

Thermal Comfort Zone for Thai People

Juntakan Taweekun^{*}, Ar-U-Wat Tantiwichien

Department of Mechanical Engineering Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla, Thailand Email: *juntakan@me.psu.ac.th, aruwat@yahoo.com

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ABSTRACT

Radiant cooling system for thermal comfort of Thai people was developed. Questionnaires for subjective experiments were examined for development of radiant cooling system for thermal comfort. Thermal sensation, humid sensation and air movement sensation were used for thermal comfort assessment. The Predicted Mean Vote (*PMV*) value was used for thermal comfort evaluation and it was observed that the *PMV* values are in the comfortable ranges during 18:00 to 10:00 for air velocity 0.2 m/s and 0.4 m/s. Comfortable periods are extended for higher air velocity. Neutral temperatures are in the ranges of 26.44°C - 33.60°C. The percentage number of dissatisfied (*PPD*) value for each air velocity was also investigate and the value of *PPD* is five for zero value of *PMV*. Simulation and experimental results were evaluated by using three indicators, namely, the coefficient of variation (*CV*), the mean bias error (*MBE*) and Chi-Square (χ^2). The values of *CV*, *MBE* and χ^2 for mean radiant temperature are 14.52%, 1.54% and 3.95°C, respectively. Zones of acceptable thermal environment were developed for Thai People. Results revealed that the comfortable zones of Thai people are in the ranges of relative humidity 50% - 70% and effective temperatures (*ET*) 24°C - 27°C.

Keywords: Thermal Comfort Zone; Radiant Cooling System; Neutral Temperature

1. Introduction

Electricity consumption in Thailand is approximately 44%, 24% and 23% of the total electricity use for industrial, commercial and residential sectors, respectively [1]. For residential buildings in urban and suburban areas, air-conditioning is also widely used approximately 70% of the total energy use. Webb (1952) pioneered thermal studies in Singapore for humid tropical regions [2]. Busch (1990) studied on field experiment in naturally ventilated office buildings in Bangkok, Thailand indicated a neutrality of 28.5°C ET, while 24.5°C ET was observed in air-conditioned buildings [3]. Neutral temperature for office workers was 26.7°C in Jakarta, Indonesia [4]. The use of radiant cooling system was suggested to offer quiet comfort and energy efficiency superior to conventional air-conditioning system [5]. Zones of acceptable operative temperature and humidity for people with light activity were developed by ASHRAE. The lower limit of ET for winter and the upper limit of ET for summer are 20°C and 26°C [6]. In the previous studies,

effects of humidity and air velocity on thermal comfort were seldom discussed. This study concentrates on the use of radiant cooling system considering effects of temperature, humidity, air velocity, metabolic rate, clothing level by subjective experiments. Subjective experiments will be carried out to evaluate thermal comfort under the radiant cooling system of Thai people. The values of *PMV* and *PPD* are considered for thermal comfort evaluation. Measured data and data obtained from questionnaire are used for development of radiant cooling system for thermal comfort. The values of *CV*, *MBE* and χ^2 are used to investigate experimental and simulation results.

2. Methodology

2.1. Design of Radiant Cooling System

In this stage, the radiant cooling panel, control system and relevant equipment were designed. The designed areas of the radiant cooling panels are 32 m^2 which calculated from heat gain into the experimental room divided by the panel cooling capacity.

^{*}Corresponding author.

2.2. Experimental Set Up and Data Collection

The experiment was set up at the low energy house in Prince of Songkla University, Thailand. The radiant cooling panels were constructed from copper tube bonded to aluminium sheet. The cooling tower produces cool water with temperature 25°C and supplies to the wall and ceiling radiant cooling panels with closed system. Temperature sensors installed at surfaces of cooling panels are controlled by PID controller for opening solenoid valve at 0% - 100%. Flow diagram of radiant cooling system is illustrated in **Figure 1**.

Thermal comfort field investigation was referred to Class I as specified in ASHRAE and ISO standards. Three heights of measurement above floor level are 0.1, 0.6 and 1.2 m. Experimental conditions for humidity and air movement were controlled by a humidifier and air speed level. Temperature and humidity sensors were used to measure the temperature and relative humidity of interior and exterior air. Surface temperatures of opaque wall and radiant cooling panels were measured by thermocouple type K. Mean radiant temperature was also recorded by globe thermometer. All of these data were continuous recorded to data logger. The interior air speed, electrical consumption and metabolic rate were measured by anemometer, continuous power meter and heart rate meter, respectively.

