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Validating Fanger's PMV model in a "real" field study.

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Abstract

Fanger's predicted mean vote (PMV) model of thermal comfort perception is criticised for the consistency of its results with the actual mean vote (AMV). This is mainly because Fanger's PMV model assumes some particular circumstances that hardly ever occur in real world experience, such as the similarity of personal variables and other psychological parameters. However, a broader ongoing research project examining thermal comfort in mosques in Riyadh, Saudi Arabia, has provided an unusually well formed vehicle to validate the PMV model in a real field study. Comparing the results of the predicted mean vote (established by monitoring the relevant variables to match the outputs of the application of PMV model), and the actual mean vote(s) of this real field study is thought to be the most appropriate basis for the validation of the PMV model.

In this paper, the overall context of the mosque as the case study is described. The methodology and the methods including the instrumentation and the questionnaire are highlighted. Preliminary results of monitoring and perception surveys are reported, including some analysis of the PMV/AMV relationship.

Keywords
Thermal comfort, PMV, AMV, Validating, Field study, Mosque.

Introduction

Fanger's PMV model uses four environmental variables, air temperature, relative humidity, air velocity and mean radiant temperature MRT, in addition to two personal variables, clothing insulation and metabolic rate. These variables are used as inputs to predict the mean comfort vote of a group of subjects on the ASHRAE seven points thermal sensation scale (Fanger, 1970). Even though the model is the most commonly adopted in academic research, it has been criticised in much of the same work regarding the consistency of the results when applying the model in a real world field study. To be correctly validated as it is originally developed; the model needs to be tested in a steady slate environment, a controlled single space. The metabolic rate of the occupants is always generalized as one input, which is misleading because it is hardly likely occur in the real world (Goto et al, 2006), especially when ignoring the differences in metabolism between males and females. Furthermore, the type of furniture affects the clothing insulation value (de Dear, Brager and Cooper, 1997; ISO 9920, 2007). Some researchers argue that poor measurement of clo value and metabolic rate caused the differences between measured and predicted mean votes in real field studies (Brager et al, 1993; de Dear, 1998; de Dear and Brager, 1998; Parsons, 2001; de Dear, 2002; Humphreys and Nicol, 2002). But perhaps most importantly, the adaptability factor affected the output of the model in field studies (Brager and de Dear, 1998 and 2000) because it is a psychological parameter that could not be prevented nor estimated.

Humphreys and Nicol (2002) were one of the first scholars to deeply question the validity of PMV model in every-day normal life. According to them, "*PMV predicts the mean comfort vote of a large group of people exposed to the same thermal environment, wearing clothes having the same level of insulation, and all having the same level of activity. This circumstance rarely, if ever, occurs in practice... How then can PMV be tested against these data?"*(Humphreys and Nicol, 2002, p.669). This concern whether the PMV model can be validated outside the laboratory is addressed by Kotbi, King and Prasad (2010), by proposing mosques in Riyadh Saudi Arabia, with their particular context as the ideal case study. This paper presents some results of the proposed study.

The case study

As it is proposed previously (Kotbi, King and Prasad; 2010), the air conditioned mosque in Riyadh, Saudi Arabia can serve as the idealised vehicle to validate Fanger's PMV model in the real world.

The mosque typically has a single large space occupied in several intermittent durations of around 15 minutes each. The mosque is occupied five times daily for the compulsory daily prayers, Fajr "dawn", Dhuhr "midday', Asr "afternoon", Maghrib "sunset", Isha "night". These five names are refered to in this paper, by "Prayer times". The functional area is easily defined, closely approximating a steady state condition environment.

The personal variables of the occupants are very consistent, as all the users are males, practicing the exact similar activity level in substantially similar clothing ensembles, with no furniture factor to be added to the clo value. Most importantly, when dealing with mosques, the adaptive opportunities (Baker and Standeven, 1995) is minimized, because any intentional movement departing from the actual performance of the prayer is not allowed by custom. Therefore, during the prayer, there is no adaptive modification to the personal environment nor the space environment by any means. Finally, the expectation factor is also minimized, as in the context of Riyadh, Saudi Arabia, all buildings are air-conditioned in the summer (Kotbi, King and Prasad; 2008).

