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Evaluation of Human Thermal Comfort and Microbial Analysis in an Evaporative Cooling Room
การประเมินสภาวะสบายและการวิเคราะห์แบคทีเรียภายในห้องที่มีการใช้พัดลมไอเย็น

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Abstract

In Thailand, evaporative air coolers (EAC) are common in outdoor and semi-outdoor areas. Exploring the possibility of using an EAC in an indoor area, this research aims to determine its benefits in a natural, ventilated room during summer and winter. In terms of human thermal comfort, these benefits are evaluated through the CBE Thermal Comfort Tool with environmental parameters collected from the testing room. Bacterial growth due to increased humidity is analyzed based on bacterial counts in the opened Petri dishes. The results from the testing room with EAC show that air temperature reduces by 1.4 - 4.4 °C during winter and 3.3 - 3.5 °C during summer with a relative humidity increase of 2.3 - 13.1%. Thermal comfort was found to depend on indoor air temperature and air velocity. During winter, it was slightly improved by the use of an EAC, with an elevated percentage of people dissatisfied (PPD) due to low air temperature and high air velocity. The evaporative, cooled air also enhances thermal comfort in summer with less PPD. Increasing air velocity to provide thermal comfort is more suitable in summer than in winter. More bacteriological colonies formed in the room with an EAC than in the room with natural air by 33-55 units. The air quality in the EAC room according to IMA standards was Fair-Good, dropped from Good-Very Good in the natural-air room. This study confirms that the EAC improved thermal comfort in the natural ventilation room during both summer and winter. However, the room air was impure with the increase in microbial activity due to high air temperature and humidity.

Keywords
Natural ventilation
Evaporative cooling
Water evaporation
Humidity
Bacterial colony
Indoor air quality

บทคัดย่อ

ในประเทศไทยพัดลมไอเย็น (EAC) พบได้ทั่วไปในพื้นที่กลางแจ้งและกึ่งกลางแจ้ง เพื่อสำรวจความเป็นไปได้ในการใช้พัดลมไอเย็นในพื้นที่ภายในอาคารในฤดูที่อากาศมีค่าความชื้นสัมพัทธ์ต่ำ งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาผลของสภาวะสบายในการใช้งานพัดลมไอเย็นในฤดูหนาวและฤดูร้อนรวมทั้งศึกษาคุณภาพอากาศในด้านจำนวนจุลชีพเมื่อใช้ EAC ในห้องที่มีการระบายอากาศตามธรรมชาติ การศึกษาประโยชน์ในแง่สภาวะสบายเชิงอุณหภาพของมนุษย์จะใช้ข้อมูลสิ่งแวดล้อมที่เก็บได้จากห้องทดสอบป้อนเข้า CBE Thermal Comfort Tool เพื่อประเมินระดับความสบายตามค่าผลโหวตเฉลี่ย (PMV) ข้อเสียเนื่องจากการเจริญเติบโตของแบคทีเรียจะวิเคราะห์โดยอาศัยการนับจำนวนโคโลนีแบคทีเรียในจานเพาะเชื้อ ผลจากห้องทดสอบที่ใช้งาน EAC แสดงให้เห็นว่าอุณหภูมิของอากาศลดลง 1.4 – 4.4 °C ในช่วงฤดูหนาวและ 3.3 – 3.5 °C ในช่วงฤดูร้อน โดยความชื้นสัมพัทธ์จะเพิ่มขึ้น 2.3 – 13.1% ระดับความสบายเชิงอุณหภาพนั้นขึ้นอยู่กับอุณหภูมิอากาศภายในอาคารและความเร็วของอากาศ ในช่วงบ่ายของฤดูหนาวที่มีอุณหภูมิอากาศสูงพบว่ามีความสบายเชิงอุณหภาพดีขึ้นเล็กน้อยโดยใช้ EAC ร้อยละของผู้ที่ไม่พอใจ (PPD) ก็มีค่าสูงขึ้นด้วยเนื่องจากอุณหภูมิของอากาศต่ำรวมกับความเร็วของอากาศที่สูง การใช้ EAC ช่วยเพิ่มความสบายเชิงอุณหภาพในฤดูร้อนได้เช่นกันโดยมีค่า PPD ที่ลดลงกว่าในฤดูหนาว การเพิ่มความเร็วของอากาศเพื่อเพิ่มความสบายเชิงอุณหภาพเหมาะกับฤดูร้อนมากกว่าในฤดูหนาว ผลการตรวจวัดจำนวนแบคทีเรียในห้องที่มี EAC พบว่ามีจำนวนมากกว่าในห้องที่มีอากาศธรรมชาติ 33–55 หน่วย คุณภาพอากาศในห้อง EAC ตามมาตรฐาน IMA จัดอยู่ในระดับพอใช้ ซึ่งลดลงจากระดับดี – ดีมากในห้องปรับอากาศตามธรรมชาติ การศึกษานี้ยืนยันว่า EAC ช่วยเพิ่มความสบายเชิงอุณหภาพในห้องระบายอากาศตามธรรมชาติทั้งในฤดูร้อนและฤดูหนาว อย่างไรก็ตามที่ ความชื้นสัมพัทธ์ 58% อุณหภูมิอากาศสูง 32 °C คุณภาพอากาศในห้องจะลดลงเนื่องจากมีการเพิ่มขึ้นของแบคทีเรีย

