An Experimental and Simulated Study on Thermal Comfort

Ar-U-Wat Tantiwichien and Juntakan Taweekun

Abstract—**This study focused on design and investigation of radiant cooling system using cool water supplied from cooling tower with varying water flowrate. The experiment was set up at the low energy house in Prince of Songkla University, Songkhla Province, Thailand. Radiant cooling panels were designed and installed at the wall and the ceiling in the experimental room with the areas of 15.17 m^2 and 16.83 m^2, respectively. The sensitivity analysis for various parameters namely, clothing level, metabolic rate and air velocity were also examined through simulation. Simulation results revealed that all parameters strongly influence to thermal comfort. The predicted mean vote (PMV) values were used for thermal comfort evaluation and results implied that the use of radiant cooling system is appropriate in the night time and early morning (until 10:00). Energy savings can be obtained at 41% by using radiant cooling system instead of the use of air conditioner. This system can be used as the alternative option for human thermal comfort. Three sensation scales are used namely, thermal sensation scale, humid sensation and air movement sensation for comfort assessment. Thermal comfort range can be obtained at the higher temperature in case of increasing air velocity. The humid sensations are mostly voted just right in the ranges of relative humidity 50% to 60% and the humid acceptability for Thai subjects are below 80% for all cases of relative humidity above 70% . The highest acceptability can be obtained at temperature 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.**

Index Terms—**Neutral temperature, radiant cooling system, simulation, predicted mean vote, thermal comfort.**

I. Introduction

Thailand is located in the tropical zone which has high temperature and humidity throughout the year. With warm and humid weather, the energy consumption of air-conditioning system could be reached 70% of its full capacity [1]. Radiant cooling is believed to be an energy efficient method of providing thermal comfort; the application of this option in tropical region is limited due to the fact that existing thermal comfort standards such as ASHRAE/ANSI 55 (1992) and ISO (1994), requires low room air temperatures, and supplying cooling water at low temperatures to radiant cooling system increases the chance of condensation on radiant cooling surfaces [2], [3]. Prapapong and Surapong (2004) studied the radiant cooling using natural air for ventilation under Thai climate. To avoid condensation of moisture on the cooling panel, the temperature of water supplied to the panel was limited to 24°C. The results showed that thermal comfort could be obtained with application of radiant cooling [4]. Thermal comfort of local parts of the body and the whole body, including the effects of humidity and small air movements, by subjective experiments under a radiant cooling system was investigated and found that small air movement with the radiant cooling system had a possibility of improving the comfortable sensation votes [5]. When radiant cooling is applied with displacement ventilation, where ventilation air is introduced at low level and flows by natural means to replace ventilation air. This system has been suggested to offer quiet comfort and energy efficiency superior to conventional air-conditioning system [6], [7]. From the previous studies, most of researchers focused on the use of chilled water supplied from chiller to radiant cooling panel and condensation can be occurred. This study concentrates on the use of radiant cooling system by using the cool water supplied from cooling tower to radiant cooling panels under weather of the southern part of Thailand. Firstly, EnergyPlus program Version 1.2.2 is used to simulate the use of radiant cooling system. Secondly, parametric studies are also examined by varying clothing level, metabolic rate and interior air velocity through simulation. Radiant cooling panels are installed at the wall and the ceiling in the experimental room. The effects of temperature, humidity, air velocity, metabolic rate, clothing level on the use of radiant cooling system are considered by subjective experiments. Subjective experiments will be carried out to evaluate thermal comfort under the radiant cooling system of Thai people.

II. Methodology

In preliminary, the weather data of Songkhla Province, external and internal heat gain were used to design areas of radiant cooling panels. Cool water was supplied from cooling tower passing through the radiant cooling panels which made from copper tube bond with aluminium sheet. The panels were installed at the wall and the ceiling of the experimental room with the areas of 15.17 m^2 and 16.83 m^2, respectively. The diameter and length of copper tubes are 0.0127 m and 310 m. The performance of cooling tower was also investigated with radiant cooling system. Parametric studies included the effects of clothing level, interior air velocity and metabolic rate were examined through simulation. The experiment was set up at the low energy house in Prince of Songkla University. Temperature sensors installed at surfaces of cooling panels were controlled by PID controller for varying water flowrate. Thermal comfort field