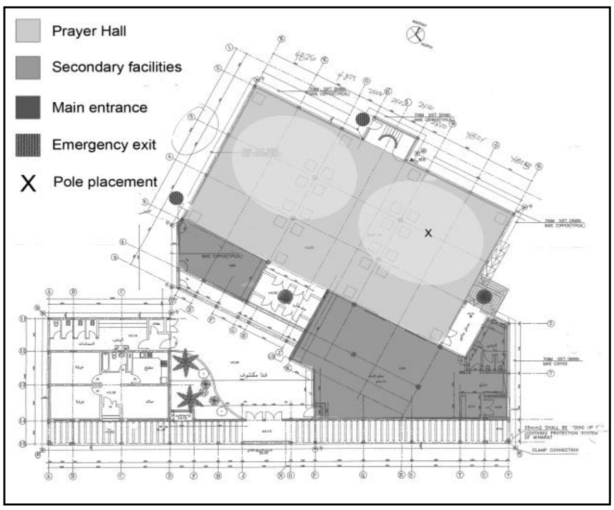


Fig. 1 The floor plan of the selected mosque

The main criteria for selecting the most appropriate mosque for this particular field study are as follow:

- It should be occupied in regular basis, i.e. occupied in all the five daily prayers;
- the occupants preferably should be highly educated, to make sure that instrumentation in the middle of the mosque for a scientific study is acceptable;
- the selected mosque should have minimum number of exits, to make it more manageable in terms of collecting questionnaires.

After reviewing some nominated mosques in Riyadh, the selected building was the mosque of a residential compound for university professors. It has only two accessible thresholds, which make it easy to manage. The praying hall is 29m by 19.2m with 5.2m height. It has window openings only on the north and south sides. The interior finishing is white painted walls and carpet floors. The average occupancy is 3.5 rows; each row holds approximately 250 persons. Fig (1) shows the selected mosque, with its secondary facilities; it should be clear that the word “mosque” from here onwards refers to the prayer hall only.

Methodology

Outdoor climatic data is collected to record outdoor climatic variables at the time of each prayer under investigation, using a Maxkon® WSAC003 weather station to record outdoor variables, at 30 minutes intervals. The weather station was installed over a roof of a neighbouring house to the mosque to monitor the outdoor temperature, relative humidity and wind velocity. It has sensors with a resolution of 0.2°C and 1% RH. Fig.(2) shows the outdoor equipment.

The Fanger PMV model requires four indoor environmental variables as inputs: air temperature, mean radiant temperature, wind velocity and relative humidity (Fanger, 1970).

Fig. 2 Outdoor weather station

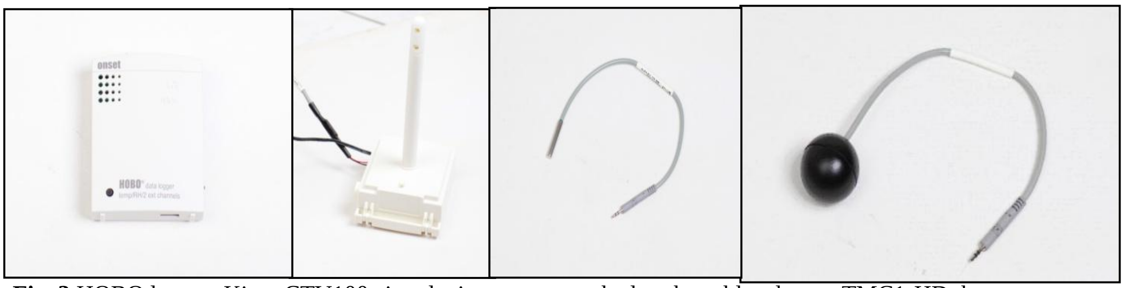


Fig. 3 HOBO logger, Kimo CTV100 air velocity sensor attached to the cable adapter, TMC1-HD thermo sensor and the same thermo sensor attached to black 40mm ping pong ball

To approximate the MRT, globe temperature data is recorded, which is then used to calculate the MRT (Hey, 1968; ISO7726,1998). According to Humphreys (1977), when the air-movement is slight, around 40mm diameter thermometer is theoretically preferable for measuring indoor globe temperature.

