Topic A7: Thermal comfort

ENERGY CONSERVATION BETWEEN NATURAL VENTILATED AND AIR-CONDITIONED CLASSROOM IN TAIWAN

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SUMMARY

The energy consumption between natural ventilated classrooms (NVs) and air-conditioned classrooms (ACs) is different in hot and humid Taiwan. Energy conservation is related with the thermal comfort of occupants in these classrooms. This study proposed an electronic questionnaire and instruments to facilitate the continuous monitoring of the physical parameters to investigate the satisfied level of thermal comfort of students in classrooms.
The investigated results show the average clothing value (clo) around 0.7. During the hot days (clo<0.7), students' acceptable range of temperature range in NVs was between 26.2℃–28.2℃ (neutral temp.=27.3℃, neutral RH=59.9%) and 24.2℃–27.7℃ (neutral temp.=26.3℃, neutral RH=57.2%) in ACs. During the cold days (clo≧0.7), students' acceptable range of temperature in NVs was between 20.9℃–25.1℃ (neutral temp.=23.0℃, neutral RH=55.3%) and 22.0℃–25.4℃ (neutral temp.=23.7℃, neutral RH=55.6%) in ACs. The maximum acceptable thermal temperature of students in NVs (27.3℃) is 1℃ higher than that in ACs (26.3℃) and 1.3℃ higher than the ASHRAE Standard 55 (26℃). The result implies that 6% energy can be saved between NVs and ACs and 7.8% energy can be saved compared with ASHRAE Standard 55. This study proposes the best solution of energy conservation between NVs and ACs.

INTRODUCTION

In order to resist the hot and humid climate, air-conditioner becomes an essential equipment to maintain a fine learning environment in Taiwan college classrooms. However, air-conditioning consumes the most energy in classrooms (the second is the lighting equipment and fans consume the least) [1]. For energy saving, schools in Taiwan follow the recommendation of air-conditioner setting at 26℃-28℃. As the temperature setting directly influences the thermal comfort of occupants, the balance between the energy saving and the comfortable thermal environment is analyzed in this study.
Many scholars around the world have studied thermal comfort assessment methods and standards. Fanger proposed a PMV-PPD model to assess the satisfaction of thermal environment. ASHRAE Standard 55 proposed the summer thermal comfort standard of 23℃-26℃, while the clothing value is 0.5 and relative humidity is 60% [2]. However, people in Taiwan used to tolerate the hot and humid climate. As metabolic rate is influenced by the

different living habit, ASHRAE Standard 55 may not suit a subtropical region. Chen [3] found that students in Taiwan can accept a higher temperature environment in a classroom and only a few students requested for a lower temperature. Kwok [4] found that 75% acceptable temperatures of students in Hawaii do not conform the ASHRAE Standard 55. These researches prove that thermal comfort is also deeply influenced by the different environment and living habit [5].

Thermal comfort is basically influenced by the four physical parameters (air temperature, radiant temperature, relative humidity and air speed) and two personal parameters [6] (metabolic rate and clothing insulation). Students in classroom are in sedentary activity and the metabolic rate of each student is almost the same. As the indoor physical environment is not easily to be adjusted, students usually adjust their clothing values or switch on the air-conditioners and fans to satisfy their thermal comfort. Ceiling fan is always installed in natural ventilation classroom because of the low energy consumption. This study discusses the suitable range of thermal comfort in natural ventilated classrooms and air-conditioned classrooms in Taiwan via the different clothing value of occupants and proposes the optimum energy saving efficiency.

METHODOLOGIES

Thermal comfort measuring instrument

Field surveys were always hard to be carried on by the restriction of instrument scale in the past. This study adopts the IEQ survey instruments, which consist of a portable IEQ system and a touch tablet PC, as shown in Fig. 1 and Table 1. These instruments can automatically collect records of physical parameters in classrooms. The dimension is small and handy and can be operated in different position. The IEQ survey instruments are placed on the desk at a height of 100-110cm [7], as shown in Fig. 2. In the meantime, subjective electronic questionnaire is answered by each occupant in order to avoid paper wasting and typing errors by traditional paper questionnaires [8]. According to the previous researches [9][10][11][12], the IEQ survey instruments can collect the objective physical parameters and subjective thermal sensation questionnaire accurately.

