Thermal comfort of Thai students in university buildings under variable indoor conditions of air conditioned space

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Abstract

The purpose of this research is to determine the thermal response time and temperature range of thermal comfort of Thai students for air-conditioned classrooms survey questionnaires and by the predicted mean vote (PMV) equations, and thereby recommend air-conditioner temperature settings that also saves energy. The students were tested in a 8×9×3 m^3 room size with two units of 40,000 Btu/h split-type air conditioners. The air-conditioner temperature setting was varied from 25, 26, 27 and 28 °C and at each temperature setting, the air speed were varied at three levels. The thermal comfort survey questionnaires were based on ASHRAE thermal sensation scale. The results of the thermal sensation vote (TSV) using the questionnaires were as follow; the air temperature at 26±0.5–28±0.5 °C at all average air speed (≈0.5-0.9 m/s) were acceptable to the research subjects. Therefore, instead of setting the temperature at 25°C, which is the normal set point in most buildings as recommended by government; the air temperatures can be set higher. It can be between 26–28 °C but with the air speed also increased. These higher air-conditioner temperature settings help reduce energy consumption of air conditioners. The range of neutral temperature (TSV, PMV = 0) from the TSV and PMV equations on air temperature (t_a) were 26.7–28.3 °C and 27.7–28.4 °C respectively, which all correspond to thermal comfort acceptability of thermal sensation vote (26±0.5–28±0.5 °C), which is the accepted temperature. In addition, with regards to the relationship of TSV and PMV with air temperature (t_a), effective temperature (ET*) and operative temperature (t_{op}) at neutral temperature (TSV, PMV = 0), the difference between neutral temperature of TSV and PMV does not exceed 1°C. The PMV equation can predict the thermal comfort of thermal sensation of subjects from the survey when the air conditioner temperature settings are changed from 25°C to 26–28°C, estimated energy savings ranged from 7.67–20.11%. This is approximately 7.30% saving for 1°C increase. The results of this research can be applied to the operation and control of classroom air-conditioners in university buildings to assure thermal comfort of students.

Keywords:

thermal comfort, Thai students, energy saving, TSV, PMV

1. Introduction

ASHRAE defines "thermal comfort" as that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation [1]. Moreover, thermal comfort leaves open as to what is meant by condition of mind or satisfaction, but it correctly emphasizes that the judgment of comfort is a cognitive process involving many inputs influenced by physical, physiological, psychological [2] and behavioral actions such as altering clothing, altering activity, changing posture or location, changing the thermostat setting, opening a window, complaining, or leaving a space.

However indoor thermal environments can significantly influence human health and comfort. In addition, thermal comfort is very important for architects and engineers to ensure comfort and health of occupants in the building [3]. Since the late 20^{th} century, the PMV (Predicted Mean Vote) model developed by Fanger has been widely used throughout the world. Although the PMV model is based on the database of European and North American subjects, many researchers around the world have conducted experiments in climate chambers and have demonstrated its validity [4].

Thailand is located in the sub-tropical zone at latitude 13°18´N and longitude 100°27´E; according to the climatological method of classification, the weather in Thailand is classified as "Humid Subtropical Climate". The climate in Thailand is outside the ASHRAE comfort zone [5]. Air-conditioning systems are installed in almost all university buildings to provide a comfortable thermal condition in classrooms, increasing highly the electricity cost of the university. To save air-conditioning energy use, the university follows the government recommendation n that the room temperature is set to 25°C. 25°C is an arbitrary choice to meet the comfort zone of ASHRAE Standard 55, thermal environmental conditions for human occupancy. This invites complaints from students who appear not to be comfortable with this room temperature setting.

Thermal comfort in classrooms has to be considered seriously because of the negative influence on learning. There is also the potential for energy conservation through careful temperature control [6] that can reduce electricity costs. Therefore, this research sought to determine the temperature of thermal comfort of Thai students under variable indoor conditions of air-conditioned space. This research was done through questionnaires to predict by PMV equations the desirable and recommended temperature settings for thermal comfort and that will also result to energy savings and electricity cost reductions.