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The authors are with the Department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University, Hat Yai, Songkhla, Thailand (e-mail: aruwat@yahoo.com, juntakan@me.psu.ac.th).

investigation was referred to Class I as specified in ASHRAE and IS0 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 relative humidity of interior and exterior air, surface temperatures of radiant panels and mean radiant temperature were continuous recorded. The interior air speed, electricity consumption and metabolic rate were measured by anemometer, continuous power meter and heart rate meter, respectively. Subjective experiments nearly 200 persons were carried out to evaluate thermal comfort under the radiant cooling system with approximately three hours per person. Firstly, research objectives, outcomes of the research and how to answer the questionnaire are clarified to the subjects. Secondly, each subject will be asked for personal information i.e. age, gender, weight, height, education level, type of clothes that the subjects wore on the day of investigation. Subjects were required to make only one choice for thermal sensation, humid sensation and air movement sensation in response to the room conditions. The subjects voted at relative humidity from 50% to 90% and air velocity passing through the body 0.2-1.0 m/s.

III. Results and Discussions

A. Simulation

Weather data of Songkhla Province can be classified into four periods as given in Table I. The period of 16 February–31 May has the highest average dry-bulb temperature, thus, this period is chosen for feasibility study of the use of radiant cooling system.

TABLE I: Weather Climate of Songkhla Province

Period	Reference day	Dry-bulb temperature (°C) Average	Min	Max
16 February–31 May	12 March	29.97	23.58	38.33
1 June–15 August	8 July	29.25	26.6	33.01
16 August–31 October	23 September	27.78	24.29	36.71
1 November–15 February	5 December	27.12	21.45	33.02

EnergyPlus is used as a simulation tool. Detailed physical description of building shape, orientation, composition of opaque wall, transparent wall, floor and roof are used as inputs for simulation. The internal load i.e. occupant, lighting, equipment, occupancy schedule, equipment and lighting usage schedules are also required in this model. The sensitivity analysis is also examined by varying the clothing level, metabolic rate and interior air velocity through the simulation as following.

1) Varying clothing level

The clothing level is varied in the ranges of 0.2-0.8 clo as illustrated in Fig. 1. The simulated results reveal that the comfort could not be achieved for higher clothing level at 0.8 clo which is in the range of unacceptably warm. For the lower clothing level at 0.2 clo, the comfort can be obtained during 18:00-20:00, occupants feel very cold and the comfort could not be fulfilled during 20:00-9:00. The comfort can be achieved for clothing level at 0.5 clo (ensembles of brief, light slacks and short sleeve shirt) during 23:00 to 8:00.

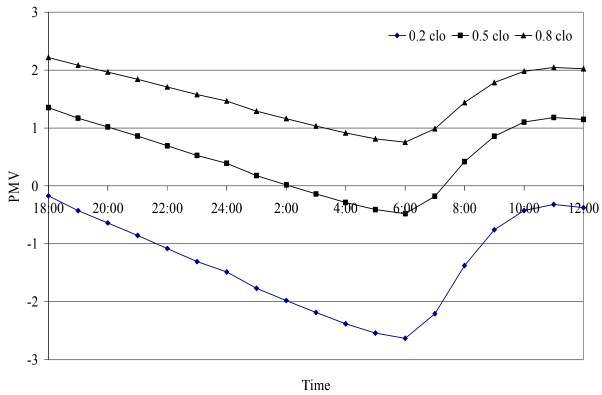

Fig. 1. Values of PMV by varying clothing level

2) Varying metabolic rate

The effects of metabolic rate are also considered for 1.0, 1.2 and 1.6 met. The resultant PMV value by varying metabolic rate is shown in Fig. 2. It can be seen that thermal comfort can be achieved at metabolic rate 1.2 met during 23:00-8:00. The radiant cooling system is not appropriate with higher activity or higher metabolic rate i.e. at the metabolic rate 1.6. In contrast, lower activity also falls in the unacceptable cool during 1:00 to 7:00.