Thermal comfort field studies are categorised into three classes (de Dear 1998). In the class I category, all the variables should be collected at three heights, 1.2m, 0.6m and

0.1m. Therefore, to record indoor environmental variables, three of each of the followings were used. ONSET® TMC1-HD temperature sensor attached to black 4cm diameter ping pong ball, Kimo CTV100 directional duct air velocity sensor, ONSET® ADAP-10 cable and HOBO® U12-13 data logger. See fig.(3). All the instruments were attached to a medical drip pole at three heights, 1.2m, 0.6m and 0.1m. Fig.(4) shows the equipment used to assemble the instrumentation, with the final look of the monitoring pole.

Fig. 4 The assembled monitoring pole

It should be stated that because of budget limitations, the air velocity sensor used in this study is a directional hot-wire sensor and not an Omni-directional sensor as recommended for a Class I field study for thermal comfort (de Dear, 1998). Therefore, a small experiment was conducted in the mosque to determine the best orientation for positioning the air velocity sensors. After assembling the sensor on the pole at the three heights, three orientations of the aperture axis of the hot wire sensor were tested during regular prayers: east-west direction (x), north-south direction (y) and vertical direction (z). The experiment confirmed that the (y) direction was the best direction to represent the general air movement in the mosque, in as much as it gave the greatest discrimination of recorded values for turbulent air movement.

The mosque was investigated for the best place to position the monitoring pole. As it has a symmetrical rectangular shape, it was decided that the middle of one identical half of the mosque is the most representative position for the environment of the mosque. The average number of rows occupied by the worshipers was also considered; based on that, the pole was positioned between the third and the fourth row. Fig.(1) shows the assigned position of the pole inside the mosque.

Fig. 5 The pole and the cards placement inside the mosque

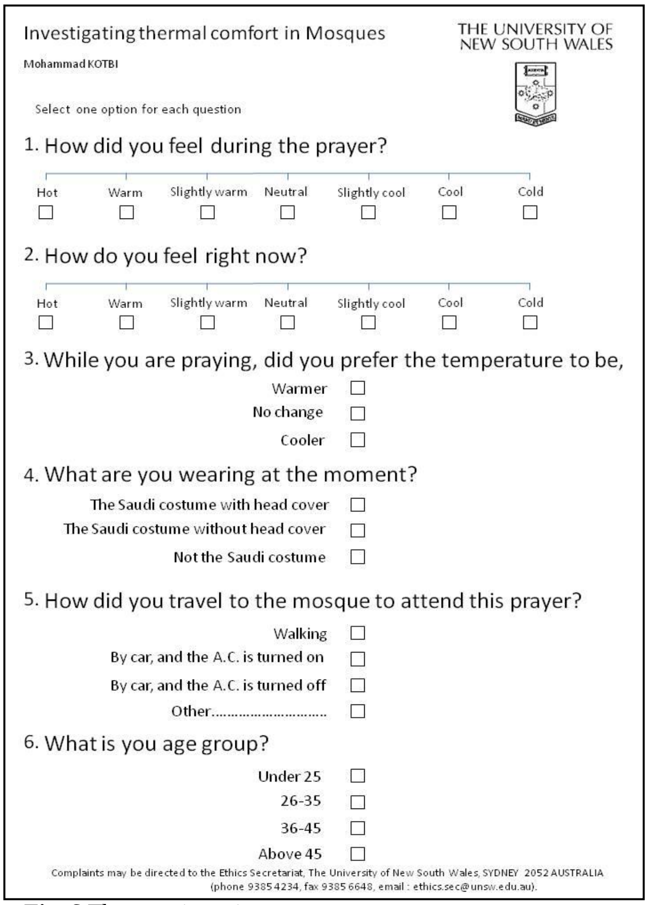
After praying for around 15 minutes, the occupants are assumed to reach appropriate steady state metabolic rate (Goto et al., 2006). In order to maintain this steady state metabolic rate of the worshippers, the questionnaire was designed to be filled within 30 seconds (Kotbi, King and Prasad, 2010 and 2011), with only six multiple choice questions. It also was purposely printed on A6 size card to minimise the filling time.

