Thermal comfort under transient seasonal conditions of a bioclimatic building in Greece

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ABSTRACT

This paper presents the thermal comfort levels in a bioclimatic building situated in the greater Athens area in Greece. The study was carried out under transient weather conditions (autumn) by the use of the PMV-PPD model during which the central heating and cooling system of the building was not operational. A survey was also conducted regarding the thermal feeling of the occupants through questionnaires according to ASHRAE standard 55-2004 for the estimation of the actual mean vote (AMV) and actual percentage of dissatisfied (APD). Since under transient conditions the most reliable control can be either the Mean Vote or the Actual Percentage Dissatisfied (APD), it was found that the most valid method of PMV calculation is the revised method that calculates the PMVnew. Also the calculation of PMVe (the PMV corrected with the expectation factor) showed its incapability to predict the Mean Vote, under the circumstances of the study. The analysis of measurements showed that the determination of the comfort temperature, by solving the PMV expression in reverse order is not accurate. Its determination as a function of the adaptive control algorithm (ACA) appeared a more precise method.

1. INTRODUCTION

A series of measurements of the environmental parameters related to thermal comfort were carried out in the bioclimatic building of CRES, situated in the greater Athens area. In parallel, a survey was conducted for the assessment of the actual thermal sensation of the building occupants, and the estimation of comfort personal parameters like the occupants’ clothing insulation and their metabolic rate (met). The autumn period was selected for two reasons: to evaluate the ability of the bioclimatic building to expand the thermal comfort zone, and to evaluate the thermal comfort PMV-PPD model under transient weather conditions. This model is the most widely used tool for the estimation of the thermal environment in buildings and the basis of standards ISO 7730, 1993 and ASHRAE 55, 2004.

The need to investigate the validity of the model under transient weather conditions, since the environment inside a building is rarely under steady conditions, has been reported in the past (Hensen, 1990). Result of this investigation was the proposal to extend the PMV model for free running buildings in hot climates through the use of a correction factor (e), the so-called expectation factor (Fanger and Toftum, 2002). The proposed relation is:

\[ \text{met}_e = \text{met}' e \]

where \( \text{met}_e \) is the reduced metabolic rate through which the PMV\(_e\) (the PMV corrected by the expectation factor) is calculated.

It was stated that this extension of the PMV combines the advantages of the other parameters used to determine it and incorporates the importance of expectation like the adaptive model.

Thorough another parallel study (Humphreys and Nicol, 2002), the revision of the PMV was proposed. Considering the expectation to be an insufficient explanation for the different human response in air-conditioned and non air-conditioned buildings, the better performance of the PMV calculation in air-conditioned buildings was attributed to their limited thermal environment range. So, a statistical model was proposed for the estimation of uncertainty by the use of regression analysis and utilizing the PMV variables together with the implementation of the operative temperature and the outdoor temperature.

Other studies scope was the determination of the variation rate of the comfort temperature, the use of an exponentially weighted running mean outdoor temperature was proposed which could represent the dependence of time, comfort temperature and thermal resistance of clothing. Finally, a similar study, whose objective was the reduction of energy consumption in buildings, developed an adaptive control algorithm (McCarty and Nicol, 2002) which uses the theory of adaptive comfort through the evaluation of the running mean temperature. This paper studies the comfort conditions in an office building and compares the different existing relations for the evaluation of the PMV and PPD indices with the AMV and APD respectively.
2. MEASUREMENT PROCEDURE - INSTRUMENTATION

The bioclimatic building is a two-story building in a suburban area with a total floor area of 356 m². The building is equipped with a plethora of passive and low energy techniques which include direct gain systems, solar atrium, greenhouse, transparent insulation, external shading devices (awnings and blinds), natural ventilation, together with a geothermal pump, solar collectors and PV systems positioned on the roof. It consists of nine office rooms and occupies approx. 20 users. At the time of the measurements the mechanical ventilation systems were not in operation. The measurements were taken in six different days, in two repetitions every day (at approx. 10:00 in the morning and 12:30 at noon) from the 26th October to the 22nd November. The measured environmental parameters are: air temperature, globe temperature, relative humidity and air velocity. The measurements took place only in the office rooms (the atrium area, and reception room were not investigated).