Fig. 1 IEQ survey instruments

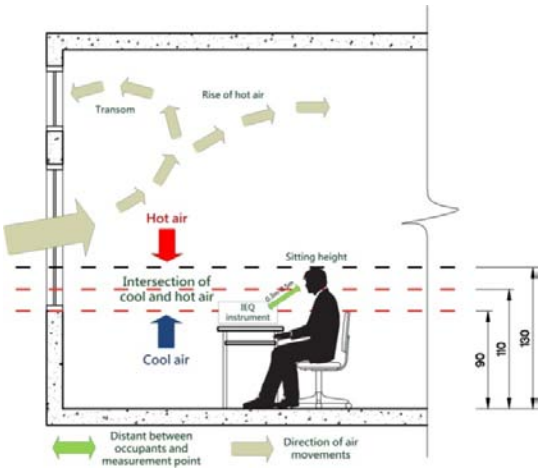

Fig. 2 The measuring position of the field survey [7]

Questionnaire design

The electronic questionnaire refers to the subjective sensation of occupants and is clearly separated into two zones, basic information and subjective environment responses. Basic information of occupants, such as gender and age, other background environment condition

with operation of air-conditioning and opening windows, is the important parameters for analysis. This study focuses on the thermal comfort via thermal sensation, humidity sensation, windy comfort and clothing value. The model of Predicted Mean Vote (PMV) is applied to assess the subjective environment response and the scale of thermal comfort is classified into 7 levels, ranging from 'Cold' (−3) to 'Hot' (+3), as shown in Table 2. This system can prevent failed fill-in and collects each data cumulatively.

Table 1. IEQ survey instruments

The scope of this study

Measuring instrument	IEQ factors	Physical parameters	Subjective sensation vote
	Thermal comfort	Air temperature Radiant temperature Relative humidity	Clothing value Thermal sensation vote Thermal satisfaction
	Indoor air quality	Carbon dioxide	IAQ sensation vote IAQ satisfaction
	Visual comfort	Illumination level	Visual sensation vote Visual satisfaction
	Aural comfort	Background noise level	Aural sensation vote Aural satisfaction

Table 2. Questionnaire design

Basic information								
Gender/ Age/ Air-condition/ Windows/ Clothing value (0.1, 0.3, 0.5, 0.8, 1.0, 1.5, 3.0)								
Subjective sensation votes								
PMV level	**-3**	**-2**	**-1**	**0**	**1**	**2**	**3**	**Acceptance**
Thermal comfort	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Accept
Humidity comfort	Very dry	Dry	Slightly dry	Neutral	Slightly wet	Wet	Very wet	or
Overall assessment	Very bad	Bad	Slightly bad	Neutral	Slightly good	Good	Very good	Not accept

FIELD SURVEYS

Field surveys were conducted in Taiwan collage classrooms from 2010 winter to 2012 winter. This study adopted random sampling. Excluded from invalid samples, 683 valid student samples were obtained. Classrooms were classified into natural ventilated classrooms (NVs) and air-conditioned classrooms (ACs). 263 students were in NVs and 420 students were in ACs, the area of most classrooms is 80m^2 (10m*8m) with a capacity of about 50 occupants.

According to the field survey, 70% classrooms were equipped with 3 air-conditioners and 6 ceiling fans, as shown in Fig. 3. When the classroom is air-conditioned, ceiling fans are always turned off. When the classroom is natural ventilated, ceiling fans are always turned on during the hot days. Students in classrooms were in sedentary activity and the metabolic rates of each student were similar (1.0met-1.2met approximately). This study found that students usually adjust their clothing values even at cold days or hot days when the thermal environment was unable to be changed. Hence, this study averages the clothing values and determines the relationship between the clothing value and thermal comfort in classrooms. Subjective sensation questionnaire and instruction of the investigation was operated after 15mins of the lesson. The IEQ survey instruments were put on the desk of each student, as

shown in Fig. 4. In the meantime, students answered the electronic questionnaire according to their instant sensation about the classroom environment. The electronic questionnaire and IEQ survey instruments were passed to another student after the first student finished the questionnaire, and so on. The operation time of each questionnaire was 2 minutes approximately.