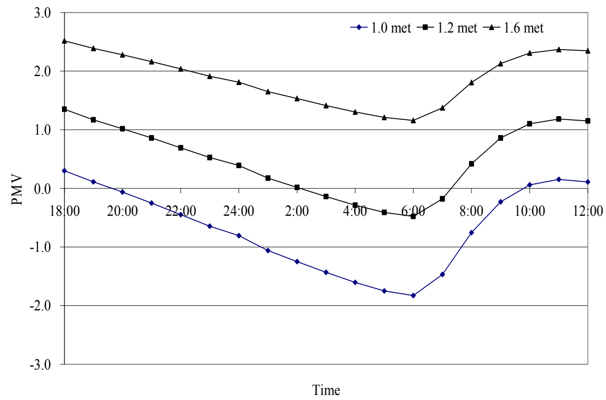

Fig. 2. Values of PMV by varying metabolic rate

3) Varying interior air velocity

Fig. 3 illustrates the PMV values by varying interior air velocity. Thermal comfort can still be fulfilled at the lower air velocity in the narrow ranges during 3:00-7:00. The higher air velocity helps at the beginning for thermal comfort achievement. Nevertheless, occupants feel cool in the night time after 4:00. The interior air velocity at 0.5 m/s can give the widely ranges for thermal comfort.

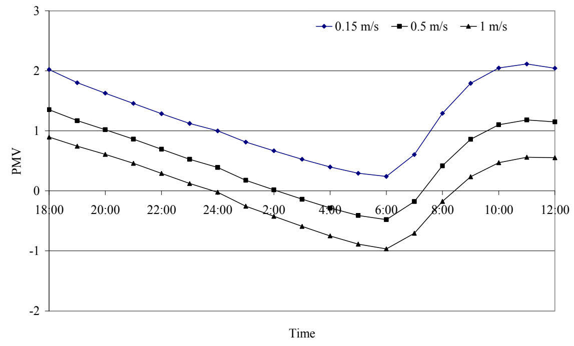

Fig. 3. Values of PMV by varying interior air velocity

B. Performance of Cooling Tower

Results showed that the performance of cooling tower is 59.96 %. The higher performance of cooling tower can be obtained if the water outlet temperature and wet-bulb temperature are slightly difference. Weather data can be divided into two periods, namely, period I: 23:00-8:00 (low temperature and high humidity) and period II: 8:00-23:00 (high temperature and low humidity). The average dry-bulb and wet-bulb temperatures of ambient air are 25.64°C and 23.66°C for period I, thus, cooling tower can produce cool water as requirement at 25°C in this period. In addition, dry-bulb and wet-bulb temperatures in period II are 33.07°C and 20.55°C which cooling tower could not produce required cool water because inlet air temperature is higher than outlet air temperature.

C. Thermal Comfort Evaluation

All subjects are in seat and quiet 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.

1) Humid sensation analysis

There has five alternatives for humid sensation vote, namely, dry (scale -2), slightly dry (scale -1), just right (scale 0), slightly humid (scale +1) and humid (scale +2). Sample experimental results for humid sensation vote at air velocity 0.6 m/s are given in Table II. 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 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% and the humid acceptability for Thai subjects are below 80% for all cases of relative humidity above 70% .

TABLE II: HUMID SENSATION VOTE FOR AIR VELOCITY 0.6 M/S

Air Velocity	Temperature	RH	Number of Humidity sensation vote					Total
(m/s)	(°C)	(%)	Dry	Slightly dry	Just right	Slightly humid	Humid	
0.6	24-24.9	70-80	-	-	26	2	-	28
		80-90	-	-	22	6	-	28
	25-25.9	50-60	-	-	25	2	-	27
	26-26.9	50-60	-	2	28	2	-	32
		60-70	-	2	28	2	-	32
		70-80	-	-	22	6	-	20
		80-90	-	-	33	13		46
	27-27.9	50-60	-	-	38	-	-	38
		60-70	-	-	34	-	-	34
		70-80	-	-	89	6	-	95
		80-90	-	-	12	20	-	32
	28-28.9	60-70	-	-	46	-	-	46
		70-80	-	-	22	4	-	26
		80-90	-	-	20	2	4	26
	29-29.9	60-70	-	-	52	-	-	52
		70-80	-	-	22	4	-	26
	30-30.9	60-70	-	-	20	3	2	25
		70-80	-	-	18	8	1	27
	31-31.9	60-70	-	18	15	5	-	38
	32-32.9	70-80	-	18	15	5	-	38