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1. Introduction

In most parts of Thailand there are three seasons, summer (March-May), rainy (June-October), and winter (November-February) seasons. During cool and summer seasons, the weather in Thailand is relatively dry. The average relative humidity during daytime in summer and winter has been found to be 30-55% (Thai Meteorological Department, 2019). Thailand's dry seasons offers opportunities to cool natural air with an evaporative air cooler. Evaporative cooling has been widely used in outdoor areas such as in a street restaurant, plaza or public space. Evaporative air cooler indoors has also been confirmed for thermal comfort during the summer. (Sudprasert, 2021). Adaptive thermal comfort models have confirmed that thermal comfort varies seasonally (ASHARE, 2017). There is still lack of research on thermal comfort achieved with an evaporative cooler during winter when air temperatures in the afternoon are too high to achieve thermal comfort naturally. In addition, the air quality in terms of microbial growth in the natural ventilated room equipped with an evaporative air cooler is a knowledge gap. Therefore, this study aims to compare human thermal comfort during summer and winter and to analyze microbes that form in the room equipped with an evaporative air cooler. In this research, the thermal comfort indices involved Predicted Mean Votes (PMV) and Standard Effective Temperature (SET). The thermal comfort indices were calculated based on environmental data collected in the experiment room. The regression analysis was employed to indicate effective variables on the derived PMV.

2. Literature Review

Human thermal comfort depends on air temperature, air humidity, wind speed, radiation, clothing, human metabolism, and heat loss due to activity (Fanger, 1970). In tropical climates, air movement is a key factor in thermal comfort. Air velocity increase through the use of a fan has been shown to increase the comfort temperature by 4 °C (Nicol, 2004) and (Atthajariyakul & Lertsatittanakorn, 2008) in hot and humid climates, wind speeds of 1.0 to 3.0 m /s increased thermal comfort at temperatures up to 36 °C (Khedari et al., 2000; Kamar et al., 2019). Spraying water mist in the outdoor area reduced air temperature and increased thermal comfort significantly because of the water evaporation from human skin (Farnham, et al., 2015; Farnham, et al., 2017). Sunlight, high wind speed, and high air temperature accelerate the water evaporation rate in the outdoor area. On the other hand, room air temperature is lower than outdoor air temperature, plus no sunlight and low natural wind speed in the room. To reach thermal comfort through water evaporation in a room, high wind speed of greater than 1.4 m/s was needed (Sudprasert, 2021). Human thermal comfort also depends on seasons and varies with outdoor air temperatures. Indoor comfort temperatures have been found to have linear relationships with monthly mean outdoor air temperature (Toe & Kubota, 2013). The comfort temperature in winter was found to be lower than that in summer. Despite the moderate relative humidity in summer and winter, thermal comfort achieved through an evaporative cooler during winter would differ from that achieved in summer.