The measuring equipment consisted of an LSI BABUC A data logger with its accompanied measuring sensors and a tripod. The equipment was placed in the middle of the room keeping the right distances from walls and openings (as suggested by the standards) at a height of 80 cm off the ground. The completion of a questionnaire from the users was conducted simultaneously with the data recording. The questionnaire comprised also questions for the estimation of personal parameters like the type of activity in order to evaluate more accurately the metabolic rate and the clothing thermal resistance since their estimation has an effect on the PMV sensitivity, and has been the subject of many discussions (Olesen and Parsons, 2002). It comprised also questions related with the behavior and habits of the person, his/her expectations, “climatic memory”, etc.

The evaluation of the PMV and PPD was carried out by the use of two software tools, Comfort from the University of Berkeley and Bioclimatics. Besides the calculation results from the software tools, an evaluation of the following additional parameters took place:
• The exponentially-weighted running mean temperature, $T_{em}$, at time t, where t is the time period of the measurements.

The comfort temperature, $T_c$, as a function of $T_{em}$ and not of $T_c$, which was suggested for free running buildings (Nicol & Humphreys, 2002) through the relation: $T_c=13.5+0.54T_{em}$
• The comfort temperature $T_c$ as a function of the adaptive control algorithm, ACA (McCartney and Nicol, 2002).
• The metabolic rate corrected from the expectation factor, $met_f$, for Athens area and the PMVe (Fanger and Tofn, 2002).
• The PMV regression relation from ASHRAE database and the PMVnew from the relations:

$$D_{PMV-ASHRAE} = -4.03 + 0.0949T_c + 0.00584RH + 1.201(met - clo) + 0.000838T_c^2$$

and

$$PMV_{new} = Q_8(\text{PMV} - D_{PMV-ASHRAE})$$

$$PPD_{new} = 100 - 9 \exp\left(0.335PMV_{new}^4 - 0.217PMV_{new}^2\right)$$

All findings are presented and discussed in the following chapter.

3. ANALYSIS OF RESULTS - DISCUSSION

For the estimation of thermal comfort conditions in the building the findings from the users survey regarding the estimation of the actual percentage of dissatisfied (APD) and the actual mean vote (AMV) for every measuring day was utilized in terms of grouping areas (ground-floor, first floor). The observations were compared from the evaluation of PMV and PPD indices from the software tools and some conclusions derived for the general comfort conditions of the building, the influence of the users behavior in the creation of comfort conditions, and the way APD and AMV are related together with their reliability according to the current measured conditions.

For the evaluation of the most appropriate method for the estimation of PMV under the transient conditions of autumn in the greater Athens area, the mean PMV values of the building calculated from the two software tools and the equations 2 to 4 together with the actual mean vote (AMV) were compared. The comparison was carried out by the use of the mean values of the maximum possible sample for the minimization of doubts. Doubts can be caused by recorded activities with high values of met, which lie in the limits or outside the limits set by ASHRAE 55-1992 or 2004 standards or validity studies of standards (Humphreys & Nicol, 2002) or finally due to local discomfort. The same procedure was followed for the estimation of PPD and APD indices.

Regarding the most likely comfort temperature, for the conditions of the study, the mean indoor air temperature of the building, $T_{air}$, and the mean values of the running mean temperature, $T_{em}$, the comfort temperature $[T_c, T_c=f(T_{air})$, $T_c=f(ACA)]$, and the neutral temperature, $T_n$ (by Humphreys, 1976 and by Auliciems, 1983) were compared.

