PREDICTION OF THERMAL SENSATION IN NON-AIR-CONDITIONED BUILDINGS IN WARM CLIMATES

PO Fanger and J Toftum*

International Centre for Indoor Environment and Energy, Technical University of Denmark

ABSTRACT
The PMV model agrees well with high-quality field studies in buildings with HVAC systems, situated in cold, temperate and warm climates, studied during both summer and winter. In non-air-conditioned buildings in warm climates, occupants may sense the warmth as being less severe than the PMV predicts. The main reason is low expectations, but a metabolic rate that is estimated too high can also contribute to explaining the difference. An extension of the PMV model that includes an expectancy factor is introduced for use in non-air-conditioned buildings in warm climates. The extended PMV model agrees well with quality field studies in non-air-conditioned buildings of three continents.

INDEX TERMS
PMV, Thermal sensation, Expectancy, Warm climates, Adaptation

INTRODUCTION
The PMV model is a widely used tool for the design of thermal environments of buildings, vehicles, etc. It predicts the thermal sensation as a function of activity, clothing and the four classical thermal environmental parameters: air temperature, mean radiant temperature, air velocity and humidity (Fanger 1970). The advantage of the PMV model is that it is a flexible tool that includes all the major variables influencing thermal sensation. It quantifies the absolute and relative impact of these six factors and can therefore be used in indoor environments with widely differing HVAC systems as well as for different activities and different clothing habits. The model has been validated in climate chamber studies with Asian subjects (de Dear et al. 1991a; Tanabe et al. 1987) as well as in the field, most recently in ASHRAE’s worldwide research in buildings with HVAC systems that were situated in cold, temperate and warm climates and were studied during both summer and winter (Cena et al. 1998; Donini et al. 1996; de Dear et al. 1993a; Schiller et al. 1988).

While the PMV model predicts thermal sensation well in buildings with HVAC systems, field studies in warm climates in buildings without air-conditioning have shown that it predicts a warmer thermal sensation than the occupants actually feel (Brager and de Dear 1998; Humphreys 1978). For such non-air-conditioned buildings an adaptive model has been proposed that relates the neutral temperature indoors to the monthly average temperature outdoors (de Dear and Brager 1998). The only variable is thus the average monthly outdoor temperature, which at its highest may have an indirect impact on the human heat balance. An obvious weakness of the adaptive model is that it does not include human clothing or activity or the four classical thermal parameters that have a well-known impact on the human heat balance and therefore on the thermal sensation. A design tool that can be used regardless of building type, usage, or ventilation mode requires a higher degree of flexibility and practical applicability than currently is offered by the adaptive model. Therefore, this paper proposes a new extension of the PMV model to non-air-conditioned buildings in warm climates.

* Contact author email: jt@mek.dtu.dk
METHODS
Our hypothesis is that the major factor in explaining why the PMV seems to overestimate the thermal sensation of occupants in non-air-conditioned buildings in warm climates is the expectations of the occupants, since there is general agreement that physiological acclimatization does not play a role (Brager and de Dear 1998). These occupants are typically people who have been living in warm environments indoors and outdoors, maybe even through generations. They may believe that it is their “destiny” to live in environments where they feel warmer than neutral. If given a chance they may not on average prefer an environment that is different from that chosen by people who are used to air-conditioned buildings. But it is likely that they would judge a given warm environment as less severe and less unacceptable than would people who are used to air-conditioning.

This may be expressed by an expectancy factor, e, to be multiplied with PMV to reach the mean thermal sensation vote of the occupants of the actual non-air-conditioned building in a warm climate. Based on professional judgment we estimate the factor e to vary between 1 and 0.5. It is 1 for air-conditioned buildings. For non-air-conditioned buildings, the expectancy factor is assumed to depend on the duration of the warm weather over the year and whether such buildings can be compared with many others in the region that are air-conditioned. If the weather is warm all year or most of the year and there are no or few other air-conditioned buildings, e may be 0.5, while it may be 0.7 if there are many other buildings with air-conditioning. For non-air-conditioned buildings in regions where the weather is warm only during the summer and no or few buildings have air-conditioning, the expectancy factor may be 0.7 to 0.8, while it may be 0.8 to 0.9 where there are many air-conditioned buildings. In regions with only brief periods of warm weather during the summer, the expectancy factor may be 0.9 to 1. Table 1 proposes a first rough estimation of ranges for the expectancy factor corresponding to high, moderate and low degrees of expectation.

