Performance Assessment of Fanger's PMV in a UK residential building in Heating Season

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ABSTRACT

Traditionally there are two approaches to thermal comfort studies in the indoor environment. The first approach is to conduct tests in fully controlled climate chambers located in laboratories which help in maintaining desired environmental conditions for the experiments. However, the thermal physics of climate chambers are very different to that of real buildings. Additionally, the numbers of participants in such studies are also limited. The alternate/second approach is to place sensors and collect data in a set of homes and offices over a period of time where researchers have virtually no control on the thermal environment. This approach does involve a large set of participants however the large variations in thermal environmental parameters make the data not very reliable to elucidate trends. This paper reports on an original approach that combines the advantages of both these methods.

In this research thermal comfort studies were conducted in a test house representative of a real residential building and a large set of participants. The thermal environmental parameters and heating strategies inside the test house were also fully controlled by researchers. The aim was to assess the performance of Fanger's thermal comfort model (PMV) in predicting the actual thermal comfort of occupants (AMV) during heating season using two different types of heating emitters. A total of 119 participants between the ages of 19 and 21 years took part in these experiments. AMV of the occupants was determined by conducting surveys whilst PMV was calculated using sensors installed in the living room. Thermal neutral temperatures were calculated and compared for both AMV and PMV indices. It was found that there is a strong and directly proportional relation of both AMV and PMV with the operative temperature in the room. It was also observed that PMV would typically overestimate the neutral temperature compared to the statistically derived neutral temperature which the occupants would consider thermally comfortable.

INTRODUCTION

Fanger's thermal comfort model (1970) is typically used by researchers and practitioners in predicting occupant's thermal sensation known as Predicted Mean Vote (PMV). The model is based on the assumption that a heat balance represents the thermal perception of person in their environment. A positive heat load would suggest them feeling hot, a negative heat load would imply them feeling cold and a zero value would represent them being thermally comfortable with their thermal environment. The model takes into account a combination of environmental (air temperature, mean radiant temperature, operative temperature, relative humidity and air velocity) and occupant data (clothing insulation and metabolic rate) to calculate this heat balance.

$$PMV = \left(\alpha \times e^{-\beta \times M} + \gamma\right) \times TL/A_{du}$$

where M is the metabolic rate (W/m^2), A_{du} is the occupant's surface area (m^2). $\alpha = 0.303$, $\beta = 0.036$ and $\gamma = 0.028$ are constants whose values are derived from the statistical analysis of data produced by Fanger's experiments. TL (kcal·m^2/h) is a heat balance for the body which is given by:

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$$TL = M \times (1-\eta) \times A_{du} - [L + E_{re} + (E_d - E_{SW}) \times A_{du}] - (C+R) \times f_{cl} \times A_{du}$$

where L (kcal/h) is the sensible heat removal by respiration, E_{re} (kcal/h), E_d(kcal/h) and E_{SW}(kcal/h) are the rate of latent heat removal by respiration, vapour diffusion through the skin and sweat evaporation, respectively. η is the efficiency of mechanical work, f_{cl} is ratio of clothed surface area to DuBois surface area, C (kcal/h) and R (kcal/h) are the convection and radiation rates of heat removal from the clothing surface.

However, thermal comfort tests conducted in countries around the world showed variation in accuracy of PMV with responses from test participants (De Dear et al., 1991; Humphreys, 1994; Humphreys and Nicol, 2002; Bouden and Ghrab, 2005). Thus the objective of this study was to validate the reliability of Fanger's PMV model for its application to residential buildings in the UK with a case study. Another aim of the research was to identify the thermal sensation patterns of occupants based on the heating strategies and gender.

TEST HOUSE

Thermal comfort experiments and surveys were carried out on real people in a test house which is located on the campus of Loughborough University, UK. It is a North-West facing, two storey residential building with a pitched roof. Multiple sensors were placed in the test house to measure environmental data such as temperature, humidity, air velocities etc. The building is installed with traditional gas boiler and radiator heating system. However, fan heaters were also used for heating during certain portions of the experiments.

