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On assuming Mean Radiant Temperature equal to Air Temperature during PMV-based Thermal Comfort Study in Air-conditioned Buildings

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Abstract—Mean Radiant Temperature (MRT) is an important factor of Fanger's PMV model, which is the most popular method to study human thermal comfort. However, it has often been a practice to assume MRT equal to air temperature (T_a) during indoor thermal studies. In this paper, we have studied the consequences of this simplistic assumption on the thermal comfort of occupants in air-conditioned buildings. A worldwide database of about 10000 occupants covering 9 climatic zones and 4 seasons has been studied. The effect on comfort indices—Predicted Mean Vote (PMV), Actual Mean Vote (AMV), Thermal Acceptability Vote (TSA) and Thermal Preference Vote (MCI) are presented. It is observed that even a small difference in T_a and MRT can lead to significant error in determination of thermal comfort. A correlation study between AMV and the six Macpherson factors reveals that MRT has the highest positive correlation with the thermal sensation reported by the occupants. Study of TSA and MCI show that the assumption is more likely to affect comfort level determination in the uncomfortable range.

I. INTRODUCTION

Study of human thermal comfort in built environments, mainly air-conditioned (HVAC) buildings has gained a lot of research interest lately because it addresses these key factors: building an indoor environment (i) that is thermally comfortable for all its occupants (ii) has optimum air quality (minimised pollutants), that prevents health risks, and (iii) has reduced energy consumption. The most popular method to study human thermal comfort is the Fanger's PMV (Predicted Mean Vote) model [1], [2]. This method is based on a heat balance approach to the human thermoregulatory system, and it quantifies thermal comfort through an index termed PMV. According to this model, human thermal comfort depends on six parameters called the Macpherson parameters [3]: four environmental (Air temperature (T_a), Mean radiant temperature (MRT), Air velocity, and Humidity), and two personal (Metabolic rate, Clothing rate). These six parameters are used to calculate PMV, a quantitative measure of how thermally comfortable an occupant is. Figure 1 shows PMV values and their corresponding comfort levels.

Reflected solar radiations in HVAC indoors can significantly alter occupants' thermal comfort [4] and MRT gives information about the extent of this influence. It is hence widely used

to evaluate heat stress and comfort indices. However, in indoor thermal studies, it has often been a practice to avoid measuring MRT and instead assume it equal to the air temperature [5]–[9], due to two reasons: (i) complicated MRT measurement methods [6], [10], (ii) a hypothesis that indoors have uniform temperature and radiation flux [11]. In this paper, we have studied how this assumption $MRT=T_a$ affects the thermal comfort assessment of occupants, and the significance of MRT compared to other Macpherson parameters.

Figure 1. ASHRAE Thermal Comfort Scale

II. METHODOLOGY

A. Dataset Processing

ASHRAE is an organisation that sets thermal comfort standards for worldwide use. For our study, we have used the ASHRAE's publicly available worldwide database named RP-884 [12]. This database is based on an extensive study of human thermal comfort carried out by ASHRAE in 160 different buildings across 4 continents (including countries UK, Australia, Canada, Greece, Singapore, Indonesia, Pakistan, Thailand and USA), amounting to about 21000 people being surveyed. The data is collected from 15 field experiments. For each person surveyed, it contains indoor and outdoor environmental data, personal physiological data, and thermal comfort survey results.

The database contained field studies for three types of buildings: centrally air conditioned (HVAC), naturally ventilated (NV) and mixed mode (MM). We extracted the data for the HVAC buildings alone, which amounted to about 12000 entries. We classified this extracted data into several climatic zones and seasons as shown in Table II. After excluding entries with missing values, the final dataset amounted to 9356 entries for PMV based study, and 9333 entries for AMV based study.

B. MRT Calculation

There are several existing methods to measure and calculate MRT which are consistent with negligible difference [10], [4]. Each of these methods have their own advantages and disadvantages. Depending on the requirement criteria, a suitable method is used during field study. However, the basic principle concept for MRT evaluation is that the amount of radiant heat gained/lost by the human body is determined by the radiation flux exchanged by the body with the surrounding surfaces in the room. It is calculated from the temperatures of surrounding surfaces and their position with respect to the occupant. This is mathematically represented by Eq. 1:

$$MRT^4 = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \dots + T_m^4 F_{p-m} \quad (1)$$

where, T_m is the temperature of surface 'm' (in Kelvins); F_{p-m} is the angle factor between the person and the surface 'm'.