3.1 Evaluation of indices and software tools

In Table 1 the mean PMV values of the building calcu-
lated from the two software tools, the actual mean vote (AMV), the PMV<sub>new</sub> and the discrepancies of the PMV indices from the AMV can be found. The comparison criterion used was the mean value of discrepancies between the AMV and the three calculated PMV indices as suggested by Humphreys & Nicol (Humphreys & Nicol, 2002). From the Table it can be seen that the PMV<sub>comfort</sub> compared to the AMV provides with the smaller mean difference (0.04 of the ASHRAE scale), followed by the PMV<sub>new</sub> with a mean difference of 0.115. The largest difference from AMV was found through the PMV<sub>bioclimatics</sub> with a mean difference of 0.3 (the maximum level of difference is considered to be ±0.25 [Humphreys & Nicol, 2002]). The latter difference can be attributed due to the fact that the Bioclimatics software is not very accurate during the data input, especially regarding the thermal resistance of clothing.

The evaluation of the PMV corrected with the factor of expectation, PMVe for the measurements of the 26th of October can be found in Figures 1 and 2. It can be seen that the PMVe shows large differences compared to the AMV, PMV<sub>comfort</sub> and PMV<sub>bioclimatics</sub>. In fact, on that measuring day, the mean outdoor temperature was 18.2 °C, the mean indoor temperature 24.8 °C, the mean vote 0.46 and the actual percentage of dissatisfied (APD) 12.6%, the evaluated PMVe was -1.05 while the mean value of all the other indices was 0.54.

The finding above depicts the incapability of PMVe to predict the thermal sensation under the circumstances of the measurements.

Table 1: Mean values of PMV, AMV and their intercomparison.

<table>
<thead>
<tr>
<th>Meas. Day</th>
<th>AMV</th>
<th>PMV&lt;sub&gt;comfort&lt;/sub&gt;</th>
<th>PMV&lt;sub&gt;new&lt;/sub&gt;</th>
<th>PMV&lt;sub&gt;bioclimatics&lt;/sub&gt;</th>
<th>AMV - PMV&lt;sub&gt;comfort&lt;/sub&gt;</th>
<th>AMV - PMV&lt;sub&gt;new&lt;/sub&gt;</th>
<th>AMV - PMV&lt;sub&gt;bioclimatics&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 Oct</td>
<td>0.45</td>
<td>0.39</td>
<td>0.47</td>
<td>-0.52</td>
<td>0.11</td>
<td>-0.01</td>
<td>-0.32</td>
</tr>
<tr>
<td>9 Nov</td>
<td>0.27</td>
<td>0.64</td>
<td>0.51</td>
<td>-0.33</td>
<td>0.13</td>
<td>-0.03</td>
<td>-0.08</td>
</tr>
<tr>
<td>14 Nov</td>
<td>0.13</td>
<td>0.10</td>
<td>0.17</td>
<td>-0.17</td>
<td>0.33</td>
<td>0.00</td>
<td>0.17</td>
</tr>
<tr>
<td>16 Nov</td>
<td>0.21</td>
<td>0.42</td>
<td>0.43</td>
<td>-0.44</td>
<td>0.13</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>17 Nov</td>
<td>0.24</td>
<td>0.29</td>
<td>0.33</td>
<td>-0.02</td>
<td>0.26</td>
<td>0.08</td>
<td>0.10</td>
</tr>
<tr>
<td>Mean</td>
<td>0.24</td>
<td>0.61</td>
<td>0.30</td>
<td>-0.20</td>
<td>0.14</td>
<td>0.11</td>
<td>0.17</td>
</tr>
</tbody>
</table>

In Table 2 the mean PPD values of the building calculated from the two software tools, the actual percentage of dissatisfied (APD), the PPD<sub>new</sub> and the differences of the PPD indices from the APD can be found. It can be seen that the comparison between the PPD<sub>new</sub> and the APD provide with the smallest difference (0.1%), followed by the difference of the PPD<sub>comfort</sub> and APD (1.97%). The largest difference was observed between the PPD<sub>bioclimatics</sub> and APD (3.59%). It can be generally said that the relative agreement of the PMV with the AMV index can be attributed as either the relative prediction capability of the PMV in transient season conditions (like autumn in Athens) in a building without the use of air-conditioning or/and as success of the bioclimatic’s building envelope to extend the comfort zone and the relatively steady indoor conditions recorded at the period of the study. The greater ability of the PMV evaluation in air-conditioned buildings can be attributed due to the reduced levels of thermal environment while the indoor conditions of a non air-conditioned building are affected from the outdoor prevailing climatic conditions.