2.3. Questionnaire Procedure

Research objectives, outcomes of the research and how to answer the questionnaire are clarified to the subjects. The first part asks about personal information age, gender, weight, height, education level, type of clothes that the subjects wore on the day of investigation. In the second part, questions were asked about thermal sensation, humid sensation and air movement sensation in response to the room conditions. The subjects are required to make only one choice from the scales as shown in **Table 1** for each question. The subjects voted at relative humidity from 50% to 90% and air velocity passing through the body in the ranges of 0.2 - 1.0 m/s.

2.4. Development of Radiant Cooling System for Thermal Comfort of Thai People

The measured data and data obtained from questionnaire are used for development of radiant cooling system for thermal comfort of Thai people. Values of *PMV* and *PPD* are investigated for thermal comfort evaluation as given in Equations (1) and (2). Value of *PMV* is used to describe the vote and imbalance condition. Ranges of *PMV* for thermal comfort conditions are -0.5 to 0.5 (Comfortable); 0.5 to 1.0 (Warm); -1.0 to -0.5 (Cool); over 1.0 (Unacceptably Warm) and under -1.0 (Unacceptably cool) [7].

$$PMV = \begin{bmatrix} 0.303 \exp(-0.036M) + 0.028 \end{bmatrix} L.$$
(1)

$$PPD = 100 - 95 \exp\left[-\left(0.03353 PMV^{4} + 0.2179 PMV^{2}\right)\right].$$
(2)

where *L* is imbalance between (*M*-*WR*) and rate of heat dissipation (W/m^2) , *M* is metabolic rate (W/m^2) and WR is work rate (W/m^2) which obtained from equation 5.5 - 15(*M* - 0.8).

3. Results and Discussions

3.1. Predicted Mean Vote and Percentage Number of Dissatisfied Evaluation

Thermal comfort can be obtained in the wider ranges at the higher air velocity. It was observed that the *PMV* values are in the range of -1 - 1 which are in the comfortable ranges during 18:00 to 10:00 at air velocity 0.2 m/s and 0.4 m/s as illustrated in **Figure 2**. Comfortable



Figure 1. Flow diagram of radiant cooling system.

periods are extended in the ranges of 15:00 to 12:00 at higher air velocity. The relationships between *PMV* and *PPD* values for each air velocity are also examined. The value of *PPD* is five for zero value of *PMV*. The number reaches "10" when *PMV* deviates from zero by 0.5 and 25 when *PMV* deviates by 1.0.

3.2. Thermal Comfort Assessment

All subjects are in seat and quiet (met 1.0) with short shirt and long sleeve. The subjects voted in the range of relative humidity 50% - 90% with air velocity 0.2 - 1.0 m/s.

3.2.1. Humid Sensation Analysis

Results implied that the subjects feel mostly just right and slightly humid at air velocity 0.2, 0.4 and 0.6 m/s. Moreover, the subjects prefer mainly just right and also feel slightly dry at air velocity 0.8 and 1.0 m/s. The humid sensations are mostly voted just right in the ranges of relative humidity 50% to 60% which is in the ranges refer to ASHRAE Standard. The humid acceptability for Thai subjects decreases at the higher relative humidity and are below 80% for all cases of relative humidity above 70% as illustrated in **Figure 3**.



Figure 2. Comparisons of PMV values.



Figure 3. Humid acceptability for air velocity 0.2 - 1.0 m/s.

Table 1. Thermal, humid and air movement sensation scales.

Value	Thermal Sensation	Humid Sensation	Air Movement Sensation		
+3	hot				
+2	warm	humid	too breezy		
+1	slightly warm	slightly humid	breezy		
0	neutral	just right	just right		
-1	slightly cool	slightly dry	too still		
-2	cool	dry			
-3	cold				

 Table 2. Thermal sensation voted (TSV) equations and neutral temperature.

Air Velocity (m/s)	TSV Equation	R^2	Neutral Temperature (°C)		
0.2	$TSV = 0.193T_i - 5.102$	0.8966	26.44 + 0.9		
0.4	$TSV = 0.17T_i - 4.573$	0.9219	26.90 + 0.9		
0.6	$TSV = 0.206T_i - 5.919$	0.7969	28.73+0.9		
0.8	$TSV = 0.275T_i - 8.165$	0.9128	29.69+0.9		
1.0	$TSV = 0.192T_i - 6.259$	0.8122	32.60 + 0.9		

3.2.2. Air Movement Sensation Analysis

The subjects feel mostly just right at air velocity 0.2 m/s and 0.4 m/s. The votes for breezy and too breezy are obtained at the higher air velocity 0.8 m/s and 1 m/s. The highest air movement acceptability can be obtained in the ranges of 25°C and 29°C for air velocity 0.2 m/s and in the ranges of 26°C and 30°C for air velocity 0.4 m/s.