However, the difficulty in measuring angle factors mainly for non-standard geometries, makes it the most complicated method. Hence, the most popular method is using globe temperature, as explained by Kuehn and Stubbs [13]. Globe temperature gives a direct evaluation of the radiative thermal load on the occupant [4]. Globe temperature, along with air velocity and air temperature are used to calculate MRT according to Eq. 2 (by ISO standard 7726 [14]). In this study, we have calculated MRT using Eq. 2.

$$MRT = [(GT + 273)^4 + \frac{h_g V_a^{0.6} (GT - T_a)^{\frac{1}{4}}}{\epsilon D^{0.4}}] - 273 \quad (2)$$

where,

$$\begin{aligned} h_g &= \text{globe's mean convection coefficient} \\ &= 1.100 \times 10^8 \times V_a^{0.60} \quad (\text{for black globe}) \\ &= 1.335 \times 10^8 \times V_a^{0.71} \quad (\text{for gray globe}) \end{aligned}$$

MRT = Mean Radiant Temperature ($^{\circ}\text{C}$)

GT = globe temperature ($^{\circ}\text{C}$)

V_a = air velocity (m/s)

ϵ = emissivity of the globe = 0.95 (for black globe)

D = diameter of the globe (m)

T_a = air temperature ($^{\circ}\text{C}$)

C. PMV Calculation

The PMV index developed by Fanger predicts the expected thermal comfort vote of an occupant on the ASHRAE thermal sensation scale (see Figure 1). It requires the six Macpherson parameters as input, and is calculated according to the following equation:

$$PMV = (0.303e^{-0.036M} + 0.28)L \quad (3)$$

where, M is the metabolic rate and L is the thermal load on the body (calculated using Macpherson factors). Another index namely PPD (Percentage of People Dissatisfied) depicts the percentage of the total number of occupants that can be expected to be decidedly dissatisfied. It is a statistical index and is related to PMV as:

$$PPD = 100 - 95e^{(-0.03353PMV^4 - 0.2179PMV^2)} \quad (4)$$

Figure 2. PMV Error Analysis

Table I
DESCRIPTIVE STATISTICS FOR ERROR (PMV₁-PMV₂)

Mean ± SD	0.02 ± 0.12
Range	(-1.26, 1.54)
Skewness	-0.1
Kurtosis	32

The database contained information about metabolic and clothing rate, air temperature, humidity, air velocity, and globe temperature. The globe temperature values were used to calculate MRT by Eq. 2 and subsequently, we calculated PMV using all the six parameters by Eq. 3 as mentioned in ASHRAE Standard 55 [15]. In this study, we calculated PMV for two cases:

- PMV₁ (MRT ≠ T_a): Here, both air temperature T_a and mean radiant temperature MRT, are separately measured and used in PMV calculation.
- PMV₂ (MRT = T_a): Here, MRT is assumed equal to T_a .

All the calculations and data analysis have been performed using Matlab R2013a and OriginPro 8.1.

III. RESULTS AND DISCUSSIONS

A. PMV Error Analysis

The error in PMV values caused by the assumption MRT= T_a are discussed in this section. The PMV error is the difference between the ideal case PMV₁ and the assumption case PMV₂. The statistical results are shown in Figure 2. The mean absolute error is low, but the maximum error (=1.54) is quite high. Such high error can easily adversely affect the determination of comfort level on the thermal comfort scale (Figure 1) which has a short range from around -3 to +3. The distribution of error (PMV₁ - PMV₂) and its descriptive statistics are presented in Figure 3 and Table I respectively. It is observed from Table I that the distribution is slightly negatively skewed and has a high kurtosis. Thus the error

Figure 3. PMV Error Distribution

($PMV_1 - PMV_2$) is mostly positive, that is, PMV_1 is mostly greater than PMV_2 . This means that the assumption $MRT=T_a$ is more likely to underestimate the true PMV value. Such incorrect PMV values can lead to misleading results about other related indices such as PPD (Eq. 4) as well.

B. Effect on thermal comfort level

Thermal comfort level is the thermal sensation felt by an occupant. There are 7 thermal comfort-levels according to ASHRAE scale (Figure 1) ranging from *cold* to *hot*. Each level is assigned a range of PMV values. In this study, we have found comfort-levels for all the PMV values for both PMV_1 and PMV_2 , and calculated the inaccuracy caused in Comfort level determination due to assumption $MRT=T_a$.