This study aims to evaluate thermal comfort and explore bacteria formation in a room with evaporation during two dry seasons in Thailand. The results can lead to using or not using an evaporative cooler to cool air in a non-air-conditioned room. If it is possible to reduce the temperature in an non-air-conditioned room during the right season, it increases the energy efficiency of the building at low cost and save electricity. The air temperature and relative humidity in Bangkok, Patum Thani, and Ayutthaya provinces during the daytimes were studied (Thai Meteorological Department, 2019). The data show that, for 24% of the total 3276 h per year, the relative humidity was less than 49% and the air temperature can range from 29°C to 39°C.

3. Methodology

This research uses the following instruments to measure and collect environmental data in the room: 1) Data logger Kestrel DROP temperature and humidity measurement with temperature measurement range of -10 °C to 55 °C, accuracy ± 0.5 °C, and relative humidity measurement range of 10% to 90% RH, accuracy 1.0% RH; 2) Lt-Lutron globe data and temperature logger, model WBGT-2010SD, with temperature measurement range of 0 °C to 50 °C, accuracy ± 0.5 °C, resolution 0.1 °C 3) and TESTO anemometer, model 435-2, and wind speed 0 - 20 m/s. The experiment procedures employed during winter (November-December) and summer (March-April) are as follows:

1. The experiment room was 2.5 x 2.5 x 2.6 m^3 with a window and a door. The window and door remain opened during the experiments. The air temperature, relative humidity, velocity, globe temperature, and Petri dishes were placed at the air inlet, at the air cooler outlet, in the middle of the room, and at the door of the room. Figure 1 shows where in the room climate values were recorded and a photo of the experiment room.

The evaporative air cooler was located 0.5 m away from the window. The air velocity can be adjusted to 3 levels: low, medium and high. The seat is placed 2.0 m away from the evaporative fan to avoid overly high air velocity. The measured at the seat was between 0.5 and 0.9 m/s (low velocity) and 1.0 and 1.5 m / s high velocity), respectively. The water flow rate of the EAC was 25 L/Hr. The evaporative rates measured from the humidity

Figure 1. Positions of the instruments and photo of the experiment room.

difference between the inlet and outlet of the EAC was 0.9-2.0 kg H_2O/kg dry air. Before the experiment, the water tank of the evaporative air cooler was filled. The water in the tank was driven through the pipe by a small pump to soak the honeycomb in the evaporative cooler. Outdoor air was flowing through the honeycomb panels to absorb moisture and reduce air temperature.

2. The air temperature, relative humidity, globe temperature and air velocity when operating evaporative air at the high and low levels were recorded every 4 minutes and are average for later computation. The data were collected between 12 am and 3 pm from November 27 through April 17. The value of clothing insulation is 0.57 (trousers, short-sleeve shirt, socks, shoes, underwear) and the metabolism is 1.0 (sitting).

3. The computation of PMV and SET was carried out with the CBE thermal comfort tool (Center for the Built Environment, 2017). Based on the environmental parameters collected from the testing room, PMV and SET was calculated. The regression analysis was used to evaluate the effect of variables on the computed PMV in the application of EAC in summer and winter. This study measures level of human thermal comfort based on a Predicted Mean Vote (PMV) score and SET values (ASHARE, 2017). Mean vote is a measure of the level of thermal comfort between -3 (cold) to +3 (hot) where PMV = 0 means normal, or comfortable. In this study, clothing, metabolism and activity are all controlled parameters. Air temperature, air humidity, and air speed vary with the evaporative fan conditioning. SET (Standard Effective Temperature) values developed from ET (Effective Temperature) in 1923. The results of SET values represent thermal sensation and thermal comfort levels as shown in Table 1.

4. A microbial test kit was used for bacteria analysis. In this research, the Petri dishes were placed in five locations: one in the middle of the room, one on the chair, and three in the corner of the room. The dish was exposed to evaporative air and natural air for 30 minutes. Then, the dishes were covered and sealed. The sealed dishes were incubated at air temperatures of 33-37°C for 24 hours. The orange spots that formed in the testing dishes represent the bacteria colonies. In this study, the number of bacteria colonies were counted to identify room air quality. The results were depicted in the number of colonies forming units (CFU) per dish area over time (CFU/dm^2/h). This method is standardized according to Index of microbial air (IMA) contamination. As shown in Table 2 (Pitzurra et al., 1997; Pasquarella et al., 2000).

Table 1. The criteria of thermal comfort based on SET value and PMVs and Physiological conditions.