Figure 1 SketchUp model of the two-storey Holywell test house

INVESTIGATION PROCEDURE

Participants

Thermal comfort experiments and surveys were conducted from 19^{th} of October 2015 up to 14^{th} of November 2015. Undergraduate students from the School of Civil and Building Engineering volunteered to participate in the thermal comfort experiments. A total of 119 students (aged between 19-21 years) took part in these experiments which was a mix of both males (88/119, ~74%) and females (31/119, ~26%).

Measuring Equipment

The Actual Mean Vote (AMV) of the occupants was found by conducting surveys on the participants. However, to determine the Predicted Mean Vote (PMV) and other comfort indices the environmental parameters of the air inside the room needed to be determined and hence the living room space was fitted with sensors. Outdoor air temperatures were also measured using temperature sensors as well.

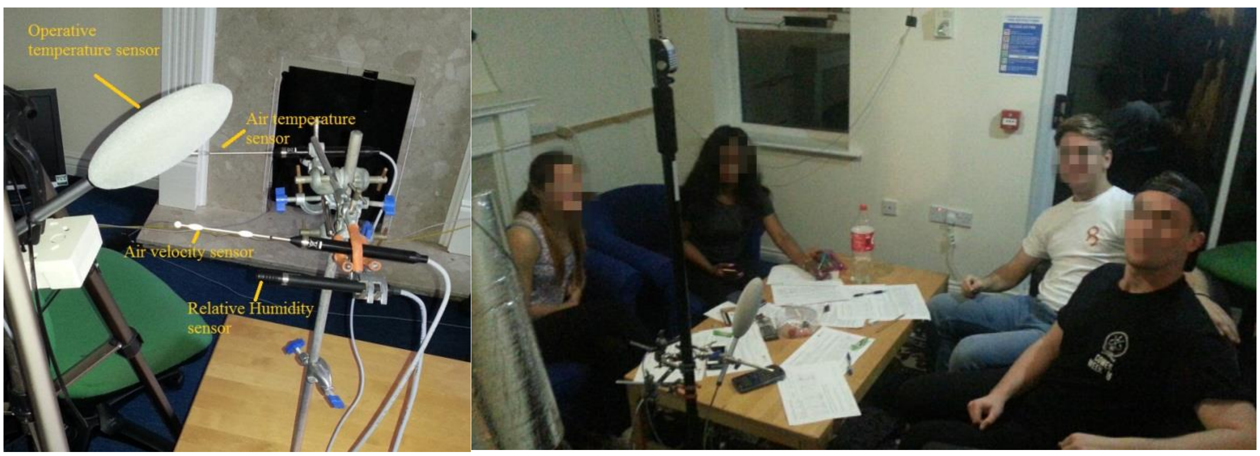

Figure 2 Left: Equipment arrangement (operative temperature sensor height 0.8m, Air Temperature sensor and Speed sensor height 0.6m and Relative humidity sensor height 0.5m). Right: Typical four participants filling in surveys

The following parameters were measured during each session: mean radiant temperature (MRT), air temperature (T_a), outdoor temperature (T_{out}), air velocity (V_a) and relative humidity (RH).

The test sessions, which were typically of 2h 15min duration, were performed in the living room of the test house with a volume size of $42m^3$. According to ASHRAE Standard 55 2010, the metabolic rate for seated sedentary activity is 1.0 met. Participants were asked to wear a t-shirt, undergarments, trousers, socks, shoes which together with the sofa fabric made up a clo-value of 0.8. CIBSE Guide B recommends a temperature range of 22-23^{o}C for occupants to feel thermally comfortable in a living room. For this reason an intermediate value of 22.5^{o}C was selected as the set point temperature which was maintained with the help of a thermostat for both radiators and the fan heater in the living room.

On the day of the test, the house was heated up to 17^{o}C (minimum allowable temperature by WHO standard) from the morning using a thermostat. When the tests were to be conducted the set point was changed to 22.5^{o}C and another 15 minutes were allowed to pass for the house to heat up. Participants were picked up in a car from a meeting point and driven to the test house so that their metabolic rate did not rise too high due to walking or cycling as that would have affected the thermal comfort test data. Participants from outside the house were then introduced into the kitchen area where they were explained the procedure of the experiments and also asked to sign a consent form. The

15min buffer in the kitchen was also created so that the participants became thermally neutral with the environment, meaning external weather affects became minimal. They were then taken to the living room where they were asked to take a seat on the sofas and carry out work such as reading or watching TV/tablet. For the first hour the living room was heated by one type of heating system. **The participants were asked to answer questionnaires at 15, 30, 45 and 60 minutes mark. For the same 15 minutes intervals readings were taken from the sensor and PMV was recorded.** At this point the first type of heating system was turned off and replaced by the alternative heating system. The procedure in **bold** was repeated again.