Collecting boxes were placed at the two exits. A poster explaining the purpose of the study is available at each exit to satisfy the requirements of the ethics approval. Before each prayer, cards with pencils were placed approximately two meters spacing along each row. After each prayer, some of the interested worshipers fill the cards as soon as they finished the prayer; they have the option of putting the filled card in the collecting box or the convenience of leaving the card wherever it was. However, all the cards are collected after each prayer. Basic information is also recorded for each prayer, such as date, prayer name, starting time, ending time, occupancy by row counting. Fig.(5) illustrates samples of the placement of the questionnaire cards around the mosque.

Fig. 6 illustrates a sample of the questionnaire in English translation. The questionnaire consists of three questions relating to thermal sensation: the worshiper's thermal sensation during the prayer and after the prayer on ASHRAE scale, and whether he would prefer any change in temperature during the prayer. Three further questions address what is considered the minimum necessary personal variables:

- Clothing: whether the worshiper is wearing Saudi national costume, and if head dress is included in the costume;
- To test if there may be an effect from the immediately preceding environmental experience on the thermal sensation, the mode of transport to the mosque;
- Age (group) of the respondent.

To complete the PMV inputs, the personal variables of clo value and metabolic rate should be addressed. Referring to the questionnaire, we know if the respondent is wearing the Saudi costume with or without head dress, or if he is wearing casual clothes. Summer clothing is made from fine layer of cotton blend fabric in white color. The headdress is optional. The literature review revealed that the clo value of Arabian Gulf men's clothing has been calculated previously using a thermal manikin (Al-Ajmi, 2006). The clo value of the summer traditional costume is 1.05 without headdress and 1.13 if headdress is worn (Al-Ajmi, 2006; ISO9920, 2007).


Investigating thermal comfort in Mosques
THE UNIVERSITY OF NEW SOUTH WALES
Mohammad KOTBI

Select one option for each question

1. How did you feel during the prayer?

Hot ☐ Warm ☐ Slightly warm ☐ Neutral ☐ Slightly cool ☐ Cool ☐ Cold ☐

2. How do you feel right now?

Hot ☐ Warm ☐ Slightly warm ☐ Neutral ☐ Slightly cool ☐ Cool ☐ Cold ☐

3. While you are praying, did you prefer the temperature to be,

Warmer ☐
No change ☐
Cooler ☐

4. What are you wearing at the moment?

The Saudi costume with head cover ☐
The Saudi costume without head cover ☐
Not the Saudi costume ☐

5. How did you travel to the mosque to attend this prayer?

Walking ☐
By car, and the A.C. is turned on ☐
By car, and the A.C. is turned off ☐
Other.............................. ☐

6. What is you age group?

Under 25 ☐
26-35 ☐
36-45 ☐
Above 45 ☐

Complaints may be directed to the Ethics Secretariat, The University of New South Wales, SYDNEY 2052 AUSTRALIA (phone 9385 4234, fax 9385 6648, email : ethics.sec@unsw.edu.au).

Fig. 6 The questionnaire

The other personal variable is the metabolic rate. As described earlier; all the worshippers perform precisely the same movements and activity level, which make it very safe to estimate the metabolic rate and generalise it to represent the metabolic rate of all the occupants of the mosque (Kotbi, King and Prasad, 2010 and 2011). The prayer consists of some bodily postures and light relaxed activity, including sitting, kneeling, bowing, prostrating and standing. It is clearly a low activity and after reviewing the literature

(ISO8996, 2004; Al-Ajmi, 2010), the metabolic rate was estimated to be 1.3 met.

Finally, to expand the range of operative temperature, the thermostat of the air-conditioner was adjusted randomly between 66°F and 78°F i.e. 19°C and 25.5°C one hour before each prayer, and never during the prayer.

Data collection

The field study was conducted during the summer month of July 2011. It should be mentioned that because the prayer times are governed by the solar calendar, it is more accurate for the study to not spread to cover all the season. Also, to maintain the coherence of the data, Nicol (2008) recommended that thermal comfort surveys should be limited by two weeks or less. Because of that, seven days within two weeks in the middle of summer season are focussed on. Furthermore, to ensure the consistency of the nature of the occupancies, the weekends, i.e. Thursday and Friday, were excluded, and only weekdays were investigated. Furthermore, assure reaching metabolic steady state (Goto, et al.,2006), any single prayer with less than 15 minutes duration was excluded.