We have defined the CL (Comfort-Level) inaccuracy as the number of cases with incorrect comfort-levels divided by the total number of cases (Eq. 5). We have defined ($\% \Delta T_m$) as the mean absolute percentage difference between T_a and MRT according to Eq. 6.

$$\frac{\text{Inaccuracy}}{100(\%)} = \frac{\text{No. of cases}(CL(PMV_1) \neq CL(PMV_2))}{\text{Total no. of cases}} \quad (5)$$

$$\% \Delta T_m = \left\langle \frac{|T_a - MRT|}{T_a} \right\rangle \quad (6)$$

We have grouped the dataset according to nine climatic zones and further regrouped them into four seasons. The results of the calculated temperature differences of these zones and their corresponding inaccuracies are presented in Table II. It is observed that a small temperature difference of 2.6% leads to 6.7% CL inaccuracy (in the overall worldwide database). 6.7% of the total database of 9356 people implies 644 people. Thus the comfort-levels (CL) of a large number of people (644) are incorrectly determined because of the simplistic assumption $MRT=T_a$.

Table II
CLIMATE ZONE AND SEASON-WISE COMFORT LEVEL INACCURACY FOR PMV_2 ($MRT = T_a$)

Climate zone	Season	Samples	$\% \Delta T_m$	Inaccuracy (%)
Tropical savanna	Dry	1820	2.80	8.08
	Wet	2578	2.76	8.61
Humid subtropical	Summer	564	2.79	6.38
	Winter	83	2.35	2.41
Mediterranean	Summer	769	1.17	3.51
	Winter	524	0.92	2.29
Westcoast marine	Summer	80	3.24	6.25
	Winter	38	3.52	5.26
Hot Arid	Summer	589	2.57	4.92
	Winter	614	1.44	2.77
Continental subarctic	Summer	443	2.65	4.97
	Winter	426	3.54	7.28
Humid midlatitude	Winter	85	0.32	2.35
Wet equatorial	Summer	234	7	14.96
Temperature marine	Summer	509	3.76	10.41
Overall Worldwide	-	9356	2.6	6.7

The CL inaccuracies are plotted against the temperature differences in Figure 4. It is seen that the inaccuracy increases almost linearly with increase in temperature difference. A linear fit of ($y = 2.01x + 0.55$) with high goodness of fit ($r^2 = 80.4\%$) implies that a certain temperature difference can cause an error/inaccuracy almost double its value. Thus the assumption $MRT=T_a$ adversely affects comfort-level determination, and can lead to misleading conclusions in indoor thermal studies, even for small temperature difference between MRT and T_a .

Figure 4. CL Inaccuracy (%) vs. $\% \Delta T_m$ for PMV_2 ($MRT=T_a$)

C. Climate Zone based Analysis

1) *Analysis of the temperature differences between different climate zones:* The temperature differences $\% \Delta T_m$, between the air temperature and mean radiant temperature MRT, can be attributed to the nature of the climate zone they belong to. The climate zones mentioned here are according to the Köppen climate zone classification [16]. It is observed in Table II that the temperature differences are higher in summer than in winter for Humid subtropical, Mediterranean and Hot Arid climate zones. The reason behind the higher temperature difference in summer could be that these three climate zones are characterised by hot summers and cool to cold winters, thus having major temperature differences between the two seasons, summer and winter. Hot summers are characterised by higher solar radiation. Higher radiation in the outdoors leads to higher MRT in the indoors. As a result, the MRT differs more from the indoor air temperature. This leads to a higher temperature difference $\% \Delta T_m$ during summers.

On the other hand, the Continental subarctic climate zone is dominated by winter season that has short clear days, low humidity and bitter cold period [16]. Clear winter days are characterised by strong solar radiation, unlike the summer days. Higher radiation leads to higher MRT compared to air temperature. This may result in the higher temperature difference in winter.

However, the Westcoast marine climate zone is characterised by almost constant temperature throughout the year. The ocean keeps the air over land cool in summer and warm in winter, thus maintaining a narrow annual temperature range [16]. This could possibly be the reason behind similar temperature difference in summer and winter, as seen in Table II. Humid midlatitude winters are mild but frosty, and Wet equatorial summers have consistent high temperature, precipitation, and humidity. The Tropical savanna climate comprises two seasons- dry and wet; however, the temperature is almost consistent throughout [16]. This could explain the similar temperature differences in dry and wet season in Table II.