**Table 1.** Expectancy factors for non-air-conditioned buildings in warm climates.

<table>
<thead>
<tr>
<th>Expectation</th>
<th>Classification of buildings</th>
<th>Expectancy factor, e</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>Non-air-conditioned buildings located in regions where air-conditioned buildings are common. Warm periods occurring briefly during the summer season.</td>
<td>0.9 - 1.0</td>
</tr>
<tr>
<td>Moderate</td>
<td>Non-air-conditioned buildings located in regions with some air-conditioned buildings. Warm summer season.</td>
<td>0.7 - 0.9</td>
</tr>
<tr>
<td>Low</td>
<td>Non-air-conditioned buildings located in regions with few air-conditioned buildings. Warm weather during all seasons.</td>
<td>0.5 - 0.7</td>
</tr>
</tbody>
</table>

A second factor that contributes erroneously to the reported difference between the calculated PMV and actual thermal sensation votes in non-air-conditioned buildings is the estimated activity. In many field studies in offices, the metabolic rate is estimated on the basis of a questionnaire identifying the percentage of time the person was sedentary, standing, or walking. This mechanistic approach does not acknowledge the fact that people, when feeling warm, unconsciously tend to slow down their activity. They adapt to the warm environment...
by decreasing their metabolic rate. The lower pace in warm environments should be acknowledged by inserting a reduced metabolic rate when calculating the PMV.

**RESULTS AND DISCUSSION**

To examine these hypotheses further, data were downloaded from the database of thermal comfort field experiments (de Dear 1998). All data of at least quality class II and obtained in non-air-conditioned buildings during the summer period in warm climates were used in the analysis. Quality class II comprises data from field studies in which all physical variables necessary for the calculation of PMV were collected at the same time and place as the questionnaires. However, measurements may not have complied with all recommendations of current thermal comfort standards (ISO 7726-1998, ASHRAE 55-1992). Data from four cities (Bangkok, Brisbane, Athens, and Singapore) were included, representing a total of more than 3200 sets of observations (Busch 1992, de Dear and Auliciems 1985, Baker and Standeven 1995, de Dear et al. 1991b). The data from these four cities with warm climates were also included in the development of the adaptive model (de Dear and Brager 1998).

To adjust for the effect of thermal sensation on activity level, recorded metabolic rates of each set of observations were reduced by 6.7% for every scale unit of PMV above neutral, i.e. a PMV of 1.5 corresponded to a reduction in the metabolic rate of 10%. Next, the PMV was recalculated with reduced metabolic rates using ASHRAE’s thermal comfort tool (Fountain and Huizenga 1997). The resulting PMV values were then adjusted for expectation by multiplication with expectancy factors estimated to be 0.9 for Brisbane, 0.7 for Athens and Singapore and 0.6 for Bangkok. Both the decrement of metabolic rate per unit PMV and the assignment of expectancy factors for the four cities were based on professional judgment. As an average for each building included in the field studies, Figure 1 and Table 2 compare the observed thermal sensation with predictions using the new extended PMV model for warm climates.

![Graph](image-url)

**Figure 1.** Thermal sensation in non-air-conditioned buildings in four cities in warm climates. Comparison of observed mean thermal sensation with predictions made using the new extension of the PMV model for non-air-conditioned buildings in warm climates. The lines...
are based on linear regression analysis weighted according to the number of responses obtained in each building.

**Table 2.** Non-air-conditioned buildings in warm climates. Comparison of observed thermal sensation votes and predictions made using the new extension of the PMV model.