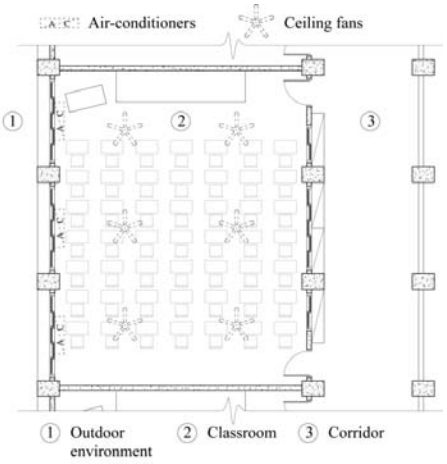

Fig. 3 The condition of classroom in college

Fig. 4 The field survey and the IEQ instruments

RESULT

According to the result from the questionnaires, the average clothing value of college students in subtropical Taiwan was 0.7clo (Number of samples = 683, standard deviation = 0.27) and this value can be used to determine the boundary of the thermal environment conditions. When the clothing value is lower than 0.7 (*clo*<0.7), the thermal environment is defined as a hot day. On the contrary, the thermal environment is defined as a cold day when the clothing value is higher than 0.7 (*clo*≧0.7), as shown in Fig. 5.

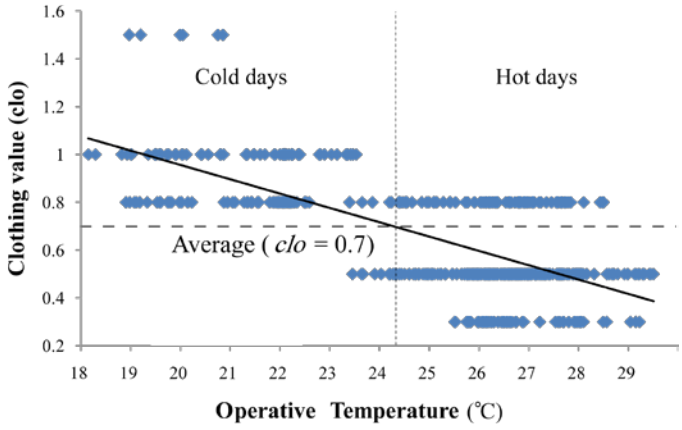

Fig. 5 The analysis of clothing value

Fig. 6a, b shows the percentages of students' thermal environment dissatisfaction in natural ventilated classrooms (NVs) and air-conditioned classrooms (ACs) through the thermal sensation vote (TSV) analysis. When TSV=0, almost all students can accept the thermal environment (99% in NVs and 97% in ACs). In NVs, no student voted "Very hot" and all students did not accept when voted in "Very cold". In ACs, only 50% students did not accept when voted in "Very cold" and all students voted "Unacceptable" while TSV=+3,. The result shows that students in ACs expect for a cooler environment, comparing with NVs.