The field study consisted in monitoring outdoor temperature and humidity all day, as well as the indoor environment of the mosque during the occupancy periods, i.e. prayer times, between 9-19 July 2011. The study collected indoor variables for 33 prayers, 6 Fajr prayers, 6 Dhuhr and 7 for each of, Asr, Maghrib and Isha prayer. During these investigated prayers, questionnaire survey was also conducted, the total number of responses being 422 with an average of 13 responses for each single session.

From the total number of questionnaire respondents, 26% are under 25 years of age and 39% are over 45 years, while 21% and 10% represent the category of 26 to 35 years and 36 to 45 respectively. Moreover, the questionnaire revealed that 66% of the occupants travel to and from the mosque by walking, while 21% use car with air-conditioning switched on, and only 8% use the car without using the air-conditioning in the car. For the clothing ensemble, around 67% of the occupants were wearing the national costume; head dress was included in the costume with nearly half and not included in the other half. For the consistency of the results and to minimise the error in estimating the clo value, the respondents that do not wear the national costume were excluded from the data analysis.

Table 1. Statistical summary

	FajrX6	DhuhrX6	AsrX7	MaghribX7	IshaX7	All
Air temperature °C						
Mean	21.01	21.88	22.14	21.70	21.72	21.72
STD	1.12	0.69	1.34	0.98	0.96	1.12
Max	22.91	23.54	24.91	23.63	23.48	24.91
Min	19.07	21.21	20.86	20.65	20.56	19.07
Air velocity m/s						
Mean	0.241	0.266	0.226	0.221	0.301	0.253
STD	0.06	0.07	0.09	0.11	0.07	0.09
Max	0.330	0.389	0.383	0.368	0.421	0.421
Min	0.145	0.192	0.057	0.087	0.187	0.057
Relative Humidity %						
Mean	34.57	34.18	32.74	29.01	30.62	31.91
STD	6.16	6.69	6.75	5.50	4.67	6.21
Max	45.20	43.71	39.23	37.28	39.15	45.2
Min	27.12	25.38	22.81	21.71	23.97	21.71

Operative temperature °C						
Mean	20.74	21.73	22.04	21.44	21.69	21.57
STD	1.04	0.74	1.31	1.05	0.90	1.12
Max	22.63	23.53	24.87	23.48	23.30	24.83
Min	18.96	20.99	20.98	20.31	20.48	18.84
Actual Mean Vote AMV						
Mean	-0.64	-0.02	0.11	-0.16	-0.46	-0.19
STD	1.34	1.24	1.22	1.09	1.11	1.06
Max	3.00	3.00	3.00	3.00	3.00	3.00
Min	-3.00	-3.00	-3.00	-3.00	-3.00	-3.00
Predicted Mean Vote PMV						
Mean	-0.14	0.04	0.12	0.01	-0.03	0.01
STD	0.27	0.19	0.29	0.26	0.19	0.26
Max	0.53	0.54	0.77	0.48	0.29	0.77
Min	-0.57	-0.17	-0.21	-0.38	-0.35	-0.57
Outdoor temperature °C						
Mean	35.72	42.11	44.62	42.57	41.54	41.60
STD	2.13	0.81	0.48	0.33	0.55	3.01
Max	38.10	43.2	45.3	43	42	45.3
Min	32.90	40.9	43.8	41.9	40.6	32.9

Table (1) provides a statistical summary of thermal environment, thermal indices and the outdoor temperature. The average of the total prayers for each "prayer time" is presented. From the table, operative temperature ranges from 18.8°C to 24.8°C, with average of 21.57°C. Air velocity ranges from 0.421m/s and 0.057m/s, with 0.253m/s average. This is because of the process of randomly adjusting the air-conditioner thermostat, which also caused the outdoor temperature to be not correlated with the indoor operative temperature or the mean vote values.

Data analysis

It is clear from table (1), that even though the average PMV is 0.01, the actual mean vote of the occupations was -0.19. That means that even when the adoptive opportunities are minimised, the clothing insulation is similar and the activity level is similar, PMV model seems to overestimate the warmth sensation on average. However, further analysis should question this result.

