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Temperature sensitivity analysis of thermal comfort in a UK residential building

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ABSTRACT

This research focuses on investigating the sensitivity of thermal comfort to temperature in a heated space. Thermal comfort test sessions are conducted in a test house representative of a typical UK house during the winter season. A total of 119 participants took part in the series of tests conducted in the test house’s living room. Operative temperature in the heated space was maintained within the comfortable range recommended by CIBSE for a living room area in a UK house. Two different heating emitters were used for heating during the tests in order to examine their effects on occupant thermal comfort. Conventional radiators supplemented by a gas boiler and an electric fan heater were investigated in the presence and absence of a circulation fan running in the corner of the room. Thermal comfort sensation of occupants was calculated using sensors installed in the living room (Fanger’s Predicted Mean Vote). At the same time the occupants were asked to fill in surveys which were used to record their Actual Mean Vote. From the test sessions conducted it was found that AMV predicted a neutral temperature of 23.5°C whilst PMV predicted a neutral temperature of 24.0°C thus PMV over predicted the occupant’s thermal sensation compared to AMV. For the four heating scenarios it was found that a convective fan heater with a circulation fan causes the smallest temperature gradient (1.0°C) between ankle and head height for a seated occupant according to ISO7730 standards. The highest temperature gradient was measured for fan heater without a circulation fan (7.3°C). Occupants reported to be most uncomfortable if the convector heater without a circulation fan was used.

Keywords: Predicted Mean Vote; Actual Mean Vote; Thermal comfort; Field-studies; Temperature gradient

1. INTRODUCTION

Thermal comfort is defined as “that condition of the mind in which satisfaction is expressed with the thermal environment” (ASHRAE, 2013). It is the main indoor environment quality for human comfort according to review by Frontczak (2011). In a growing awareness for a need to reduce building energy use and improve indoor thermal environment, it has becomes increasingly significant to efficiently monitor and control indoor environment.

The majority of thermal comfort standards such as ASHRAE Standard 55, CIBSE and ISO 7730 use Fanger’s PMV 7 scale as a thermal comfort index for occupants in air-conditioned buildings. It is the most understood thermal comfort model and largely implemented in a building design (Wei et al., 2010). This paper presents the results of multi-regression analysis study of thermal comfort tests comprising of 119 participants that were performed in a residential unit in Loughborough, United Kingdom. The residential unit was a test house which represents the thermal properties of a real house and allows strict control of environmental parameters of a test chamber. The participation of large set of test subjects and
the state of the art test house facility allows for an accurate analysis of thermal comfort. The goal of the study was to determine:

1) To investigate the influence of operative temperature in a living space on occupant thermal comfort
2) To determine the accuracy of the PMV thermal comfort model in predicting the AMV of the participants in a heated space using different heating strategies.

2. METHODOLOGY

2.1 Participants in the studies

A total of 119 participants took part in these experiments with 4 participants invited to each experimental session. The participants were asked to wear a t-shirt and jeans in order to set their clothing value (including the sofa fabric on which they were seated) at about 0.8 clo with tolerance of 0.04 clo. Their metabolic rate is 1.0 according to ASHRAE standard 55, 2010 for sedentary activity.

![Participants filling in thermal comfort surveys](image)

Figure 1: Participants filling in thermal comfort surveys

2.2 Case-study Building

Experiments were conducted in a two-storey detached test house located on the campus of Loughborough University and constructed in the year 2000 (Figure 2. A detached house was chosen as it would be affected by weather and sun radiation and should be targeted for energy improvement while maintaining thermal comfort (Shipworth et al., 2010). The test house known as Holywell test house faces 45° North West and is located at 52°75' N, -1°245, W. It consists of 2 bedrooms, 1 kitchen, 1 living room, 1 toilet and 1 bathroom. The test house has a heat loss coefficient of 136.44 W/K and an infiltration rate of 0.87 ach.