2) *Analysis of the CL Inaccuracies between different climate zones:* It is observed in Section III-B that comfort level inaccuracy increases with temperature difference almost linearly. Humid midlatitude winters are mild and frosty, and study shows it has the minimum temperature difference of 0.32%. Therefore its corresponding CL inaccuracy is also the minimum at 2.35%. The highest CL inaccuracy is observed for Wet equatorial summer, which has the highest temperature difference of 7%. The wet equatorial summer has very little annual temperature variation, with high temperatures, and high humidity all year round. Thus the variation in temperature difference $\% \Delta T_m$ depends on the nature of the climate zone it belongs to, while the variation in CL inaccuracy depends on the temperature difference, irrespective of the sample size studied.

D. MRT and Actual Mean Vote

While PMV is a predicted vote of the occupant's comfort because it is determined by calculations, comfort indices

Table III
(A) CORRELATION TEST AND (B) SIGNIFICANCE TEST (P VALUE)
RESULTS

Parameters	(A)	(B)
MRT	.32331	0
Air Temperature	.2904	0
Air Velocity	-.08769	0
Relative humidity	-.0908	0
Metabolic Rate	.11942	0
Clothing Rate	.05112	7.76E-07

such as AMV, TSA, MCI are based on direct feedback from occupant. Actual Mean Vote (AMV) is an important comfort index and it is the value on the thermal scale (in Figure 1) directly mentioned by the occupant.

The six Macpherson factors that influence thermal comfort are MRT, T_a , Air velocity, Humidity, Metabolic rate and clothing rate [1]. A comparative analysis of significance and correlation between these six factors and AMV have been performed. All the results are at 95% confidence level. Correlation test is done for Pearson measure. The results are presented in Table III. Lower the P value, higher is the significance of the factor. The P values are mostly equal to zero which means all the factors are highly significant for AMV. However, correlation test shows that MRT has the highest correlation with AMV. This means MRT has a stronger influence on thermal comfort compared to the other factors. Heat stress due to the surrounding radiant temperature influences how the occupants report sensation on thermal scale.

E. MRT and Thermal Acceptability Vote (TSA)

Thermal acceptability (TSA) is the vote reported by the occupant as a reply to the following survey question:

'At the present time, is this thermal environment acceptable to you or not?'

The voting options are numbered as:

- 1- unacceptable
- 2- acceptable

The responses reported by the occupants in the worldwide study are accumulated and studied. An analysis of PMV error with the acceptability vote TSA is done. Results are presented in Figure 5. It is observed that the error in PMV is higher in case of TSA=1, i.e., when the occupant reports the thermal environment as unacceptable. Thus a higher PMV error is associated with the occupant feeling uncomfortable. This implies that the assumption $MRT = T_a$ is more likely to affect comfort level determination in the uncomfortable range (cold, cool, warm, hot).

F. MRT and Thermal Preference Vote (MCI)

The most common thermal preference scale is the McIntyre scale [12], which we refer as MCI here. Thermal Preference Vote (MCI) is the vote reported by occupant as a reply to the following survey question:

'At this point in time, would you prefer to feel warmer, cooler,

Figure 5. Absolute PMV Error vs. Thermal Acceptability Vote

Figure 6. Absolute PMV Error vs. Thermal Preference Vote for TSA=1

or no change?"

The voting options are numbered as:

- 1- want cooler
- 2- no change
- 3- want warmer

When thermal environment is unacceptable (TSA=1), occupant usually prefers a change in the sensation. So we have studied the preference vote MCI only when TSA=1. The results are presented in Figure 6. It is seen that majority of people, about 63% prefer cooler sensation. The absolute PMV error is highest in case of people preferring cooler sensation, which means error is higher in case of comfort level on the higher end of the thermal scale (towards +3). Therefore, the assumption $MRT = T_a$ is more likely to affect comfort level determination of people experiencing warmer sensation in the uncomfortable range (*warm, hot*).

IV. EFFECT ON BUILDING OPERATION

One of the main functions of building operation is to maintain a thermally comfortable indoor environment for the occupants. This objective is met by performing indoor thermal study such as PMV modelling. This study quantifies the thermal comfort of the occupants by calculating several indices: PMV, AMV, TSA and MCI. Such quantification of thermal comfort portrays whether the building conditions are within the acceptable comfort limits recommended by ASHRAE international standards. In this paper, it is shown how all of these thermal indices are adversely affected when MRT is neglected during PMV modelling. The simplistic assumption $MRT = T_a$ has lead to

- Underestimation of PMV value
- Wrong interpretation of comfort level on thermal scale
- Health and comfort of people feeling warm/hot being compromised

Such misinterpretations are a hindrance to effective building operation.