2. The predicted mean vote (PMV)

The Predicted Mean Vote (PMV) equations developed and suggested by Fanger has been used worldwide to predict and assess indoor thermal comfort in residential buildings, office, school etc. The PMV predicts the mean thermal sensation vote response of a large group of people according to the ASHRAE thermal sensation scale. Fanger's equations are used to calculate the PMV of a large group of subjects for a particular combination of air temperature, mean radiant temperature, relative humidity, air speed, metabolic rate, and clothing insulation [7] by the shown following equation.

$$PMV = (0.303\exp(-0.36M)+0.028)[(M-W)-3.05\times10^{-3}[5733-6.99(M-W)-P_a]-0.42[(M-W)-58.2] -1.73\times10^{-5}M(5867-P_a)-0.0014M(34-t_a)-3.96\times10^{-8}f_{cl}[(t_{cl}+273.15)^4-(t_{mrt}+273.15)^4] -f_{cl}h_c(t_{cl}-t_a)] \quad (1)$$

Where
- M metabolic heat production (W/m^2)
- W external work (W/m^2)
- P_a partial water vapor pressure (Pa)
- t_a air temperature (°C)
- f_{cl} clothing area factor
- t_{cl} the outer surface temperature of clothed body(°C)
- t_{mrt} mean radiant temperature (°C)
- h_c convective heat transfer coefficient (W/m^2 K)

3. The effective temperature (ET*)

The effective temperature (ET*) is defined as the temperature of a still and saturated atmosphere which would, in the absence of radiation, produce the same effect as the temperature in question. In addition effective temperature is the temperature in an environment with 100% humidity and no air movements which will induce the same level of thermal comfort as in the present situation [8]. Equation of effective temperature is shown equation (2).

$$ET^* = 049t_a + 0.19P_a + 6.47 \qquad (2)$$

Where t_a air temperature (°C)

P_a partial water vapor pressure (Pa)

4. The operative temperature (t_{op})

The operative temperature (t_{op}) is the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment [1]. Equation of operative temperature is shown equation (3).

$$t_{op} = \frac{h_r t_{mrt} + h_c t_a}{h_r + h_c} \qquad (3)$$

Where t_a air temperature (°C)

t_{mrt} mean radiant temperature (°C)

h_c convective heat transfer coefficient (W/m^2 K)

h_r radiative heat transfer coefficient (W/m^2 K)

5. Materials and method

This research was done to determine temperature setting for thermal comfort of Thai students under variable indoor conditions of air-conditioned space. The total number of subjects were 424 males and 236 females. They all wore normal clothes, the various uniforms used in the university (Fig. 1). The field measurements were performed in a room of size 8 × 9 × 3 m^3 installed with 2 units of split-type air conditioner with capacity of 40,000 Btu/h 2 (see Fig. 2). The subjects' designated positions are shown in Fig. 3. The room air temperature was varied from 25, 26, 27 and 28 °C and in each temperature the air speed was varied at 3 levels: (low, medium and high). The numbers of subjects did not exceed 30 persons per each condition testing. The subjects entered and stayed in the testing room for 15 minutes [9] to adjust to the thermal sensation and of environment inside the testing room. Then the subjects started recording their thermal sensation using the questionnaires. The questionnaires addressed the following areas: (i) subjects' background and personal information; (ii) subjects' current clothing garments; and (iii) subjective thermal sensation vote (TSV) based on the ASHRAE sensation scale. The evaluation had seven levels, from -3 to +3 (Table 1). Data on the indoor environment of the classroom were also collected, i.e. temperature, relative humidity and air speed.

Table 1 ASHRAE sensation scale [1]

Thermal sensation	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Level	-3	-2	-1	0	+1	+2	+3

Table 2 Data of the subjects.

Gender	Number	Age(year) min-max	Weight (kg.) min-max	Height (m.) min-max	Clothing (clo) min-max
Male	424	21-25	52-85	1.65-1.84	0.61-1.28
Female	236	20-23	48-68	1.55-1.76	0.73-1.36
Male + Female	660	20-25	48-85	1.55-1.84	0.61-1.36

Fig. 1 normal clothes under uniform of university.