It is important to note that PMV predicts mean comfort vote of a large number of people exposed to the same thermal environment, wearing clothes having identical clo value and having the same activity level. This kind of scenario rarely takes place in real life which is precisely why these experiments were conducted on a specific test house, in a specific climate with a particular set of participants. The overall aim was not to assess the reliability of Fanger's PMV over a breadth of conditions but in depth for a specific set of conditions in an exhaustive manner. Further research should be conducted to assess Fanger's PMV over a broad range of conditions.

RESULTS

Overall PMV performance

Figure 3 presents the scatter plot of thermal sensation versus operative temperature (T_{op}) data points collected at 15min intervals for all the test sessions conducted. The figure combines both AMV (blue dots) and PMV (red dots) values against operative temperatures. A linear trend line is also plotted for both AMV and PMV datasets. As expected both AMV and PMV increased with increase in operative temperature for the entire test session data as well as individual heating strategy. However, thermal sensation is a combination of other (hygro-thermal and personal) factors and hence the spread of thermal sensation at every T_{op} value and also the small correlation coefficient in the linear regression. According to AMV the neutral temperature (Tn_{AMV}) was 23.5°C whereas PMV over predicted the neutral temperature (Tn_{PMV}) as 24.0°C (RMSE 0.76).

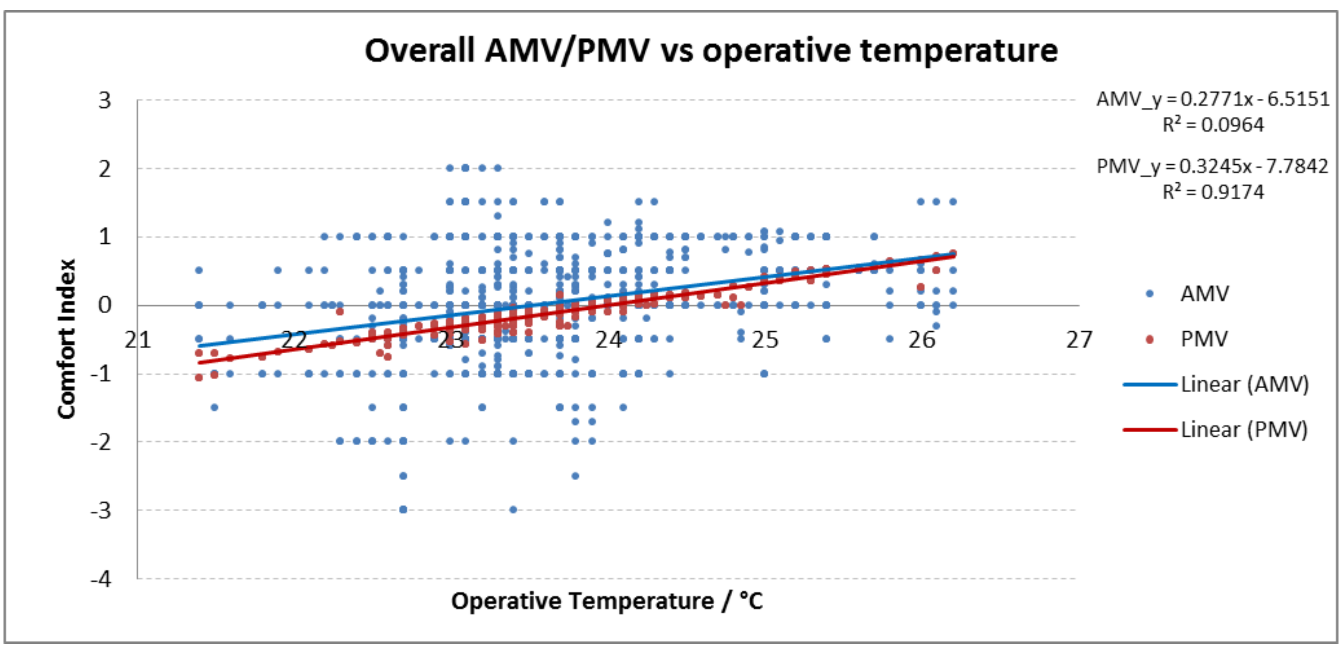

Figure 3 Overall PMV and AMV versus Operative Temperature (data points recorded at 15min intervals)