V. CONCLUSION

This paper analyzed the effect of considering MRT equal to air temperature during indoor thermal studies by PMV modelling. It is found that this assumption, even for small temperature differences in MRT and T_a , can lead to incorrect determination of PMV and comfort level. Larger the temperature difference, larger is the inaccuracy (almost double). Highest correlation of MRT with AMV signifies the importance of MRT. Study of TSA and MCI indices show that the assumption is more likely to affect comfort level determination in the uncomfortable range. Hence, it is recommended to avoid assumption of $MRT = T_a$ as it can lead to misleading conclusions in indoor thermal comfort studies, and can compromise the occupant's thermal comfort and health.

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REFERENCES

- [1] P. O. Fanger, *Thermal comfort, analysis and application in environmental engineering*. Copenhagen:: Danish Technical Press, 1970.
- [2] P. O. Fanger, "Assessment of man's thermal comfort in practice," *British Journal of Industrial Medicine*, vol. 30, no. 4, pp. 313–324, 1973.
- [3] Z. Lin and S. Deng, "A study on the thermal comfort in sleeping environments in the subtropics Developing a thermal comfort model for sleeping environments," *Building and Environment*, vol. 43, no. 1, pp. 70 – 81, 2008.
- [4] F. R. dAmbrosio Alfano, M. Dellisola, B. I. Palella, G. Riccio, and A. Russi, "On the measurement of the mean radiant temperature and its influence on the indoor thermal environment assessment," *Building and Environment*, vol. 63, pp. 79 – 88, 2013.
- [5] A. Matzarakis and B. Amelung, "Physiological equivalent temperature as indicator for impacts of climate change on thermal comfort of humans," in *Seasonal Forecasts, Climatic Change and Human Health* (M. Thomson, R. Garcia-Herrera, and M. Beniston, eds.), vol. 30 of *Advances in Global Change Research*, pp. 161–172, Springer Netherlands, 2008.

- [6] K. N. and U. J., "The most problematic variable in the course of human-biometeorological comfort assessment - The mean radiant temperature," *Central European Journal of Geosciences*, vol. 3, no. 1, pp. 90–100, 2011.
- [7] L. M., S. K., and E. W.R., "Indoor heat stress: An assessment of human bioclimate using the utci in different buildings in berlin," *Erde*, vol. 144, no. 3-4, pp. 260–273, 2013.
- [8] O. Kaynakli and M. Kilic, "Investigation of indoor thermal comfort under transient conditions," *Building and Environment*, vol. 40, no. 2, pp. 165 – 174, 2005.
- [9] B. Olesen and K. Parsons, "Introduction to thermal comfort standards and to the proposed new version of {EN} {ISO} 7730," *Energy and Buildings*, vol. 34, no. 6, pp. 537 – 548, 2002. Special Issue on Thermal Comfort Standards.
- [10] N. Walikewitz, B. Jnicke, M. Langner, F. Meier, and W. Endlicher, "The difference between the mean radiant temperature and the air temperature within indoor environments: A case study during summer conditions," *Building and Environment*, vol. 84, pp. 151 – 161, 2015.
- [11] H. Mayer, J. Holst, P. Dostal, F. Imbery, and D. Schindler, "Human thermal comfort in summer within an urban street canyon in central europe," *Meteorologische Zeitschrift*, vol. 17, no. 3, pp. 241–250, 2008.
- [12] G. S. de Dear, Richard; Brager, "Developing an adaptive model of thermal comfort and preference," *Center for the Built Environment*, 1998.
- [13] L. A. Kuehn, R. A. Stubbs, and R. S. Weaver, "Theory of the globe thermometer," *Journal of Applied Physiology*, vol. 29, no. 5, pp. 750–757, 1970.
- [14] S. Ithurria and B. Dubertret, "ISO 7726. Ergonomics of the thermal environment - Instrument for measuring physical quantities: International Organization for Standardization," 1998.
- [15] ASHRAE, "Thermal Environmental Conditions for Human Occupancy," *ASHRAE Standard 55*, 2013.
- [16] M. Kottek, J. Grieser, C. Beck, B. Rudolf, and F. Rubel, "World map of the köppen-geiger climate classification updated," *Meteorologische Zeitschrift*, vol. 15, no. 3, pp. 259–263, 2006.