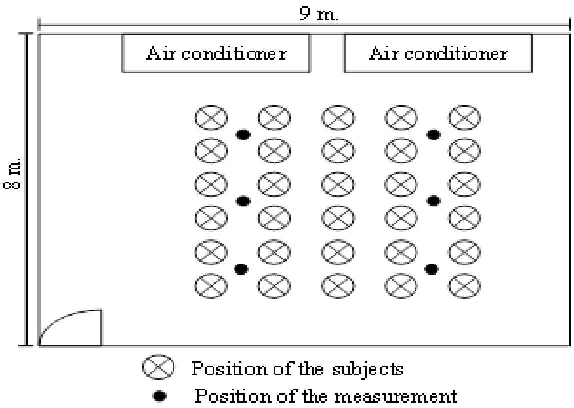

Fig. 2 Layout of the testing room.

Fig. 3 Position of the subjects.

6. Results

6.1 The general data

The total numbers of test subjects were 424 males and 236 females. Average age of subjects was 23.3 years for male and 21.3 years for female, average weight was 65 kg. for male and 59 kg. for female, average height was 1.77 m. for male and 1.66 m. for female. The subjects wore clothing that hasan average thermal resistance of s 0.931 clo for male and 1.041 clo for female (see Table 2 below for details).

The indoor environment data are as follows: air condition temperature setting 25, 26, 27 and 28°C, air speed level: low, medium, high and relative humidity (50-80%). All data are shown in Table 3 below.

Table 3 Data of condition test.

Air condition temperature setting (°C)	air speed level	Temp. (min-max) (°C)	Air speed (min-max) (m/s)	Average air speed (m/s)
	L	24.5–25.3	0.4–0.6	0.5
25	M	24.8–25.4	0.6–0.8	0.7
	H	24.9–25.3	0.8–1.0	0.9
	L	25.7–26.1	0.4–0.6	0.5
26	M	25.9–26.3	0.6–0.8	0.7
	H	26.0–26.2	0.8–1.0	0.9
	L	26.8–27.2	0.4–0.6	0.5
27	M	26.6–27.1	0.6–0.8	0.7
	H	26.8–27.2	0.8–1.0	0.9
	L	27.5–28.2	0.4–0.6	0.5
28	M	27.5–28.0	0.6–0.8	0.7
	H	27.6–28.1	0.8–1.0	0.9

6.2 The percentages of thermal sensation vote (TSV) [9]

The percentage distribution of thermal sensation votes (TSV), collected through the questionnaires; under various room temperature, air speed and relative humidity (50–80%) conditions are shown in Fig. 4 a)–d) below. It can be seen that when the air speed is increased with the air-conditioner temperature remaining the same, higher percentage of thermal sensation vote moved to the cool sensation vote side. While, if the air-conditioner temperature was increased with the air speed remaining the same, the percent of sensation vote tends to move to the hot sensation vote side. Therefore, thermal comfort can be provided by increasing the air speed to compensate for the higher temperature. The subjects can feel comfortable at higher air-conditioner temperatures if the air speed were increased [10].