<table>
<thead>
<tr>
<th>City</th>
<th>Expectancy factor</th>
<th>Unadjusted PMV</th>
<th>PMV adjusted to proper activity</th>
<th>PMV&lt;sub&gt;e&lt;/sub&gt; adjusted for expectation</th>
<th>Observed mean vote</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bangkok</td>
<td>0.6</td>
<td>2.1</td>
<td>2.0</td>
<td>1.2</td>
<td>1.3</td>
</tr>
<tr>
<td>Singapore</td>
<td>0.7</td>
<td>1.3</td>
<td>1.2</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>Athens</td>
<td>0.7</td>
<td>1.4</td>
<td>1.5</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Brisbane</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

The new extension of the PMV model for non-air-conditioned buildings in warm climates predicts the actual votes well. The extension combines the best of the PMV and the adaptive model. It acknowledges the importance of expectations already accounted for by the adaptive model, while maintaining the PMV model’s classical thermal parameters that have direct impact on the human heat balance.

It should also be noted that the new PMV extension predicts a higher upper temperature limit when the expectancy factor is low. People with low expectations are ready to accept a warmer indoor environment, which also agrees well with the observations behind the adaptive model. An example: the relation between PMV and PPD predicts that 10% of a large group of occupants will be dissatisfied at a PMV of 0.5. Assuming that this relation remains unchanged also with occupants of low expectations, an expectancy factor, e, will result in a higher upper temperature limit corresponding to a PMV of 0.5/e, but with no more than 10% dissatisfied. Table 3 shows upper temperature limits adjusted for expectation calculated both for 10% and 20% dissatisfied. A low expectation may change the upper temperature limit by 2°C. It is only the upper temperature limit of the comfort zone that is affected by the expectancy factor, and no adjustment of the lower limit is expected.

**Table 3.** Example of upper temperature limits of the comfort zone adjusted for expectation in non-air-conditioned buildings in warm climates. The calculations were made with a metabolic rate of 1 met, a clothing insulation of 0.5 clo, an air velocity of 0.3 m/s, and a relative humidity of 70%.

<table>
<thead>
<tr>
<th>Expectancy factor, e</th>
<th>PPD (%)</th>
<th>PMV&lt;sub&gt;e&lt;/sub&gt;</th>
<th>Unadjusted PMV</th>
<th>Upper temperature limit (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10/20</td>
<td>0.5/0.85</td>
<td>0.5/0.85</td>
<td>27.9/28.7</td>
</tr>
<tr>
<td>0.7</td>
<td>10/20</td>
<td>0.5/0.85</td>
<td>0.7/1.2</td>
<td>28.3/29.4</td>
</tr>
<tr>
<td>0.5</td>
<td>10/20</td>
<td>0.5/0.85</td>
<td>1/1.7</td>
<td>29.0/30.5</td>
</tr>
</tbody>
</table>

The database of quality field studies in non-air-conditioned buildings in warm climates is still rather modest. Additional field studies in such buildings in different parts of the world would therefore be useful to further refine the extended PMV model and to determine and validate expectancy factors at different locations in warm climate regions. Such studies with measurements of class II, or even better class I, should include questions on occupants’
expectations, acceptability and previous experience. It would also be useful to study the impact of warm office environments on work pace and metabolic rate.

CONCLUSIONS
The PMV model agrees well with high-quality field studies in buildings with HVAC systems, situated in cold, temperate and warm climates and studied during both summer and winter. In non-air-conditioned buildings in warm climates, occupants may, however, perceive the warmth as being less severe than the PMV predicts. This is mainly caused by low expectations, but a metabolic rate that is estimated too high under warm conditions also contributes to explain the difference.

An extension of the PMV model that includes an expectancy factor is proposed for use in non-air-conditioned buildings in warm climates. The extended PMV model agrees well with available quality field studies in non-air-conditioned buildings in warm climates of three continents.

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de Dear, R.J. (1998), A global database of thermal comfort field experiments. ASHRAE Transactions, 104(1b), pp 1141-1152.