The neutral temperature being overpredicted by PMV means that most of the PMVs were under predicted. This invites investigation into the contributing variables of the PMV equation and their joint effect in the prediction of PMV. Referring to Humphreys and Nicol (2002) each individual variable is investigated for their corresponding bias in PMV. For the average operative temperature and square root air speed of 23.6^{o}C and 0.18m/s respectively, PMV shows bias to be under predicted, although very slightly. For a metabolic rate, clothing value and average relative humidity of 1.0met, 0.8clo and 24.8% (maintained in these experiments) PMV shows no bias. For an average outdoor temperature of 12.9^{o}C PMV shows a significant bias to be under predicted to an order of approximately -0.3. Thus, it seems most of the individual variables especially outdoor air temperature and their combined contribution made PMV biased to be under predicted. In the following section PMV continues to be under predicted and thence PMV neutral temperatures continue to be over predicted. The sessional average data for AMV, PMV and Top is given in Table 1.

Table 1: Sessional average data for AMV, PMV and Top

	Top[^{o}C]	AMV	PMV	Relative humidity[%]	Air velocity[m/s]
Average	23.6	0.0	-0.1	24.0	0.03
Minimum	21.4	-3.0	-1.0	21.5	0.00
Maximum	26.2	2.0	0.8	26.9	0.20

PMV performance based on heating strategy

The test sessions were of two hours; for the first hour the living room would be heated by a conventional boiler and radiator system and for the next hour by a convective fan heater or vice versa. Figure 4 presents data points recorded for the test sessions with the radiators on. For the radiator heating Tn_{AMV} was found to be 23.6^{o}C whereas Tn_{PMV} was again over predicted to be 24.0^{o}C (RMSE 0.77). In case of the fan heater (Figure 5) Tn_{AMV} of 22.9^{o}C was determined whereas Tn_{PMV} predicted a value of 24.0 ^{o}C (RMSE 0.75).

Again in both cases PMV overpredicted the neutral temperature i.e. it under predicted occupant's thermal sensation vote. It is also worth noting that occupants were inclined to lower temperatures in the case of the fan heater. This is due a warmer micro climate that was created across the living room by the fan heater in the area where occupants were seated. The presence of a micro climate was confirmed by multiple temperature sensors placed in the living room space. With radiator heating the temperature across the plane at height 0.6m was within a range of 22.5±0.5^{o}C whereas in the case of a fan heater the temperature range was 22.5±1.1^{o}C. The differences between Tn_{AMV} and Tn_{PMV} are found to be similar for the case of radiators and fan heater thus Fanger's thermal model works well in both heating emitter types

Gender based performance

Another interesting aim of this research was to determine the performance of Fanger's PMV model based on gender. As the test subjects that participated in these experiments constituted of both male and female hence their gender wise perception could be investigated. However, the number of male to female participants was considerably higher thus to conduct an accurate comparison, only those test sessions where both male and female (28 to 25 ratio) participated were isolated for the following analysis. Although the number of male and female participants for this specific analysis is low, and further studies with a higher number is recommended, previous studies have analysed fewer participants (e.g. 10 participants by Schellen et al. (2012)). Figure 6 and 7 present AMV and corresponding PMV for male and female participants respectively. For males Tn_{AMV} was 23.5^{o}C whereas Tn_{PMV} was 24.0^{o}C (RMSE 0.8). Similarly, for females Tn_{AMV} was 23.8^{o}C while Tn_{PMV} was 24.0^{o}C (RMSE 0.97). It is observed that PMV continues to over predict the neutral temperatures for both data sets however Fanger's model showed lower prediction error for males. Additionally as expected PMV predicted approximately the same neutral temperature for both genders as it does not take into account gender in its calculation. However, male participants reported of a lower neutral temperature (~0.3ºC) compared to females. This suggested that females desired higher temperatures compared to males.