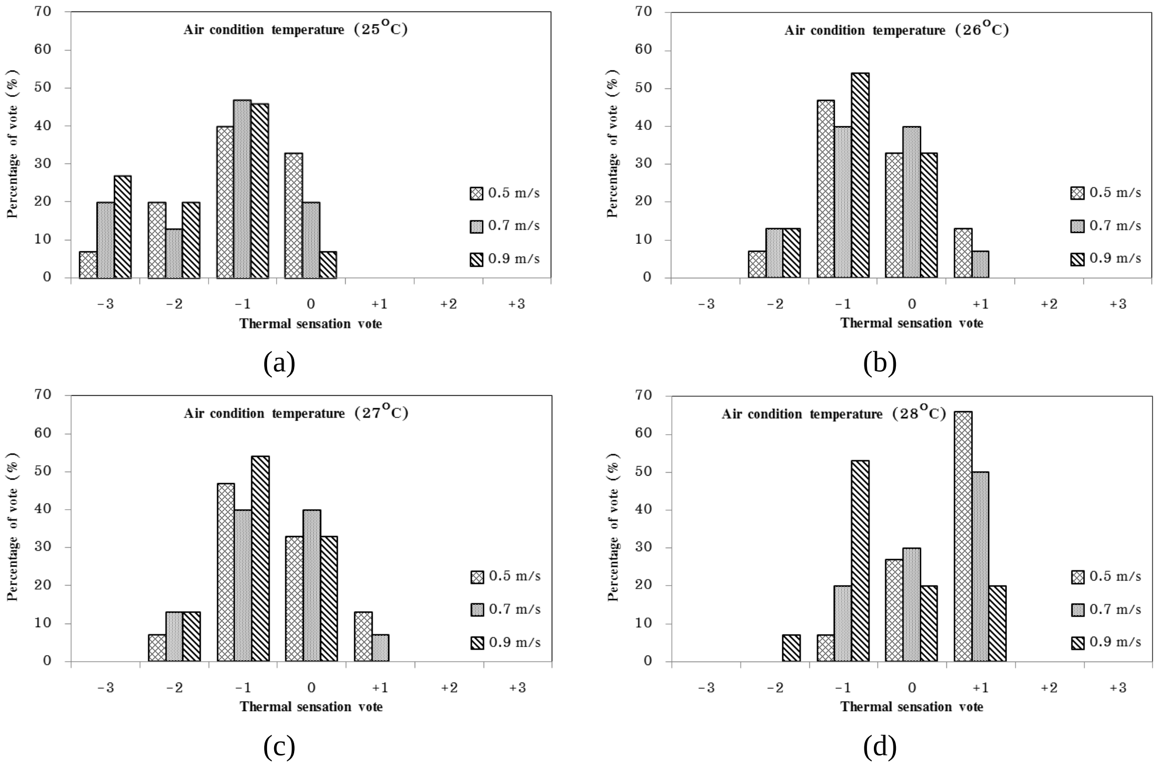

Fig. 4 Percentage of thermal sensation vote on air condition temperature: (a) 25 °C, (b) 26 °C, (c) 27 °C and d) 28 °C.

Table 4 Mean vote and percentage of -1 to +1 of thermal sensation vote [9].

Average air speed (m/s)	Air condition temperature (°C)							
	25±0.5		26±0.5		27±0.5		28±0.5	
	Mean vote	Percentage of -1 to +1	Mean vote	Percentage of -1 to +1	Mean vote	Percentage of -1 to +1	Mean vote	Percentage of -1 to +1
0.5	-1.0	73	-0.5	93	-0.4	93	0.6	100
0.7	-1.3	67	-0.6	87	-0.5	91	0.3	100
0.9	-1.7	53	-0.8	87	-0.7	87	-0.5	93

When the percentages of thermal sensation vote between -1 to +1 (Table 4) are considered, it was found that at air-conditioner temperature of 25±0.5 °C and at all air speed, the percentages of thermal sensation vote is between 53–73% and the sensation vote remains the on cool sensation vote side (mean vote -1.0 to -1.7), at all air speed. While at room air temperature of 26±0.5 °C, 27±0.5 °C and at all air speed, the percentages of thermal sensation vote is between 87–93%, and the sensation vote remains on the slightly cool sensation vote side (mean vote -0.5 to -0.8 for 26±0.5 °C and -0.4 to -0.7 for 27±0.5 °C). At room air temperature of 28±0.5°C and at all air speed, the percentages of thermal sensation vote is between 93–100% and the sensation vote remains on the averagely neutral sensation vote side (mean vote of between -0.5 to +0.6). If the definition of the conditions for thermal comfort acceptability is that, more than 80% of subjects vote for the thermal sensation of slightly cool, neutral and slightly warm or level from -1 to +1 [11]; the conditions at room air temperature 25±0.5 °C at all air speed, are not accepted. While the conditions at room air temperatures of 26±0.5 °C, 27±0.5 °C, 28±0.5 °C at all air speed, are accepted. Especially, at the room air temperature 28±0.5°C and average air speed 0.5, 0.7 m/s, the percent of thermal sensation vote between -1 to +1 is equal to 100%. This can indicate that most Thai students can accept temperature as high as 28±0.5 °C by adjust air speed of air conditioner. It is interesting to see that that the room air temperature can be set as high as 28 °C but with increased of air speed, instead of setting the temperature at 25 °C as is the normal set point in most buildings as recommended by the government. Consequently, this will help in reducing electricity consumption of air conditioners. The 1 °C increase in temperature setting represents a significant reduction in energy consumption, estimated at 7-10% [12].

