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Yao et al. explored adaptive comfort with 3D curve fit method on PMV data [3]. Gao et al. developed eTSV and modified SET* model based on his dataset by using aPMV and ePMV methods [9]. This research distinguished the methods by air speeds of less than and more than 0.2 m/s. Gao et al. also found that the modified SET* had better accuracy in predicting the reported thermal sensation (TSV) compared to the modified PMV [9].

The performance of each of these models needs to be verified in predicting thermal comfort with the help of distinct databases. Thus, in this study the suitability of PMV-based models such as Fanger's PMV, Gagge Pierce two-node: SET* and new effective temperature ET* models were evaluated in a test house. Little research has been conducted in residential buildings with a large set of participants thus the aim is to use a large number of participants as test subjects. Additionally, as residential buildings with smaller volumes and radiator heating are more prone to sharp gradients in vertical air temperatures (temperature gradients). This is because of smaller volumes with 0.87 ACH may contribute to uneven air temperature during winter as a lower air change rate will reduce vertical air stratification [10].

In this paper, a new comfort model has been developed that incorporates temperature gradient of the space in predicting suitable temperatures for occupants. This was possible using the polynomial plot method [6]. In this method a 3D curve fit is plotted between three influential parameters to define the neutral temperature of the participants. This is different to linear fits that are plotted between two influential parameters. This method was chosen as it has the capability to correlate a second indoor environmental parameter with AMV [11].

Methodology

The test house

Thermal comfort tests were conducted from October to November of 2015 and November to December of 2016 in a two-storey detached test house with exposed mass located in the Midlands (Figure 1). The test house located in the Holywell Park of the Loughborough University campus is a North-West facing, two storey residential detached building with a pitched roof. The exterior of the test house is exposed brick work and was built in the 1998. 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 W/K and an infiltration rate of 0.87 ach measured in 3 consecutive seasons by Jack R. The infiltration rate was measured using a blow door test and is relatively high compared to an average of 0.4 each for a UK home. The house is classified as medium air tightness and is moderately insulated according to BSI-13790 [12]. All the comfort surveys and tests were carried out in the living room the dimensions of which are presented in Table 1.

Figure 1: Exterior isometric view of the test house.

Experimental procedure

A total of 119 students (both male and female) took part in the thermal comfort experiments. On average four subjects were present at each thermal comfort session. Participants from outside the house were then introduced into the kitchen area where they were explained the procedure of the experiments and asked to sign a consent form. The 30 min buffer in the kitchen was also created so that the participants became thermal 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. The four subjects were allowed for any adaptive opportunities such as changing their clothing levels, opening a window or tempering with the heating system throughout the duration of the test sessions. The participants were asked to answer questionnaires at 0, 15, 30, 45 …. 120 minutes mark. For the same 15 minutes intervals readings were taken from the sensors and PMV was calculated. A total of 54 sessions of thermal comfort survey with different subjects were conducted and 1837 datasets were collected.

Sensor measurements consisted of 4 environmental indoor parameters (air temperature, mean radiant temperature, air velocity and relative humidity). These were measured by the thermal comfort kit (Figure 2a and 2b) with the detail specifications in Table 2. The operative temperature was measured via sensor whilst Tmrt was calculated using eqn. (1). The thermal comfort kit was placed in front of participants with a distance greater than 30 cm away from the subjects and at a height of 60 cm from the floor in the living room [13]. A data logger was used to measure the outdoor air temperature together with the air temperature stratification inside the room at heights of 0.1 m, 0.6 m, 1.1 m and 1.7 m from the floor. The participants were observed for their clothing levels and the activities they were conducting. These were then reference with CIBSE guide A to calculate an average clo value with the sofa resistivity of 0.76 clo with a tolerance of ± 0.04 and the sedentary metabolic rate of 1.0 met which is equivalent to 58.2 W/m^2.

$$= (T \times 2) - \quad (1)$$

The survey measurements were based on the 7-point Bedford comfort scale and ASHRAE Standard 55 questionnaire on thermal sensation [14]. e participants were asked to report their thermal sensation (TSV/AMV) between -3 to 3 every 15 minutes. is may seem short time duration for the human body to adapt but skin sensation does adapt quickly. Another reason this time duration was chosen is because it is what past researchers have also utilised [15].

Performance Analysis of Current PMV Based Models

Before a new comfort model is generated for the current experimental data it was important to see which of the currently established comfort models perform the best in predicting thermal comfort of the participants. To conduct the performance analysis of the various comfort models a datum parameter was selected. For this study it was the neutral temperature (Tn) which is the temperature at which participants would feel the most comfortable with their thermal environment. Tn is calculated using the linear regression method on the AMV data points versus operative temperature (Top). e following PMV based models were chosen as the candidates:

ePMV=e × PMV (Fanger and To um) [2]

aPMV=PMV/(1+λ PMV) (Yao et al.) [3]

PMVnew=0.8(PMV − Dpmv − vote) (Nicol and Humphreys) [7]

PMVn=−5.151+0.202Ta+0.553Vp (Orosa) [7]

TSVse=ePTS (Gao et al.) [9]

TSVsa=PTS/(1+λPTS) (Gao et al.) [9]

PMVashrae=−6.802+0.243Ta+0.278Vp (ASHRAE) [6]

PMVSET =(0.028+0.303 −0.036) × (H − Lset) (Gagge) [1]

ePMVgao=ep × PMV (Gao et al.) [9]

Please note: H is the internal heat production rate per unit area (W/m^2). L represents all modes of energy loss from body (W/m^2) in PMV. SET* will replace Top in PMV to become PMVSET*.

Also, $ep = \frac{\sum_{i=1}^{n} TSVi \; PMV}{\sum_{i=1}^{n} PMVi^{2}}$

e neutral temperature based on the AMV of all the occupants was determined using linear regression to be 23.4°C. is is higher than the recommended temperature range of 22-23°C by CIBSE for living rooms in a residential property [16]. It was interesting to understand how the di erent comfort models stated previously perform in predicting this neutral temperature. Fanger's famous PMV model predicted a neutral temperature of 24.2°C which results in a standard deviation (SD) of 0.8°C which is illustrated by red bars in Figure 3. In the same gure,

Instruments	Description	Range	Accuracy
Lumisense INNOVA 1221 Thermal comfort controller	Thermal comfort controller	N/A	±0.1°C
Operative temperature Model number: MM0060	Read indoor operative temperature	5-40°C	±0.3°C
Air temperature Model number: MM0034	Read indoor air temperature	5-40°C	±0.2°C
Relative Humidity Model number: MM0037	Read relative humidity, Dew bulb temperature	-20 to 50°C with Operating temperature: 5-40°C	ta-td < 10 K: ±0.5 K or ±0.05 kPa 10 K < ta-td <25 K: ±1.0 K or ±0.1 kPa

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that the five models LPMV1 to LPMV5 have significantly less SD in predicting occupant's neutral temperature.

In order to conduct scientific rigour, the five LMPV models will be tested against unrelated thermal comfort data that was compiled from different experiments by other researchers in different locations in the UK. For this reason, data from the RP-884 database in South Wales and Liverpool, UK have been utilised. Figure 10 presents the