SET	PMVs	Thermal Sensation	Physiology
>37.5	>3	Very hot, great discomfort	Failure of evaporative regulation
37.5-34.5	+2 to +3	Hot, very unacceptable	Profuse sweating
34.5-30.0	+1 to +2	Warm, uncomfortable, unacceptable	Sweating
30.0-25.6	+0.5 to +1	Slightly warm, slightly unacceptable	Slight sweat, casolidation
25.6-22.2	-0.5, +0.5	Comfortable, acceptable	Physiological thermal neutrality
22.2-17.5	-1 to -0.5	Slightly cool, slightly unacceptable	Initial vasoconstriction
17.5-14.5	-2 to -1	Cool, unacceptable	Slow body cooling
14.5-10.0	-3 to -2	Cold, very unacceptable	Beginning of shivering

Table 2. Microbial air quality according to IMA standards in CFU/dm^2/h units and assessment levels (Phanombualert et al., 2016).

IMA value	CFU/dm^2/h	Class
0-5	0-9	Very good
6-25	10-39	Good
26-50	40-84	Fair
51-75	85-124	Poor
>76	>125	Very poor

4. Results and Discussions

4.1 Thermal comfort in winter

A total of 24 data sets were collected in 24 days between November and early January. Tables 3 and 4 show the results average, maximum and minimum values of temperature ($T_{a,out}$) relative humidity (R_{Hout}) of entering air, temperature ($T_{a,in}$) and relative humidity (RH_{in}) of the indoor air (with evaporative air cooler), and air velocity (V), globe temperature (T_g). The computed results of SET, PMV and PPD in Tables 3 and Table 4 present the results at low and high air velocity, respectively.

As shown in Table 3, the average indoor air temperature of 28.7 °C reduced from the average outdoor air temperature of 30.7 °C. The indoor relative humidity increased by 8-11%, which accounted for 2.0-3.0 g/kg dry air. The computed results of PMV range from -1.2 to 1.0, implying that people felt slightly cool to slightly warm using the evaporative air cooler during winter afternoons. Accordingly, the calculated SET was 21.3 °C to 27.8 °C, meaning the air conditioning was slightly cool and acceptable. The percentage of people who were dissatisfied (PPD) was 40.1%. The 'cool' sensation (PMV=-1.2) occurred under indoor air temperature of 24.7°C. The effects of increasing velocity on thermal comfort are shown in Table 4. The relative humidity under high air velocity is slightly lower than that under low air velocity because the air briskly blows through the wet honeycomb and then rapidly exits. Under high air velocity, the air absorbs less water and leaves the room before mixing with the room air. The PMV index shows that people tend to feel slightly cool (PMV = -0.4) or cool (PMV=-1.7), both of which are uncomfortable thermal sensations. Therefore, using an evaporative air cooler with low air velocity was appropriate to human thermal comfort during winter.

4.2 Thermal comfort in summer

Table 5 shows the results of environmental data and computed thermal comfort during summer under low air velocity. The average outdoor air temperature was 33.8 °C and the relative humidity was 46.3%. The outdoor air was pulled from the window into the evaporative air cooler. The average air temperature at the seat reduced to 29.3 °C while the relative humidity increased to 54.3%. The average PMV was 0.6, implying a thermal sensation of comfortable-slightly warm. The maximum PPD was 37.1, which is lower than the 40.1-57.9 average PPD of winter. Accordingly, the SET value of 27 °C means slightly unacceptable. As shown in Table 6, increasing air velocity improves thermal comfort as PMV approaches 0.0. The PPD and SET under high air velocity remain similar to those under low air velocity. From Table 5 and Table 6, $T_{a,in}$ and T_{globe} are similar. Thus, air velocity is the most effective parameter for thermal comfort indexes during summer.

The results of calculated PMV shows that EAC can be used in both summer and winter in Thailand. In winter, air velocity less than 1.0 m/s was appropriate to provide thermal comfort in the PMV range of -0.4 to 0.5 (comfortable with slightly cool and slight warm). In summer, using the EAC with high air velocity of 1.0-1.5 m/s assured thermal comfort in the room with high air temperature of 32.0-35.7°C.