6.3 The thermal sensation vote (TSV) and predicted mean vote (PMV) on air temperature (t_a) [9]

The TSV and PMV on air temperature (t_a) were plotted under each average air speed as shown in Fig. 5. The TSV and PMV at each point were obtained by sensation vote at the same air temperature and air speed. It was seen that when the air speed increased, the neutral vote shifts to higher air temperature.

To consider correlations between the TSV and PMV on air temperature (t_a) of each average air speed was applied to construct the TSV and PMV equation on linear regression form with the least square method. The resulting equations showed the correlation between TSV, PMV and air temperature and air speed [11], see Eq. (4) and (5) below:

$$TSV = 0.3749t_a - 1.5091v - 9.2695 \quad (4)$$

$$PMV = 0.4708t_a - 1.0600v - 12.4597 \quad (5)$$

when t_a is air temperature (°C) and v is air speed (m/s)

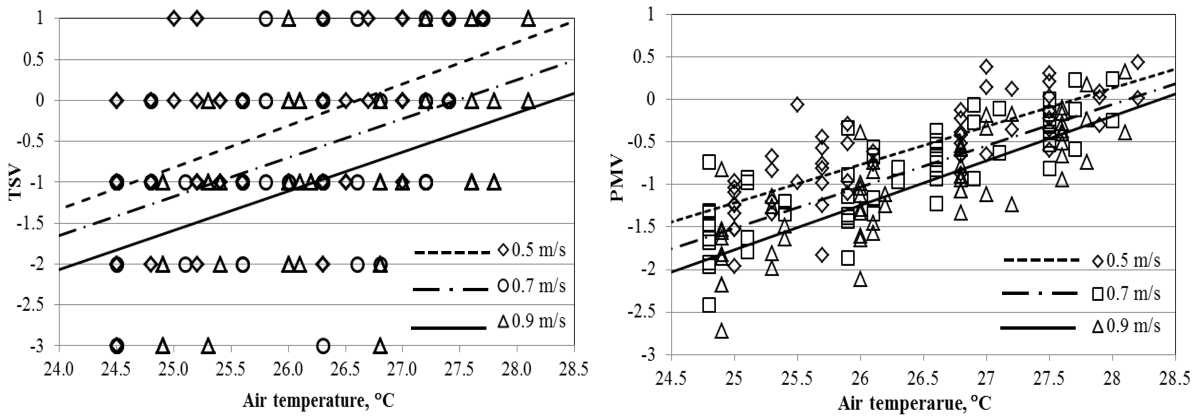

Fig. 5 TSV and PMV vs air temperature under air speed [9].

The neutral temperature air temperature (t_a) for each average air speed was calculated from Eq. (4) – (5) for TSV and PMV were shown in Table 5 and Table 6. It was found that at the air speed 0.5, 0.7 and 0.9 m/s, neutral temperature of TSV equation (TSV=0) were 26.7 °C, 27.5 °C and 28.3 °C respectively and neutral temperature of PMV equation (PMV=0) were 27.7 °C, 28.1 °C and 28.4 °C respectively. The neutral temperature of the TSV and PMV were increased with increasing of the air speed. Moreover range of neutral temperature of TSV (26.7–28.3 °C) and PMV (27.7–28.4 °C) at all air speed corresponded with thermal comfort acceptability of thermal sensation vote (26±0.5–28±0.5 °C), which is the accepted temperature. One can say that the TSV and PMV equations can predict the thermal comfort of thermal sensation of subjects from survey.

Table 5 Neutral temperature TSV equation (TSV = 0) on air temperature (t_a).

TSV	Average air speed (m/s)		
	0.5	0.7	0.9
Neutral temperature (t_a,°C) (TSV=0)	26.7	27.5	28.3
Recommend temperature limit (t_a,°C) (-0.5<TSV<0.5)	25.4–28.1	26.2–28.8	27.0–29.7

Table 6 Neutral temperature PMV equation (PMV = 0) on air temperature (t_a).