2) Thermal sensation analysis

Different scales of thermal sensation have been used, namely, cold (scale -3), cool (scale -2), slightly cool(scale -1), neutral(scale 0), slightly warm(scale +1), warm(scale +2) and hot(scale +3). Neutral temperatures are in the ranges of 26.44°C-32.60°C. Thermal comfort range can be obtained at the higher temperature in case of increasing air velocity. Nevertheless, thermal acceptability for Thai subjects for air velocity 1.0 m/s at percent of vote "0" is only 37% which supports ASHRAE recommendation as air velocity be 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. The highest percent of vote "0" were obtained in case of air velocity 0.2 m/s and 0.4 m/s.

3) Air movement sensation analysis

Air movement sensation vote are classified to four alternatives, namely, too still (scale -1), just right (scale 0), breezy (scale +1) and too breezy(scale +2). Subjective results for air velocity 0.6 m/s are given in Table III. At air velocity 0.2 and 0.4 m/s, the subjects feel mostly just right. The votes for breezy and too breezy are obtained at the higher air velocity 0.8 and 1 m/s. The highest acceptability can be obtained at temperature 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.

D. Energy Saving

Comparison between the use of radiant cooling system and split type air-conditioner were also examined. Results implied that electricity consumption for radiant cooling system and split type air conditioner are approximately 535 W and 901 W, respectively. Energy savings can be obtained approximately 41% by using radiant cooling instead of air conditioner.

TABLE III: AIR MOVEMENT SENSATION VOTE FOR AIR VELOCITY 0.6 M/S

Air Velocity (m/s)	Temperature (°C)	RH (%)	Number of Air movement sensation vote				Total
			Too still	Just right	Breezy	Too breezy	
0.6	24-24.9	70-80	-	5	22	-	27
	25-25.9	50-60	-	12	24	-	36
	26-26.9	50-60	-	18	10	-	28
		60-70	-	10	20	-	30
		70-80	-	26	39	-	65
		80-90	-	20	26	-	46
	27-27.9	50-60	-	52	7	-	59
		60-70	-	20	26	-	46
		70-80	-	59	46	-	105
		80-90	7	14	33	-	54
	28-28.9	50-60	-	22	9	-	31
		60-70	-	40	2	-	42
		70-80	-	20	5	-	25
		80-90	9	10	9	-	28
	29-29.9	60-70	-	65	26	-	91
		70-80	-	19	14	-	33
	30-30.9	60-70	-	46	26	-	72
		70-80	-	52	7	-	59
	31-31.9	60-70	2	24	-	-	26
		70-80	5	20	2	-	27
	32-32.9	70-80	2	24	-	-	26

IV. CONCLUSION

The radiant cooling system can be applied for buildings under the tropical climate and consumes less energy consumption approximately 41% comparing with the use of air conditioner. Cooling tower could be employed to provide cool water for radiant cooling panels. The performance of cooling tower was 59% and depended on the temperature and humidity of exterior air. Values of PMV were used to examine thermal comfort and found that the use of radiant cooling system is appropriate for the night time and early morning.

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Ar-U-Wat Tantiwichien was born in Songkhla, Thailand, in 1970. He received the M.Eng degree in mechanical engineering from Prince of Songkla University, Thailand in 2006. He is now a doctoral student in Department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University, Thailand. His research interests include thermal comfort, radiant cooling system, energy conservation in buildings and factories, building energy simulation.

Juntakan Taweekun was born in Yala, Thailand, in 1969. She received the B.Eng degree in mechanical engineering from King Mongkut University of Technology Thonburi, Bangkok, Thailand in 1991, and then received the M.Eng and D.Eng degrees in Energy Technology from Asian Institute of Technology, Bangkok, Thailand in 1996 and 2003, respectively. She works in Department of Mechanical Engineering, Faculty of Engineering, Prince of Songkla University, Thailand as an assistant professor.

Her research interests include energy efficient in buildings and industries, low energy buildings, thermal comfort assessment, building energy analysis and simulation i.e. DOE-2, Neural network, EnergyPlus, TRANSYS, biomass energy, renewable energy, daylighting E-mail: juntakan@me.psu.ac.th