To compare the actual mean vote (AMV) with the PMV of the occupants of the mosque, a linear regression is generated after PMV was binned to 0.10 intervals and analysed to reveal the bin's mean thermal sensation. Each value of average AMV is weighted according the sample size that it represents.

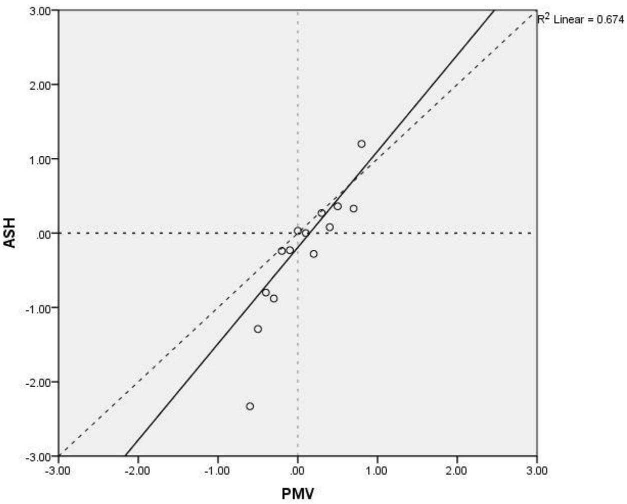


Figure 7. AMV-PMV correlation

Figure (7) shows a linear regression of the following equation:

AMV= 1.29PMV-0.2 (r^2=0.674). Eq.(1)

From Eq.(1), when PMV model predicts the mean thermal sensation to be neutral "Zero", the actual mean thermal sensation is -0.2. However, according to the same equation, when PMV is (+1), AMV is (+1.09), and when PMV is (+2), AMV is (+2.38). On the other hand, when PMV is (-1), AMV is (-1.49), and when PMV is (-2), AMV is (-2.78). This suggests that with neutral and cool air-conditioned environments, PMV over estimate the perception of warmth, while with warmer air-conditioned environments it tend to under estimate the warmth slightly.

In the next step the regression function was derived for PMV and AMV as a function of operative temperature. Indoor operative temperatures of each case were binned into 0.5^{o}c intervals and analysed to reveal the bin's mean score of PMV and AMV. Again, each case was weighted according to its sample size, to generate the linear regression in Figure (8). Equations for AMV and PMV according to the operative temperature are as follow:

AMV= 0.307top - 6.85 (r^2=0.697) Eq.(2)
PMV= 0.214 top – 4.62 (r^2=0.979) Eq.(3)

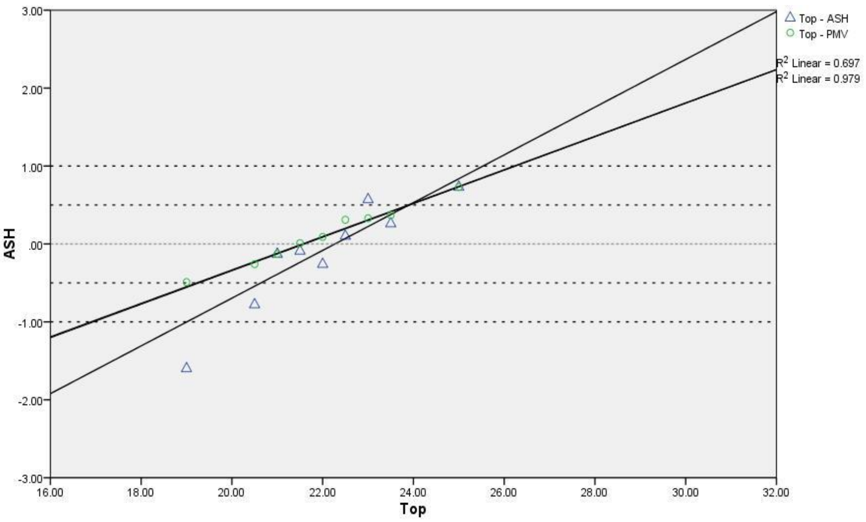


Figure 8. Linear regression calculation based on binned AMV and PMV (vs.) operative

The neutral operative temperature i.e. when the mean vote is (0) is calculated from these equations as 22.31^{o}C for AMV and 21.59^{o}C for PMV. For operative temperature neutrality, PMV underestimates the observed neutrality by 0.72K.