3.2.3. Thermal Sensation Analysis

The relationships between thermal sensation vote and interior air temperature (T_i) in the ranges of relative humidity 50% to 90% at air velocity 0.4 and 0.6 m/s are given in **Figures 4** and **5**, respectively. The corresponding neutral temperature is the temperature at which the regression line crosses x-axis.

Results showed that neutral temperatures are in the ranges of 26.44° C - 32.60° C as given in **Table 2**.

Subjective experimental results for air velocity 0.4 m/s and various relative humidity are shown in **Table 3**.

The relations between the percentage of the subjects voting "0" and the interior temperature are shown in **Figure 6** for air velocity 0.4 m/s and **Figure 7** for air velocity 0.6 m/s. Temperature and air velocity have significant effect to thermal sensation vote. The higher percent of vote "0" were obtained in case of air velocity 0.2 m/s and 0.4 m/s. The comfort temperature can be extended to 32.60°C in case of air velocity 1.0 m/s. Never-

Temperature (°C)	RH (%)	Number of Thermal Sensation Vote						Frequency	Percent of "0"		
		-3	-2	-1	0	1	2	3	Number	Vote	Mean Vote
24 + 0.9	80 - 90		4	8	20				32	62.50	-0.50
25 + 0.9	50 - 60			6	22				28	78.57	-0.21
	70 - 80			6	22				28	78.57	-0.21
26 + 0.9	50 - 60		2	2	26				30	86.67	-0.20
	60 - 70			6	22				28	78.57	-0.21
	70 - 80				22				22	100	0.00
	80 - 90				45				45	100	0.00
27 + 0.9	50 - 60				33	6			39	84.62	0.15
	60 - 70			13	25				38	65.79	-0.34
	70 - 80			13	78	6			97	80.41	0.07
	80 - 90			6	32	6	6		50	64.00	0.24
28 + 0.9	60 - 70				58				58	100	0.00
29 + 0.9	60 - 70				39	6			45	86.67	0.13
	70 - 80				25	2	1		28	89.29	0.14
30 + 0.9	60 - 70				5	8	13		26	19.23	1.31
	70 - 80				32	6			38	84.21	0.16
31 + 0.9	60 - 70				9	15	3		27	33.33	0.78
32 + 0.9	70 - 80				8	15	4		27	29.63	0.85

Table 3. Distribution of thermal sensation votes at air velocity 0.4 m/s.







Figure 5. Relationships between mean thermal sensation vote and interior temperature at air velocity 0.6 m/s.



Figure 6. Thermal acceptability for air velocity 0.4 m/s.



Figure 7. Thermal acceptability for air velocity 0.6 m/s.

theless, thermal acceptability for Thai subjects at air velocity 1.0 m/s for percent of vote "0" are only 37% which supports recommendation by ASHRAE as air velocity limited to 0.8 m/s to avoid a sensation of draft, which occurs when there is non-uniform heat transfer between different parts of the body.

3.3. Statistic Evaluation

This study uses three indicators to evaluate the experimental and simulation results, namely *CV*, *MBE* and χ^2 . EnergyPlus Program was used in this study. These indicators have been extensively used for estimation of the accuracy of neural networks and other black-box type models predicting electrical consumption [8-10]. The coefficient of variation is the root mean square error divided by the mean value of the actual output. The resultant values of *CV*, *MBE* and χ^2 for mean radiant temperature are 14.52%, 1.54% and 3.95°C, respectively.

3.4. Thermal Comfort Zone

As mentioned earlier, the lower limit and upper limit of effective temperature is 24° C, and 26° C, respectively and the upper limit of relative humidity is 60% developed by ASHRAE. In this study, experimental results with the values of clothing level, type of activity and air speed are used to develop zone of acceptable thermal environment of Thai People. Experimental results revealed that the comfortable zones of Thai people are in the ranges of relative humidity 50% - 70% and effective temperatures 24° C - 27° C for air velocity 0.2 m/s.

4. Conclusion

Experimental results implied that radiant cooling system can be applied for buildings under tropical climate and cooling tower can provide cool water for radiant cooling panels. At the higher air velocity, thermal comfort range can be obtained at the higher temperature. Thermal comfort zone for Thai people has wider ranges than ASH-RAE comfort zone. This is due to high relative humidity throughout the year in Thailand and the people can adapt in the wider ranges.

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