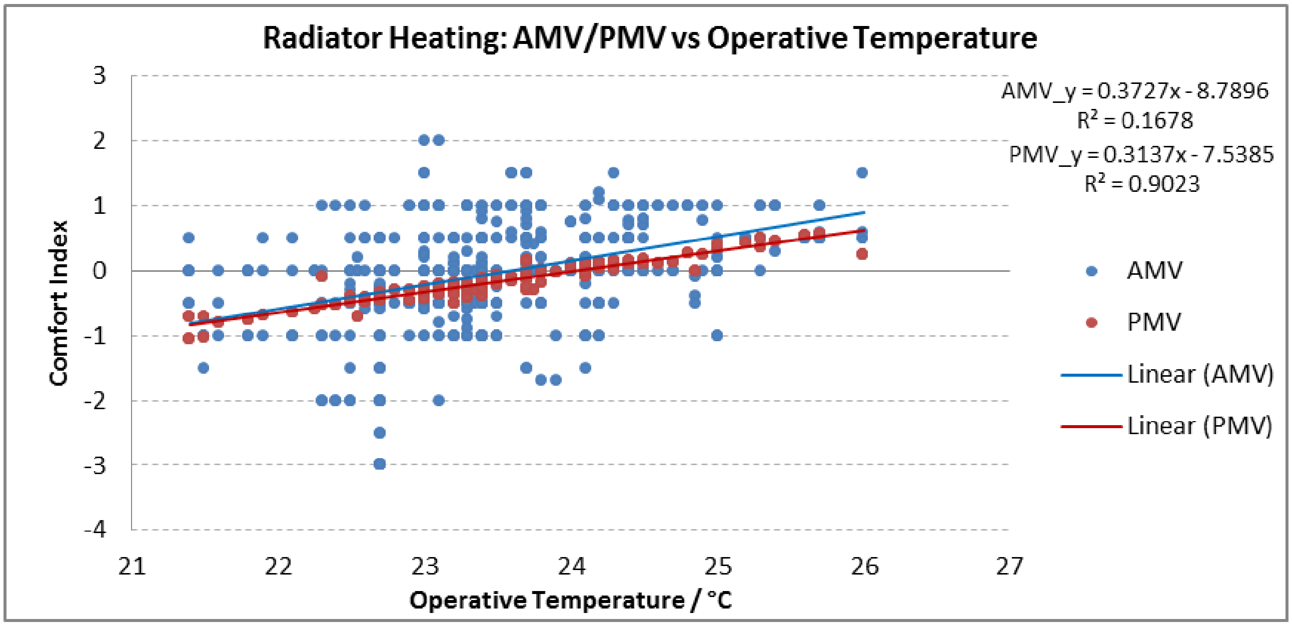

Figure 4 PMV and AMV versus Operative Temperature for radiator heating

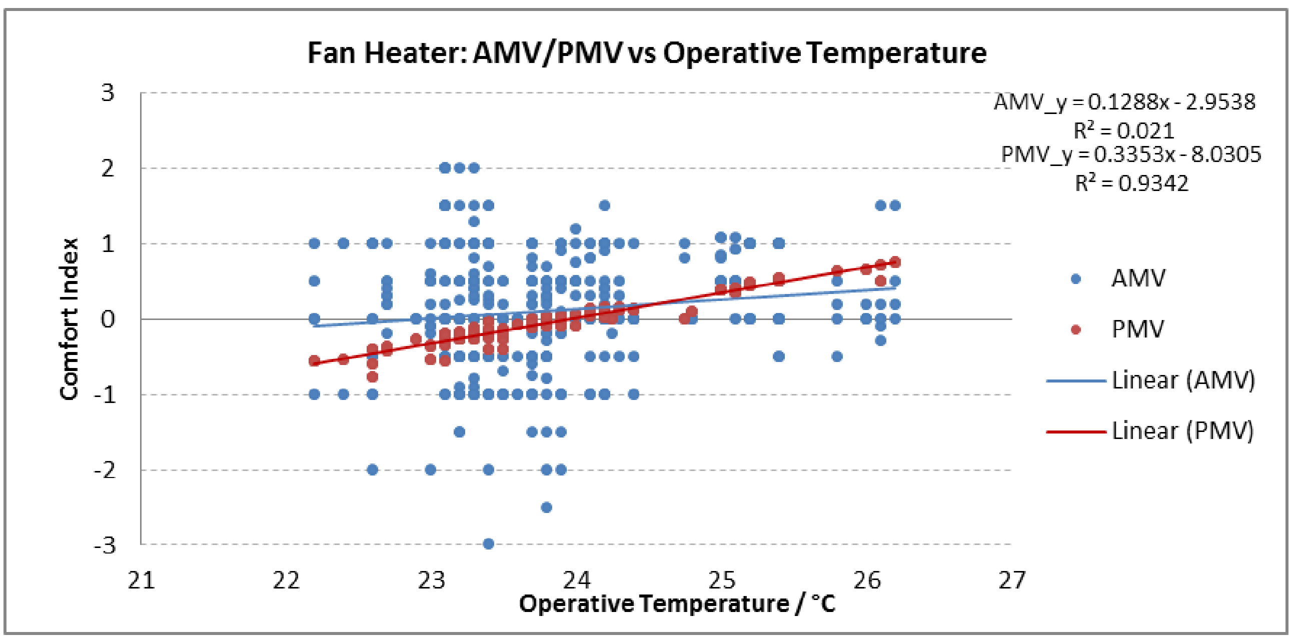

Figure 5 PMV and AMV versus Operative Temperature for fan heater

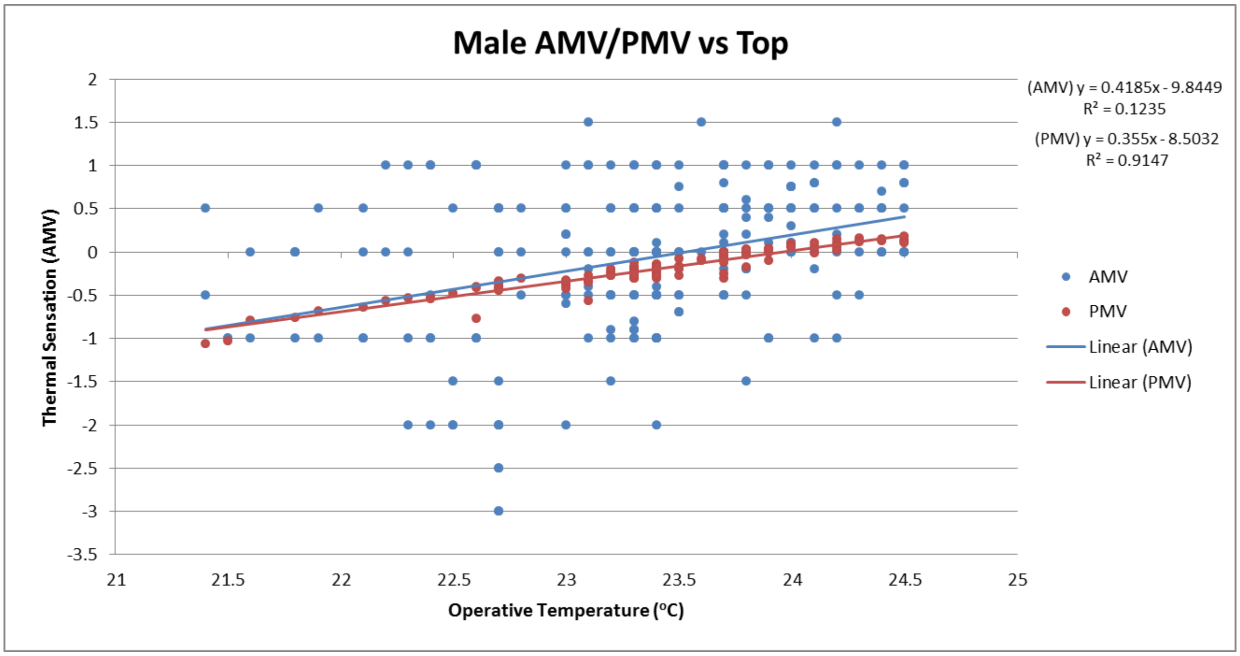

Figure 6 AMV/PMV for male participants

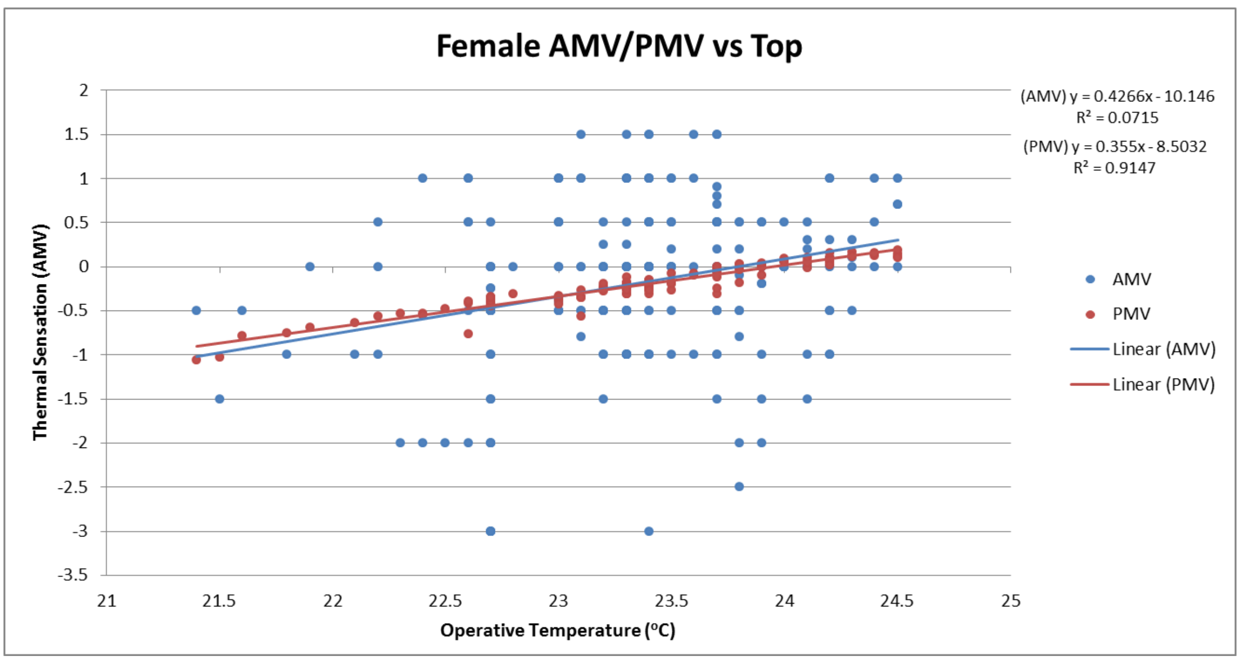

Figure 7 AMV/PMV for female participants

CONCLUSIONS

It was found that for 119 occupants in a heated residential building in the UK, Fanger's PMV model continuously under predicts occupant's thermal comfort in comparison to their actual sensation AMV. This results in the neutral temperatures predicted by PMV to be always higher than those reported by AMV. Linear regression for recorded thermal sensation (AMV) versus operative temperatures was weak which is due to the fact that both indices are based on a combination of hygro-thermal and personal factors rather than operative temperatures alone. On the other hand, linear regression for predicted thermal sensation (PMV) versus operative temperatures was strong. Overall it was found that Fanger's PMV predicted AMV with an overall RMSE of 0.76 compared to AMV. It was also found that Fanger's model performs better for both type of heat emitters i.e. radiators and fan heaters. It was also observed that PMV was able to better predict males thermal perception (RMSE 0.8) compared to females (RMSE 0.97). It was also determined that females preferred a 0.3°C higher temperature compared to males in a heated residential building in the UK. However, the number of female participants in these experiments was small which makes this aspect an interesting area of further research.

ACKNOWLEDGMENTS

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NOMENCLATURE

AMV = Actual Mean Vote

MRT = mean radiant temperature

PMV = Predicted Mean Vote

RH = relative humidity

T_a = air temperature

T_{MMO} = mean monthly outdoor temperature

T_n = neutral temperature

T_{op} = operative temperature

T_{out} = outdoor temperature

V_a = air velocity

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