The living room is facing south east and during the test sessions there was only 1 session with sun direct incident on one of the participants for less than 1 hour. Therefore, only one test session (0.2% of the entire test sessions conducted) were affected by direct sun radiation which presents only 30 minutes in total amongst 288 hours during the 32 sessions.
Table 1.1: Living room’s specification

<table>
<thead>
<tr>
<th>Description</th>
<th>Area</th>
<th>Description</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor to ceiling height</td>
<td>2.35m</td>
<td>Door area</td>
<td>1.68m²</td>
</tr>
<tr>
<td>Floor area</td>
<td>16.66m²</td>
<td>Windows area</td>
<td>4.49m²</td>
</tr>
</tbody>
</table>

2.3 Experimental method

A total of 32 sessions were conducted in the living room for 2 hours each. The room was preheated with at a set point of 22.5°C as CIBSE Guide A: KS6 recommends a temperature range of 22.0-23.0°C for occupants to feel thermally comfortable in a living room during cold season (Race et al., 2006). The operative and air temperatures were measured at height of 0.6m from the floor. The participants were asked to answer questionnaires from the beginning of the 2 hour session till the end at every 15 minutes intervals.

The 32 experimental sessions were divided into four different scenarios as shown in table 1.2. The conditions were achieved by either running the radiator heater in the first half of the session or the second half and vice versa for the convective heater. The additional two conditions were employed by having a fan circulate the air in the living room in randomly selected test sessions.

Table 1.2: Experiment's scenario

<table>
<thead>
<tr>
<th>No.</th>
<th>First Half (1 hour)</th>
<th>Second half (1 hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Radiator heating (Fan off)</td>
<td>Convector heating (Fan off)</td>
</tr>
<tr>
<td>2</td>
<td>Radiator heating (Fan on)</td>
<td>Convector heating (Fan on)</td>
</tr>
<tr>
<td>3</td>
<td>Convector heating (Fan off)</td>
<td>Radiator heating (Fan off)</td>
</tr>
<tr>
<td>4</td>
<td>Convector heating (Fan on)</td>
<td>Radiator heating (Fan on)</td>
</tr>
</tbody>
</table>

The questionnaire was based on the 7-point Bedford scales based on the ASHRAE 55 standard, 2010 shown in Figure 3:
2.3.1 Measuring equipment

The selection of measuring equipment was based on gold standard setup by Limbachiya et al. (2012) and a thermal comfort kit. Nine temperature sensors were installed in different locations in the living room. Six U-type thermistors were installed for measuring temperature gradients, wall surface temperatures, and radiator panel’s surface temperature. One globe bulb thermistor was placed at 1.7 meters from the floor (height for a standing person). To measure vertical temperature gradients, temperature thermistors were mounted on a tripod stand at 0.1, 0.6, and 1.1 meters height above the floor as recommended by CIBSE Guide A: KS6 and ISO 7730 standards (Race et al., 2006; ISO 7730, 1994). The tripod was positioned at the center of the living room. An additional temperature sensor was installed on a tripod at 1 meter and an air velocity sensor mounted at 0.6 meter (Figure 4b).

Operative temperature, air temperature, air velocity and relative humidity were measured at a height of 0.6 meters and were fed to the INNOVA 1221 Thermal Comfort kit (Figure 5). This thermal comfort kit would help in automatically calculating PMV at a certain time interval.
2.3.3 Heating equipment

Two heating emitters were used during the thermal comfort test. Each heating emitter was used randomly either in the first hour or in the second hour of the two hour sessions to make sure there was no influence of the operation order on the data gathered.

The heat output for the two radiator panels was 1640W and for the fan heater was 1500W. The fan heater was positioned close to the radiator panel 1 illustrated in Figure 2b. The average water supply temperature to the radiator panels was 50.0°C. The fan heater was directed away from the occupants in order to avoid any local thermal affects.