PMV	Average air speed (m/s)		
	0.5	0.7	0.9
Neutral temperature (t_a,°C) (PMV=0)	27.6	28.0	28.5
Recommend temperature limit (t_a,°C) (-0.5<PMV<0.5)	26.5–28.6	27.0–29.1	27.4–29.5

6.4 The thermal sensation vote (TSV) and predicted mean vote (PMV) on effective temperature (ET*)

The TSV and PMV on effective temperature (ET*) were plotted under each average air speed as shown in Fig. 6. The TSV and PMV at each point were obtained by sensation vote at the same air temperature and air speed. It was seen that when the air speed is increased, the neutral vote shifts to higher air temperature.

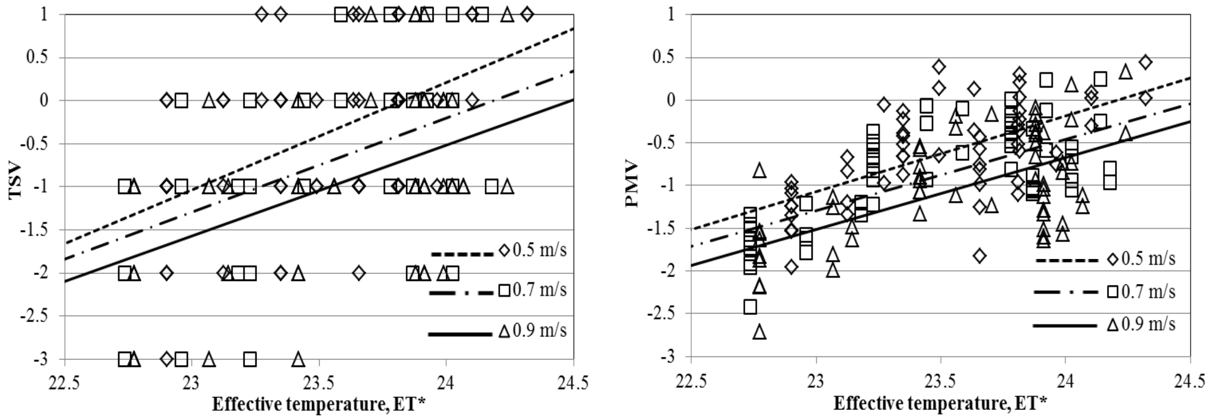

Fig. 6 TSV and PMV vs effective temperature (ET*).

To consider correlations between TSV, PMV and effective temperature (ET*) of each average air speed was applied to construct the TSV and PMV equation on linear regression form with the least square technique. The obtained equation showed the correlation between PMV and effective temperature (ET*) and air speed as shown in Eq. (6) and (7)

$$TSV = 1.0464ET^* - 1.4342v - 24.2551 \quad (6)$$

$$PMV = 0.7976ET^* - 1.0416v - 18.3840 \quad (7)$$

when ET* is effective temperature (°C) and v is air speed (m/s)

The neutral temperature on effective temperature (ET*) for each average air speed was calculated from Eq. (6) – (7) for TSV and PMV were shown in Table 7 and Table 8. It was found that at the air speed 0.5, 0.7 and 0.9 m/s, neutral temperature of TSV equation (TSV=0) were 23.9 °C, 24.1 °C and 24.4 °C respectively and neutral temperature of PMV equation (PMV=0) were 24.3 °C, 24.5 °C and 24.8 °C respectively. The neutral temperature of the PMV was increased with increasing of the air speed. In addition, when consider the recommend temperature limit of TSV (-0.5<TSV<0.5) and PMV (-0.5<PMV<0.5) on effective temperature (ET*) of each average air speed. It was found that the recommend temperature limit were 23.4–24.3 °C, 23.7–24.6 °C and 23.9–24.9 °C respectively for TSV, and 23.6–24.9 °C, 23.9–25.2 °C and 24.2–25.4 °C respectively for PMV.

Table 7 Neutral temperature of TSV equation (TSV = 0) on effective temperature (ET*).