To further analyse the equations, thermal acceptability is considered. Any mean vote between the range of -1, +1 or -0.5, +0.5 on ASHRAE seven point scale accounts for 80% and 90% thermal acceptability respectively (Fanger,1970; ASHRAE,2004; ISO 7730, 2005). From the equations Eq.2 and Eq.3, PMV predicts 80% and 90% thermal acceptability to be between 16.92^{o}C-26.26^{o}C and 19.25^{o}C-23.93^{o}C respectively. On the other hand, the observed 80% and 90% thermal acceptability from the AMV were found to be between 19.06^{o}C-25.57^{o}C and 20.68^{o}C-23.94^{o}C respectively. Surprisingly, this result shows that PMV predicted a *wider* range of thermal acceptability than has been observed. To further investigate this result, the sensitivity of each of AMV and PMV from Figure (8) is examined. Sensitivity of AMV and

PMV that is reflected by the change in operative temperature were found to be $0.307/^{o}c$ and $0.214/^{o}c$ respectively. It is clear that in this particular case study, with the extreme limitation of adaptive opportunity, the observed thermal sensation is very sensitive with the change in temperature. It is actually more sensitive than the PMV model is. Previous research in the field shows that increased adaptive opportunity reduces discomfort and dissatisfaction and the thermal sensation tends to be less sensitive to temperature difference (Leaman and Bordass, 1997; Brager and de Dear, 2000).

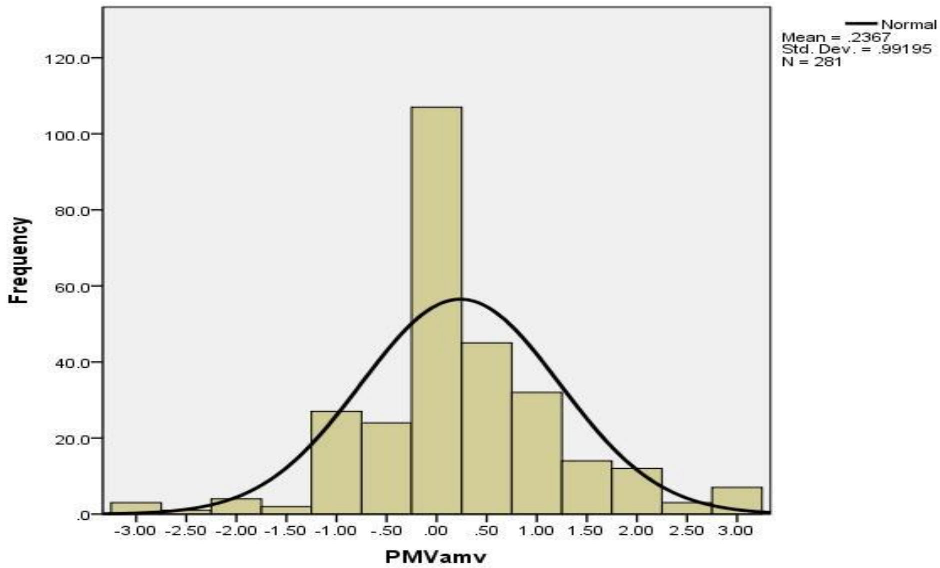


Figure 9. Histogram of PMV-AMV discrepancies.

To further investigate how much different was the PMV from the AMV at different temperatures, the discrepancy between PMV and AMV was analysed. According to Humphreys and Nicol (2002), an unbiased estimate of the discrepancy between PMV and AMV can be obtained by subtracting the AMV from the corresponding PMV score for each subject, and if the mean value of all discrepancies of all the subjects is close to zero, then the PMV model is accurate. However, they suggest that if the mean difference between PMV and AMV is more than 0.25 or less than -0.25 scale unit, then the PMV has significant bias in predicting the mean thermal sensation.