4.3 Effects of temperature, air velocity and humidity on PMV

Figures 2a and 2b show the results of PMV with respect to Ta,in during summer and winter under low and high air velocities, respectively. The linear

Table 3. Results of thermal comfort in winter under low air velocity.

	$T_{a,out}$ (°C)	RH_{out} (%)	$T_{a,in}$ (°C)	T_{globe} (°C)	V (m/s)	RH (%)	SET	PMV	PPD
Average	30.7	47.1	28.7	28.5	0.6	57.6	26	0.5	10.7
Max	33.0	55.4	30	29.8	0.8	63.1	27.8	1.0	40.1
Min	26.5	40.3	24.7	24.5	0.3	51.4	21.3	-1.2	5.2

Table 4. Results of thermal comfort in winter under high air velocity.

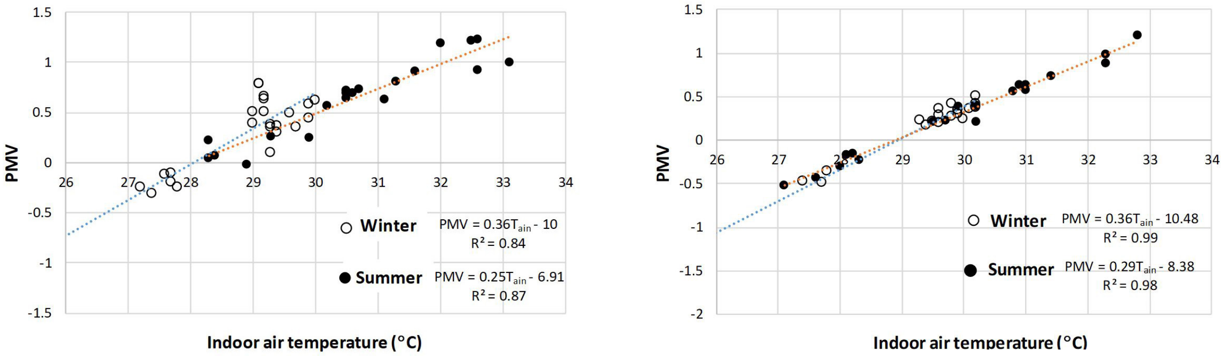
	$T_{a,out}$ (°C)	RH_{out} (%)	$T_{a,in}$ (°C)	T_{globe} (°C)	V (m/s)	RH (%)	SET	PMV	PPD
Average	30.7	47.1	28.9	28.7	1.1	55.1	25.2	-0.4	13.6
Max	33.0	55.4	30.2	30.0	1.4	61.7	26.9	0.5	57.9
Min	26.5	40.3	24.6	24.4	1.1	48.4	20.3	-1.7	5.6

Table 5. Results of thermal comfort in summer under low air velocity.

	$T_{a,out}$ (°C)	RH_{out} (%)	$T_{a,in}$ (°C)	T_{globe} (°C)	V (m/s)	RH (%)	SET	PMV	PPD
Average	33.8	46.3	30.6	29.3	0.7	54.3	27	0.6	16.8
Max	35.7	44.3	33.1	32.2	0.8	58.9	28.9	1.5	37.1
Min	32.1	35.6	28.3	25.9	0.5	47.1	24.8	0.0	5.0

Table 6. Results of thermal comfort in summer under high air velocity.

	$T_{a,out}$ (°C)	RH_{out} (%)	$T_{a,in}$ (°C)	T_{globe} (°C)	V (m/s)	RH (%)	SET	PMV	PPD
Average	33.8	46.3	30	29.4	1.3	50.2	26.2	0.1	12.8
Max	35.7	44.3	32.8	32.4	1.8	55.8	28.1	1.2	35.6
Min	32.1	35.6	27.1	26.7	1.0	44.1	23.3	-0.5	5.4



a) Low air velocity b) High air velocity

Figure 2. The results of PMV relate to indoor air temperature.

relationships between PMV and $T_{a,in}$ in Figure 2a, allow the comfort temperature of 28.0 °C for both summer and winter. For low air velocity, the slope of the graph PMV-$T_{a,in}$ in the winter is higher than that in the summer. This means that the changing of the air temperature in winter is more sensitive to PMV value than that changing air temperature in summer. In Figure 2b, the comfort temperature is approximately 29.0 °C for both summer and winter. The higher comfort temperature extended by 1.0 °C for increasing air velocity from 0.9 (low air velocity) to 1.5 m/s (high air velocity). For high air velocity, the slope of the graph PMV-Ta,in in the winter is similar to that in the summer. Therefore, the results of comfort temperature in a room with an evaporative air cooler depends on air velocity.