![Figure 6: (a)- Position of the fan heater and radiator panel in the living room (b)- Fan heater type](image)

2.3.2 Heat Gains

Internal gains in the test house were due to occupancy, a 26W minicomputer, a 20W LCD PC monitor, a 2.6W Thermal Comfort INNOVA data logger and a 0.72W Squirrel data logger set which were all placed in the living room. Lighting was also a major contributor to the internal gains which were 20W with the use of white light bulb and 160W with yellow light bulb in the living room. However, for office related equipment such as PC monitor and minicomputer, the thermal load would be only 50% of its rated capacity (Hashiguchi, N. et al., 2010). Thus, the heat gain from all the equipment inside the living room was at a minimum of 4.1W/m² (with white bulbs on) and a maximum of 12.5W/m² (with yellow bulbs on). Different coloured light bulbs were used in order to understand the impact of lighting on occupant’s thermal sensation but no significant difference were observed.

2.3.3 Calculating PMV

PMV was calculated in accordance with ISO 7730 Standard using the INNOVA thermal comfort kit.

\[
PMV = TS \times (MW - \sum_{j=1}^{6} HL_j) 
\]

Where:

- TS: Thermal sensation
- MW: Internal human body heat production
- \(\sum_{j=1}^{6} HL_j\): Heat losses

3. Results and analysis

3.1 Overall thermal comfort votes

The AMV data points recorded for all the participants’ during the use of both radiator and fan heater were plotted on a linear regression graph. Based on the results from the 1071 data points (see Figure 7), the
Root mean squared error (RMSE) between PMV and AMV was calculated as 0.75. The Root Mean Square Error (RMSE) is an indicator for the prediction agreement. There is no benchmark to assess if the value achieved in this study is acceptable but compared to a research study by Thitisawat et al. (2011) who had an RMSE of 1.24 for outdoor comfort in Florida, USA it seems PMV is reliable in a steady state condition for indoor environments. However PMV needs to be further investigated by applying it to participants who fall outside the range of 18-21 years age.

Neutral temperature based on occupant’s actual mean vote (TnAMV) was 23.5°C whilst TnPMV was determined to be 24.0°C. The value of r-squared for AMV vs operative temperature was 0.1 which suggests that a higher number of data points may not fall on the linear fit but still shows a strong significance (i.e. change in one parameter affects the other). Hence, it is observed that PMV model over predicted the thermal perception of the occupants in the detached house.

\[
\begin{align*}
\text{AMV}_y &= 0.2771x - 6.5151 \quad R^2 = 0.0964 \\
\text{PMV}_y &= 0.3245x - 7.7842 \quad R^2 = 0.9174
\end{align*}
\]

Figure 7: PMV and AMV regression by operative temperature for 1071 datasets

### 3.2 Radiator heating

The mean radiant temperature (Tmrt) was calculated using operative (Top) and air temperature (Ta) measured by the INNOVA Thermal comfort kit. For mean air speed less than 0.2 m s\(^{-1}\), Tmrt can be calculated using equation (3). This formula was also recommended in CIBSE Guide A (Race et al., 2006)

\[
T_{mrt} = (\text{Top} \times 2) - T_a \quad (3)
\]

The overall neutral temperatures for a radiator heating system was 24.0°C (TnPMV) and 23.6°C (TnAMV). The TnAMV with the use of circulation fan is 23.8°C and without a circulation fan is 22.6°C. In both cases (with and without circulation fan) the PMV still over predicted the participants’ thermal sensation as both scenarios have a TnPMV of 24.0°C. When the comfort index data points were plotted against air temperature instead of operative temperatures it was found that TnAMV equated to 22.3°C (with circulation fan) and 20.8°C (without circulation fan). This means there is a difference of 1.5 to 1.8°C
in the neutral temperature based on air temperature and operative temperatures, with air temperature resulting in lower neutral temperatures.