Finally, from the interpretation of results it can be stated that the PMVnew seems to be the most appropriate index for the evaluation of the thermal sensation in a building under transient climatic conditions (through the most accurate criterion of lower standard deviation of mean discrepancies), while the PPDnew provides with the better agreement in relation to the APD.

Table 2: Mean values of PPD, APD and their intercomparison.

<table>
<thead>
<tr>
<th>Meas. Day</th>
<th>APD</th>
<th>PPD&lt;sub&gt;comfort&lt;/sub&gt;</th>
<th>PPD&lt;sub&gt;new&lt;/sub&gt;</th>
<th>PPD&lt;sub&gt;bioclimatics&lt;/sub&gt;</th>
<th>APD - PPD&lt;sub&gt;comfort&lt;/sub&gt;</th>
<th>APD - PPD&lt;sub&gt;new&lt;/sub&gt;</th>
<th>APD - PPD&lt;sub&gt;bioclimatics&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 Oct</td>
<td>12.50</td>
<td>21.27</td>
<td>11.06</td>
<td>-8.77</td>
<td>5.90</td>
<td>1.44</td>
<td>4.46</td>
</tr>
<tr>
<td>9 Nov</td>
<td>5.50</td>
<td>13.03</td>
<td>9.52</td>
<td>-3.51</td>
<td>-1.50</td>
<td>-5.02</td>
<td>-3.51</td>
</tr>
<tr>
<td>11 Nov</td>
<td>5.40</td>
<td>7.10</td>
<td>5.65</td>
<td>-1.25</td>
<td>-0.10</td>
<td>-2.5</td>
<td>-1.25</td>
</tr>
<tr>
<td>16 Nov</td>
<td>7.14</td>
<td>17.29</td>
<td>9.98</td>
<td>-10.31</td>
<td>-1.86</td>
<td>-2.84</td>
<td>-10.31</td>
</tr>
<tr>
<td>17 Nov</td>
<td>5.60</td>
<td>10.82</td>
<td>6.17</td>
<td>-4.65</td>
<td>-0.63</td>
<td>-5.02</td>
<td>-4.65</td>
</tr>
<tr>
<td>Mean</td>
<td>9.12</td>
<td>8.56</td>
<td>6.55</td>
<td>-2.01</td>
<td>1.97</td>
<td>0.08</td>
<td>1.97</td>
</tr>
</tbody>
</table>
3.2 Evaluation of temperatures related to thermal comfort

In Table 3 the mean indoor air temperature of the building, $T_{\text{air}}$, and the mean values of the running mean temperature, $T_{\text{rm}}$, the comfort temperature [$T_c = f(T_{\text{rm}})$, $T_c = f(ACA)$], and the neutral temperature, $T_{nHumphreys}$ by Humphreys, and by Auliciems, $T_{nAuliciems}$ can be found.

From the Table, the following can be drawn:

• The correlation between the indoor air temperature and the comfort temperature, $T_c$ is highly negative (Covar=-0.8 and $r=-0.7$) resulting to the conclusion that the evaluation of $T_c$ by the inverse solution of the PMV equation (for PMV=0) is not appropriate. This solution is based on the simple fact that when the environment becomes warmer, the lower the comfort temperature is (or lower the thermostat setting in an air-conditioned building) as can also be seen in Figure 3.

• The indoor air temperature is highly correlated with the neutral temperature, by Auliciems (covar=0.51, $r=0.94$) since their interconnection is linear ($T_{nAuliciems} = 0.48T_{\text{air}} + 0.14T_{\text{out}} + 9.22$, where $T_{\text{out}}$ is the mean outdoor temperature). Better covariance, however, was found between $T_{\text{air}}$ and $T_{nHumphreys}$ (covar=0.29).