TSV	Average air speed(m/s)		
	0.5	0.7	0.9
Neutral temperature (ET*,°C) (TSV =0)	23.9	24.1	24.4
Recommend temperature limit (ET*,°C) (-0.5<TSV<0.5)	23.4–24.3	23.7–24.6	23.9–24.9

Table 8 Neutral temperature of PMV equation (PMV = 0) on effective temperature (ET*).

PMV	Average air speed(m/s)		
	0.5	0.7	0.9
Neutral temperature (ET*,°C) (PMV=0)	24.3	24.5	24.8
Recommend temperature limit (ET*,°C) (-0.5<PMV<0.5)	23.6–24.9	23.9–25.2	24.2–25.4

6.5 The thermal sensation vote (TSV) *predicted mean vote* (PMV) *on operative temperature* (t_{op})

The TSV and PMV on operative temperature (t_{op}) were plotted under each average air speed as shown in Fig. 7. The PMV at each point was obtained through sensation vote at the same air temperature and air speed. It was seen that when the air speed is increased, the neutral vote shifts to higher air temperature.

To consider the correlations between TSV, PMV and operative temperature (t_{op}), a linear regression analysis using the least square method was applied for each air speed to construct the TSV and PMV equations. The obtained equations show the correlation between TSV, PMV and operative temperature (t_{op}) at various air speed, see Eq. (8) and (9) below:

$$TSV = 0.4951t_{op} - 1.3547v - 11.6034 \quad (8)$$

$$PMV = 0.4941t_{op} - 0.9838v - 12.0196 \quad (9)$$

when t_{op} is operative temperature (°C) and v is air speed (m/s)

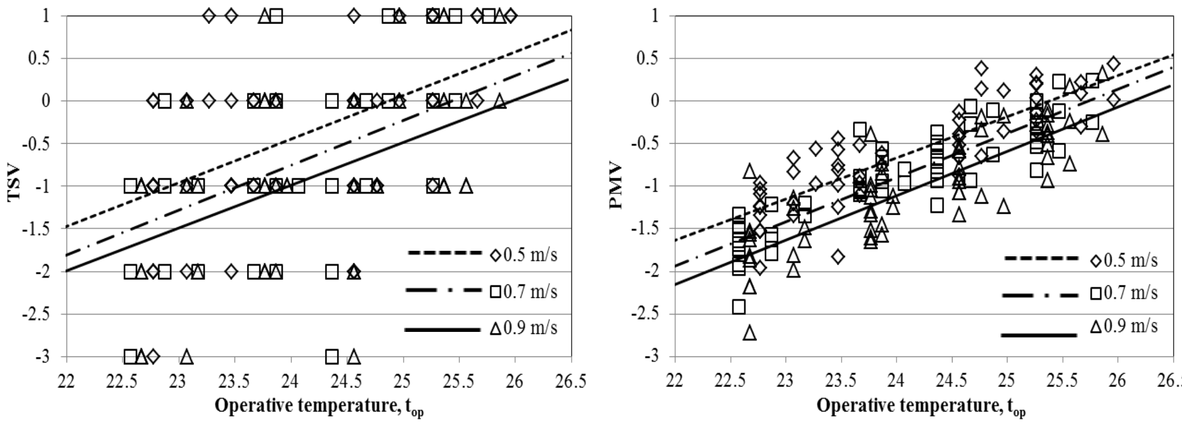

Fig. 7 TSV and PMV vs operative temperature (t_{op}).

The neutral temperature for the operative temperature (t_{op}) for each average air speed were calculated from Eq. (8) and (9) for TSV and PMV, and aree shown in Table 9 and Table 10. At average air speeds of 0.5, 0.7 and 0.9 m/s, the neutral temperature given by the TSV equation (TSV=0) were at 24.8 °C, 25.4 °C and 25.9 °C respectively, and neutral temperature given by the PMV equation (PMV=0) were 25.3 °C, 25.7 °C and 26.1 °C respectively. The neutral temperature of the TSV and PMV were increasing with increasing air speed. The recommend temperature limit of TSV (-0.5<TSV<0.5) and PMV (-0.5<PMV<0.5) on operative temperature (t_{op}) for each air speed level were considered. The results show that the recommend temperature limits were 23.8–25.8 °C, 24.3–26.5 °C and 24.9–26.9 °C respectively for TSV, and 24.3–26.3 °C, 24.7–26.7 °C and 25.1–27.1 °C respectively for PMV.

