants. Fanger asserts that people in warm climates unconsciously lower their activity level to adapt to the warmer environment; however, he provides no references or experimental studies supporting this claim. The second correction factor is an expectancy factor that accounts for the lowered thermal expectations that allow occupants of NV buildings to feel comfortable in warmer environments. This factor e varies from 0.5 to 1 depending on the length of the warm period and the prevalence of NV buildings for the region under study. It multiplies PMV and in effect modulates the TS, so that the PMV for occupants of NV buildings in regions where warm periods are brief and HVAC buildings are common remains unchanged (e = 1) while the PMV for occupants of NV buildings in regions where the warm period spans the entire year and NV buildings are common is halved (e = 0.5). When incorporating these correction factors, the model does predict thermal sensation votes that agree much better with the observed votes [32].

It is both interesting and important to point out that by proposing a correction factor to lower occupants' metabolic rate in warm climates, Fanger is effectively changing their T_{skin}^{comf} to be higher in warm climates (Fig. 8), and this correlation of T_{skin}^{comf} to outdoor climate is what the present research has demonstrated to be plausible without utilizing the metabolic rate correction factor that some studies [28] have deemed unlikely and almost nonsensical. Likewise, e is a multiplicative factor that modifies the TS by half in predominantly warm climates where NV buildings are common; this yields a TS that is nearly equivalent to the TS at sedentary activity level developed in Section 5.5.2, which was derived by accommodating for the differing thermal comfort preferences of occupants of NV buildings. Thus, the improvements suggested in the present analysis agree with Fanger's extension of the model in the sense that they both affect the comfort predictions in a similar way. The actual corrections, however, are different, and the current research provides more fundamental reasons and supporting derivations as to why such specific corrections are necessary given the original assumptions in Fanger's empirical studies.

6. Summary and Conclusions

The purpose of this analysis was to investigate if the integral parameters in Fanger's heat balance model had been specified appropriately, and to use such an analysis as a starting point in determining if the model's comfort predictions for NV buildings could be improved by re-specifying the values of these parameters. To this end, a sensitivity analysis was conducted, which revealed that the T_{skin}^{comf} - M regression constant is the parameter to which the T_{comf} prediction line happens to be by far most sensitive to. Arguments were presented for a re-specification of T_{skin}^{comf} applicable only to NV environments. Changing the values of the T_{skin}^{comf} - M regression constant and coefficient, however, did not improve the model's T_{comf} predictions for NV buildings since this type of re-specification only shifted the predicted T_{comf} regression line but did not rotate it to better match field study results. To obtain the desired rotation, T_{skin}^{comf} values needed to be higher at high ET_{out}^{*} and lower at low ET_{out}^{*}, that is, T_{skin}^{comf} needed to be a range of values for a given M rather than just one value per M as was originally defined by Fanger. Correlating T_{skin}^{comf} to ET_{out}^{*} using proper first order estimates for the T_{skin} range at which occupants of NV buildings would still vote neutral, a new predicted T_{comf} regression line was obtained that matched observed data quite well. It is hypothesized that at high ET_{out}^{*}, occupants of NV buildings vote neutral at higher T_{skin} due to psychological adaptations such as lowered thermal expectations. At these higher T_{skin}^{comf}, T_{in}^{op} then also need to be higher to maintain the Fanger condition of zero thermal load necessary for comfort, hence agreeing with the higher T_{comf} observed in field studies of NV buildings. A modification to the thermal sensation transfer coefficient was also presented. Incorporating the new TS with the new T_{skin}^{comf} in the Fanger model produced vote predictions that agree well with observed.

A key point to remember is that Fanger's model is not purely a physics model but includes empirically-derived coefficients that required assumptions on his part in regards to what the definition of comfort conditions is for the majority of people. If the definition of thermal comfort is not the same for everyone but varies significantly between different groups of people, and if the differing thermal comfort preferences affect the values of the coefficients in his model, then his assumptions need to be revisited and the model needs to be revised. Since the experiments to obtain T_{skin}^{comf} were conducted at the subjectively-determined comfort conditions of climate chamber test subjects, the thermal comfort preferences of occupants of NV buildings, and consequently any psychological adaptations influencing these thermal comfort preferences, were largely ignored. Hence, these experiments need to be repeated in NV buildings, so that the different but equally valid psychological state of these occupants and its possible effect on the physiological requirements for thermal comfort is considered in the construction of thermal comfort models. The goal of this investigation was to hone in on such reasonable improvements to the Fanger model that could help focus future experiments. A critical next step for experimentalists is to conduct field study experiments that measure T_{skin}^{comf}, so that the behavior of this important physiological variable and its relationship to the psychological aspects of thermal comfort in HVAC, NV, and mixed-mode buildings can be better understood.

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