Figure 3 shows the computed PMVs plotted against the relative humidity. The relative humidity shows a moderate correlation with the PMV in in both summer and winter. The relative humidity varies from 35-55%. The added water into the air stream affects the PMV less than the $T_{a,in}$ and the air velocities. The regression analysis in Table 7 shows that indoor air ($T_{a,in}$) and air velocity (V) significantly affects the PMVs ($p=<0.05$). On the other hand, the relative humidity (RH) insignificantly affects the PMVs ($p>0.05$).

4.4 Results of microbial analysis

Figure 4 shows the results of bacteria found in a room with an evaporative cooler fan. With an air temperature of 32 °C and relative humidity of 58%, the number of colonies were 38-80 per square decimeter per hour (CFU/dm^2/hr), which is 'Fair-Good' according to the IMA standard. Figure 5 shows bacterial colony results in a room with a natural air fan. The number of colonies growing in the dish was 5-25 CFU/dm^2/hr, which is 'Good-Very good' according to the IMA standard. Table 8 shows the average number of bacteria during three days in which natural and evaporative air were applied. Clearly, the number of colonies in the natural air room was lower than that in the evaporative air room, which can be attributed to the higher relative humidity in the evaporative air. The latter has been shown to be required for sustained growth. It appears that the added humidity provides a more conducive environment for bacterial growth, with microbial growth taking place at high temperatures (> 36°C) and humidity. Therefore, an evaporative air cooler is recommended when the relative humidity in the room is lower than 58%. To cope with air quality problems, high ventilation is required. Alternating between the evaporative cooling mode and the natural air mode to drive the humidity out of the room helped reduce the occurrence of microorganisms.

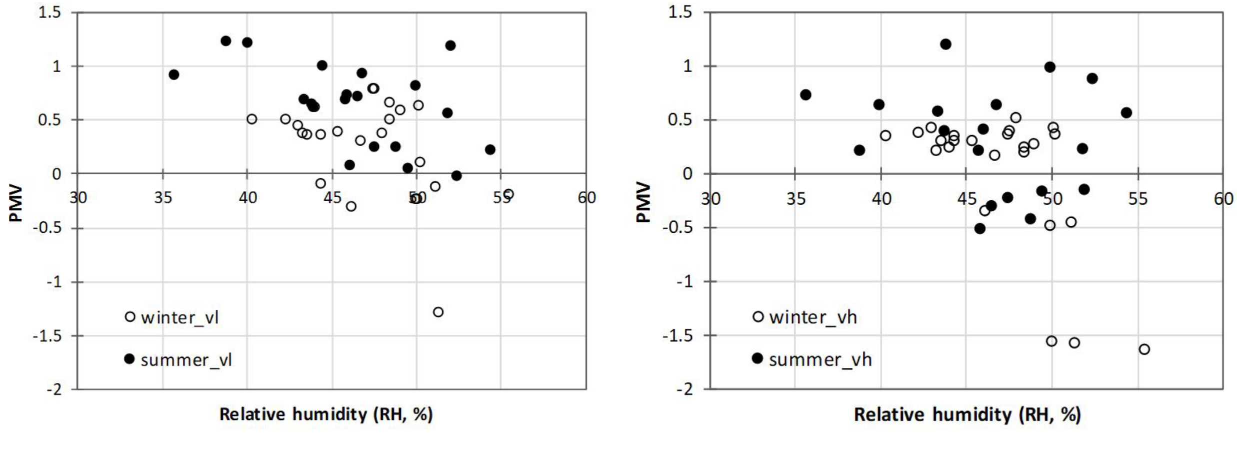
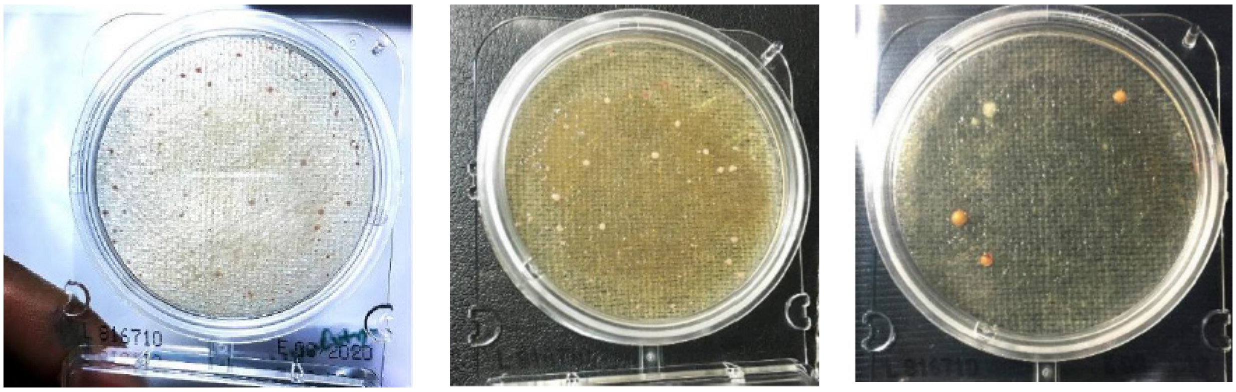