Table 9 Neutral temperature TSV equation (TSV = 0) on operative temperature (t_{op}).

PMV	Average air speed(m/s)		
	0.5	0.7	0.9
Neutral temperature (t_{op},°C) (TSV =0)	24.8	25.4	25.9
Recommend temperature limit (t_{op},°C) (-0.5<TSV<0.5)	23.8–25.8	24.3–26.5	24.9–26.9

Table 10 Neutral temperature (PMV = 0) on operative temperature (T_{op}).

PMV	Average air speed(m/s)		
	0.5	0.7	0.9
Neutral temperature (t_{op},°C) (PMV=0)	25.3	25.7	26.1
Recommend temperature limit (t_{op},°C) (-0.5<PMV<0.5)	24.3–26.3	24.7–26.7	25.1–27.1

The relationship of TSV and PMV on air temperature (t_a), effective temperature (ET*) and operative temperature (t_{op}) at neutral temperature (TSV, PMV = 0) were then considered (see Table 5–10). It was seen that the difference between the neutral temperature of TSV and PMV should not exceed 1°C, and the neutral temperature of PMV should be more than TSV. One can say that PMV can predict the thermal comfort of thermal sensation of subjects from survey.

6.6 Energy savings from changing the temperature setting of air conditioners

Data in Table 9 show t energy consumption at temperature setting of air conditioners of 25, 26, 27 and 28 °C, at the same air speed level (i.e; highest level); and the energy saving from changing temperature setting of air conditioners. This was calculated based on a temperature setting at 25 °C. It was found out that the average energy consumption of temperature settings of air conditioners at 25, 26, 27 and 28 °C were about 3.78, 3.49, 3.21 and 3.02 kW/hr. respectively.

Changing temperature settings of air conditioners from 25 °C to 26, 27 and 28 °C, which are the acceptable air temperature settings; can reduce energy consumption by about 7.67, 15.08 and 20.11% respectively. The energy saving when the temperature setting changed from 25 to 26-28 °C was between 7.67-20.11%, which is s approximately 7.30% savings for 1 °C increase.

Table 10 Energy consumption and energy saving from changing temperature setting of air conditioner.

	Temperature setting of air conditioner (°C)			
	25	26	27	28
Average energy consumption of air conditioner (kW/hr.)	3.78	3.49	3.21	3.02
Energy saving (%)	-	7.67	15.08	20.11

7. Conclusion

The study on temperature of thermal comfort for Thai students in classrooms under variable indoor conditions of air-conditioned space, to determine acceptable air-conditioner temperature settings for energy saving found that: The temperature of thermal comfort can be increased by increasing of the air speed to compensate for the higher temperature. The subjects can feel comfortable at higher temperatures if the air speed were increased. The acceptable range of air temperature is between 26±0.5–28±0.5 °C at average air speed of between 0.5 to 0.9 m/s based on the thermal sensation votes of subjects. The range of neutral temperature (TSV, PMV = 0) from the TSV and PMV equations on air temperature (t_a) are 26.7–28.3 °C and 27.7–28.4 °C respectively, which correspond to the acceptable temperatures. The PMV equation can predict the thermal comfort of thermal sensation of subjects from survey questionnaires. In addition the difference between neutral temperature of TSV and PMV on air temperature (t_a), effective temperature (ET*) and operative temperature (t_{op}) at neutral temperature (TSV, PMV = 0) should not exceed 1°C. Finally, energy saving from temperature setting of air conditioners that are set normally at 25 °C (the setting in in most buildings as recommended by government); setting can be increased to 26, 27 and 28 °C. These are the temperature settings that study found out to be acceptable. These settings can reduce energy consumption by about 7.67, 15.08 and 20.11% respectively, which as approximately 7.30% saving for 1 °C increase. The results of this research can be applied to air-conditioning systems in university buildings for thermal comfort of Thai students and at the same time reducing electricity expenditures of the university.

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