• The correlation of the comfort temperature as a function of the running mean temperature, and the indoor air temperature, for $T_{\text{rm}} < 10^\circ\text{C}$ is negative, showing that below this limit, the relation $T_c = f(T_{\text{rm}})$ has no applicability. The same result applies to the relation of the $T_c = f(ACA)$ with $T_{\text{air}}$ (this explains the omission of these parameters in Table 3).

Table 3: Comfort temperature, neutral temperature and indoor mean air temperature during the period of the measurements (all values in °C).

<table>
<thead>
<tr>
<th>Mean Day</th>
<th>Tair</th>
<th>Tc</th>
<th>TnHumphreys</th>
<th>TnAuliciems</th>
<th>Tc=f(Trm)</th>
<th>Tc=f(ACA)</th>
<th>Tn(?)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26 Oct</td>
<td>24.3</td>
<td>22.8</td>
<td>21.5</td>
<td>23.3</td>
<td>19.8</td>
<td>24.1</td>
<td>11.7</td>
</tr>
<tr>
<td>9 Nov</td>
<td>23.6</td>
<td>22.8</td>
<td>21.5</td>
<td>23.3</td>
<td>19.8</td>
<td>24.1</td>
<td>11.7</td>
</tr>
<tr>
<td>11 Nov</td>
<td>22.7</td>
<td>21.7</td>
<td>22.1</td>
<td>19.8</td>
<td>24.1</td>
<td>11.7</td>
<td>11.7</td>
</tr>
<tr>
<td>16 Nov</td>
<td>22.6</td>
<td>21.7</td>
<td>22.2</td>
<td>19.8</td>
<td>24.0</td>
<td>11.0</td>
<td>11.0</td>
</tr>
<tr>
<td>17 Nov</td>
<td>22.8</td>
<td>21.7</td>
<td>22.1</td>
<td>N/A</td>
<td>24.1</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>22 Nov</td>
<td>22.3</td>
<td>21.7</td>
<td>22.1</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>4.1</td>
</tr>
<tr>
<td>Mean</td>
<td>23.6</td>
<td>21.7</td>
<td>22.6</td>
<td>20.3</td>
<td>24.3</td>
<td>4.7</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Figure 3: Relation between comfort temperature and indoor air temperature.

• The best agreement, in terms of correlation, was found between the $T_c$ as a function of the adaptive control algorithm and $T_{\text{air}}$ (covar=0.15).

4. CONCLUSIONS

A thermal comfort study was carried out in a bioclimatic office building under autumn weather conditions in the greater Athens area. The purpose of the study was to investigate the comfort conditions in that particular season period and to compare different existing relations for the evaluation of the PMV and PPD indices with the actual mean vote (AMV) and percentage of dissatisfied (APD) respectively.

The main results can be summarized as follows:

• The actual mean vote of the users is lying in acceptable thermal comfort levels which show the ability of the bioclimatic design and operation of the building to overcome these seasonal energy needs without the use of air-conditioning. Also, the APD varied in acceptable limits.

• The best relation between the actual mean user sensation and evaluated PMV was found by the use of PMVnew followed by the PMV calculated by the Comfort software. Additionally, the PPDnew provided with the better agreement in relation to the APD.

• The evaluation of the PMV corrected with the factor of expectation, PMVe showed the incapability of the latter to predict the thermal sensation under the circumstances of the measurements.

• Regarding the relation of the comfort temperature and the indoor air temperature, the study showed that the best agreement was found between the $T_c$ as a function of the adaptive control algorithm and $T_{\text{air}}$.

• The indoor air temperature is highly correlated with the neutral temperature, evaluated by Humphreys, followed by the neutral temperature evaluated by Auliciems.

• Finally, the evaluation of $T_c$ by the inverse solution of the PMV relation is not an appropriate way to relate these parameters.

REFERENCES