In this study, the overall mean discrepancy of PMV-AMV for all the subjects is around +0.24 scale unit, and the standard deviation is 0.99 for 281 subjects. Figure (9) illustrates a histogram of PMV-AMV discrepancy. The pattern is approximately a normal distribution with a maximum discrepancy of 3 scale units of thermal sensation. According to Humphries and Nicol (2002), a mean discrepancy of +0.24 indicates that the PMV has marginally acceptable bias.

Discussion

The aim of this paper was to investigate validation of the Fanger PMV model by applying it in a real field study. The main finding is very significant, as it not only suggested the validity of the PMV model, but it demonstrates that with extremely minimised adaptive opportunities, the actual acceptable ranges of thermal comfort are in fact even narrower than the predicted acceptable ranges.

Previous research has suggested that with more adaptive opportunities, a wider range of thermal acceptability is achieved, and the occupants become more tolerant to the thermal environment (Nicol and Humphreys, 1973; Fountain, Brager and de Dear, 1996; van Hoof, Mazej and Hensen, 2010; Rajasekar and Ramachandraiah, 2010). Other studies have suggested that in centrally air-conditioned building the thermal acceptability ranges are narrower than in naturally ventilated buildings because the occupants in air-conditioned buildings don't rely on adaptation any more, and with no control of their environment they become less tolerant to the thermal environment (Leaman and Bordass, 1997; Raja, Nicol and McCartney, 2001; Yun, Steemers and Baker, 2008; van Hoof, Mazej and Hensen, 2010). However, there is no previous field study that could examine the thermal acceptability ranges of the occupants if the adaptive opportunity is actively minimised, i.e. not just by the choice of not relying on adaptation, without any control over their environment. This study revealed that with neither adaptable opportunities nor perceived control over the environment, the occupants would be thermally sensitive to any change in operative temperature and become extremely intolerant to the thermal environment with any slight feeling of discomfort, even more than the PMV model predicts.

In the context of the mosque under investigation, being a centrally air-conditioned building, with extreme hot outdoor climate, it is important to question if the high expectation of the occupants for a superior thermal experience inside the building in Riyadh, Saudi Arabia, has an effect on the intolerant judgment of the indoor thermal environment.

Conclusion

Fanger's PMV model was tested in a unique context field study in Riyadh, Saudi Arabia. The methodology and methods are summarised. Preliminary results of monitoring and perception surveys are reported.

Only the subjects that wore the Saudi national costume are included in the data analysis, yielding 281 sets of data from 281 participants during 33 sessions i.e. prayers, within the summer month of July 2011. Assumptions are:

- The clo value was 1.13 with headdress and 1.05 without headdress, according to Al-Ajmi (2006).
- Metabolic rates were estimated to be 1.3 met, according to Al-Ajmi (2010).

The main conclusions from this study are:

- The average operative temperature was 21.57°C and ranged between 18.84-24.83°C. It should be noted that the indoor air temperature was randomly adjusted intentionally, which made the indoor operative temperature not correlated with the outdoor temperature, which ranged from 32.90 to 45.30°C, with an average of 41.60°C.
- The average PMV score was 0.01 with a range within -0.57 and 0.77 scale unit. While the average of the AMVs was -0.19 scale unit.
- The correlation between PMV and AMV was a liner regression governed by the equation, AMV= 1.29PMV-0.2 (r^2=0.674).
- By comparing the PMV and AMV linear regression as the function of operative temperature, it is noted that the Actual Mean Votes of the occupants,

significantly, are more sensitive to any change in operative temperature than predicted by the PMV.

- The actual neutral operative temperature according to the occupants' votes was 22.31^{o}C, 0.72K more than Fanger's PMV model predicted, 21.59 ^{o}c.
- The average of the discrepancy between PMV and AMV was 0.237 scale units, which is within the accepted range of discrepancy according to Humphreys and Nicol (2002).
- The study suggests that even though the subjects voted for higher neutral temperature than the PMV model predicted, the PMV model seems to be free from serious bias when the adaptive opportunities are not applicable. Furthermore, the combined effect of having no control over the environment and no adaptive opportunity with some high expectations, leads to intolerant judgment of any slight discomfort caused by the thermal environment.

The findings of the study may have greater applicability than the specific building type, in reviewing thermal comfort models in institutional settings, particularly in culturally homogeneous contexts in very hot climates.

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