Figure 3. Results of PMV vs. indoor relative humidity.

Table 7. Results of regression of PMV - air temperature ($T_{a,in}$), PMV-velocity (V) and PMV-relative humidity (RH) for 102 data sets (two seasons).

Dependent variables	Independent variable/ intercept	Coefficients	Standard Error	t-Stat	P-value
PMV	Intercept	-1.466	0.353	-4.15	$p<0.05$
	Air temperature, $T_{a,in}$	0.060	0.012	4.96	$p<0.05$
PMV	Intercept	0.513	0.234	2.18	$p<0.05$
	Air velocity, V	-0.506	0.254	-1.98	$p=0.05$
PMV	Intercept	0.842	0.322	2.61	$p<0.05$
	Relative humidity, RH	-0.011	0.006	-1.82	$p>0.05$



38 CFU/dm^2 /hr

25 CFU/dm^2 /hr

4 CFU/dm^2 /hr

Figure 4. Orange spots represent bacteria forming in the opened dishes.

Table 8. Bacteria counts from samples collected in the room.

	Evaporative air					Natural air				
Location	**#1**	**#2**	**#3**	**#4**	**#5**	**#1**	**#2**	**#3**	**#4**	**#5**
3-day Average (CFU/dm^2 /hr)	20	25	40	33	60	6	12	8	4	25

5. Conclusions

This research evaluates thermal comfort in a room with an evaporative air cooler during winter and summer. The environmental data collected from the testing room were input into a CBE Thermal Comfort Tool to analyze the thermal comfort indexes PMV, SET and PPD. The maximum outdoor temperatures were 33 °C in winter and 35.7 °C in summer, which were too high to maintain thermal comfort in natural air. Using an evaporative air cooler can reduce air temperatures by up to 3.5-4.4 °C, with a maximum increase of relative humidity to 63% in winter and 58.9% in summer. Thermal comfort is improved to the level of “slightly cool-cool” in winter and “comfort-slightly warm” in summer. An evaporative air cooler is recommended to improved thermal comfort for both seasons, provided that the air velocity is regulated properly. High air velocity enhances thermal comfort in summer, but diminishes it in winter. To use an evaporative air cooler appropriately in the winter low air velocity of less than 1.0 m/s is recommended. The results of regression analysis showed that air velocity is the most effective environmental variable, followed by the room air temperature when using an evaporative.

The room with an evaporative air cooler shows higher bacteria growth than the room with natural air. The microbial air quality in the evaporative air room is categorized into the “Fair-Good” class, which is lower than the “Good-Very good” class in the natural air room. This research confirms thermal comfort achievement through the use of an evaporative air cooler in the two warm-dry seasons in Thailand, in the afternoon of winter and summer. However, inferior air quality due to the growth of bacteria and other microorganism must be improved. Alternating between high ventilation of natural air and evaporative air could be a viable method of reducing accumulated moist air and microorganisms.

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