3.3 Convective Fan Heating

In the scenario when the fan heater was used for heating the velocity sensor near the occupants did not record any noticeable air velocities. This is due to the fact that the convector heater was facing away from the occupants. The overall neutral temperature calculated during the operation of fan heater was Tn PMV = 24.0°C and Tn AMV = 22.9°C. During additional air circulation TnPMV was calculated as 23.9°C and TnAMV as 23.6°C. It was found that lower neutral temperatures (TnAMV = 21.0°C and TnPMV = 24.0°C) were obtained without additional air circulation. It was depicted in this study that PMV is accurate in predicting the occupant’s neutral temperature. Again, with plotting thermal comfort data points against air temperature it was found that TnAMV was 23.5°C (with circulation fan) and 23.5°C (without circulation fan). In this scenario it is found that the neutral temperature based on air temperatures was 0.1°C lower than based on operative temperature in the case of additional air circulation. On the other hand without additional air circulation it was found that TnAMV based on air temperature is actually 2.5°C higher than TnAMV based on operative temperature. This is understood to be due to lower radiant temperatures (colder walls) in the case of a fan heater without an additional circulation fan.

Figure 8: Thermal comfort values vs operative temperature for radiator heating
3.4 Temperature gradient and air speed

A vertical air temperature gradient of more than 3°C can cause discomfort to occupants in an indoor environment. The temperature gradient is measured between ankle and head height whilst the participant is seated (Olesen et al., 2002). For all the test sessions conducted the average temperature gradient calculated was 2.7°C with a minimum recorded temperature gradient of 1.0°C (during the operation of fan heater with a circulation fan) and a maximum of 7.3°C (with the operation of a fan heater without circulation fan). Average temperature gradients recorded were; 1.8°C (fan heater with circulation fan), 2.0°C (radiator with circulation fan), 3.5°C (radiator without circulation fan) and 3.5°C (fan heater).

Figure 10 presents the temperature gradients recorded for different air speeds in the room during all scenarios. It is reconfirmed that lower air velocities in the room cause air stratification whilst higher velocities cause mixing of the air and thus reduced temperature gradients. One can conclude that emitters having higher velocities will help avoid discomfort caused by temperature gradients.
3.5 Gender thermal preference in a steady state low temperature heating supply system

Hasigushi et al., (2010) found out that females are more sensitive to thermal comfort in lab experiment in terms of temperature gradients. Karjalainen, (2007) also found out that females are more sensitive during winter and summer compared to males as they preferred colder operative temperature. Schellen et al. (2012) found out that females are more sensitive and dissatisfied during cooling season in both convective and radiant cooling. It was thus interesting to consider how AMV and PMV varied for different gender groups in this study. About 252 datasets of males and 225 datasets of females who participated in the same-session were analyzed using statistical methods.

In this research study, the same pattern was observed as female preferred Tn of 23.8°C compared to male counterparts who reported a Tn of 23.5°C in the same thermal environments. The standard deviation between TnPMV and TnAMV for male and female datasets was 1.9% and 11.5% respectively. Furthermore, the RMSE of PMV vs AMV was 0.79 for males and 0.97 for females.
4. Conclusion

In summary, PMV predicted higher neutral temperature compared to the AMV in a residential indoor environment. This result is in agreement with studies by Beizee et al. (2012) on houses, Hussin et al. (2014) on a mosque and Humphrey and Nicol (2002) on residential buildings for an ASHRAE RP-884 data set. The satisfactory indoor operative temperature was reported as 23.5°C which is slightly higher than that recommended by ASHRAE and CIBSE for a living room during winter season.

For the entire test sessions the average temperature gradient was 2.7°C which is less than 3.0°C above which occupants feel uncomfortable. It was reconfirmed that emitters with higher air velocities help avoid temperature stratification and thus cause smaller temperature gradients. This was proved in the case of fan heater running with an additional circulation fan. It was also found that females were more sensitive to their thermal environment compared to males and preferred the indoor temperature to be 0.3°C higher compared to males in these experiments.

Overall, it was found that although Fanger’s PMV can predict neutral temperatures similar to AMV, in UK residential buildings with radiator and fan heating systems, there is still an RMSE of 0.75 found between the two in this study. It was also established that neutral temperatures based on air temperatures are typically lower compared to those based on operative temperatures (except in the case of a fan heater without an additional circulation fan).

5. Acknowledgments

We gratefully acknowledged the participation of 119 students in Loughborough University who participated in the thermal comfort surveys. This research has been funded with the help of Mitsubishi Electric R&D Centre Europe B.V.

6. References