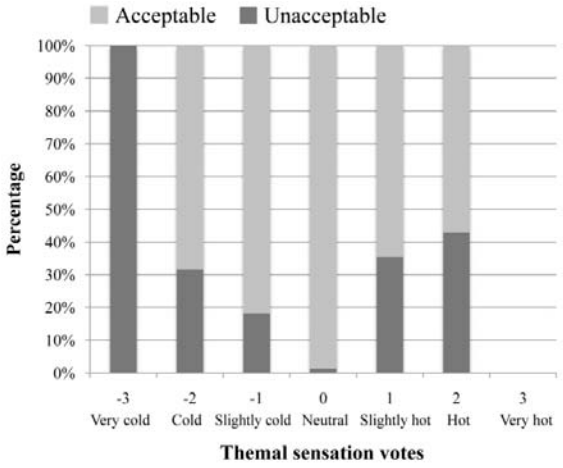

Fig. 6a Students' thermal acceptance in NVs

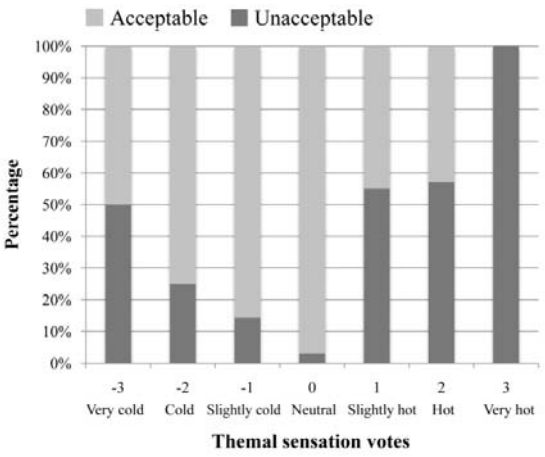

Fig. 6b Students' thermal acceptance in ACs

In order to find out the neutral temperature and the acceptable range for students in Taiwan, this study applied the equation of thermal comfort proposed by Mui and Wong [13] and the operative temperature equation proposed by ASHRAE Standard 55 in Equation (1), and (2).

$$\phi_1 = (2-i) + (2i-3)\int_{-\infty}^{T_{op}} \tilde{T}_{op}\left(\mu_{op,i}, \sigma_{op,i}\right) dT_{op} \quad i = \begin{cases} 1; & \theta < 0 \\ 2; & \theta > 0 \end{cases} \tag{1}$$

where $\tilde{T}_{op}$ is the operative temperature, μ is the mean value, σ is the standard deviation, θ<0 represents "feeling cold" and θ>0 represents "feeling hot"

$$T_{op} = C_{OP} T_a + (1 - C_{op}) T_r \qquad C_{op} = \begin{cases} 0.5 & ; V < 0.2 \\ 0.6 & ; 0.2 \le V < 0.6 \\ 0.7 & ; 0.6 \le V < 1 \end{cases} \tag{2}$$

Where T_{op} is the operative temperature, T_a is the air temperature, T_r is the radiant temperature and V is the velocity

Hot days

In hot days (*clo*<0.7), 117 students in natural ventilated classrooms (NVs) and 286 students in air-conditioned classrooms (ACs) were surveyed. The result implies that students prefer switching on air-conditioner during the hot days in subtropical Taiwan. According to the subjective questionnaire result in NVs, the average neutral temperature was 27.3℃ (standard deviation=0.5℃, neutral RH=59.9%). In ACs, students used air-conditioner to maintain a comfortable thermal environment and 159 students (55%) felt comfort (PMV=0). 82 students (29%) felt cold (PMV<0) and 45 students (16%) felt hot (PMV>0). The neutral temperature was 26.3℃ (standard deviation= 0.7℃, neutral RH=57.2%). The maximum acceptable temperature in NVs (27.3℃) is 1℃ higher than that in ACs (26.3℃), as shown in Table 3. The result implies that students in NVs can tolerate a higher temperature during the hot days. Moreover, they can accept a wider range of temperature, as shown in Fig. 7a, b.

Cold days

In cold days (*clo*≧0.7), 146 students in natural ventilated classrooms (NVs) and 134 students in air-conditioned classrooms (ACs) were surveyed. The neutral temperature of students in NVs was 23℃(standard deviation=2.1℃, neutral RH=55.3%). This result is similar to the ASHARE Standard 55 about the comfort zone in cold days. In Taiwan, the average outdoor temperature in cold days is relatively high, and hence, heating equipment are not suggested to

be used in order to save energy. In ACs, all students wore sweaters or other outer garment to protect from the cold temperature. The average neutral temperature was 23.7℃, (standard deviation=1.7℃, neutral RH=55.6%) as shown in Table 4. The neutral temperature in ACs is higher than that in NVs, as shown in 8a, b. The relative humidity in cold days is lower than that in hot days, but no significant difference was found between NVs and ACs in Taiwan.

Table 3. Acceptable range of temperature and relative humidity during the hot days (clo. <0.7)

Ventilation type	Samples	Operative temperature (℃)	Relative humidity (%)
Natural ventilated	117	Neutral temperature = 27.3℃ Standard deviation = 0.5℃	Neutral humidity =59.9% Standard deviation = 4.3%
Air-conditioned	286	Neutral temperature = 26.3℃ Standard deviation = 0.7℃	Neutral humidity = 57.2% Standard deviation = 4.8%

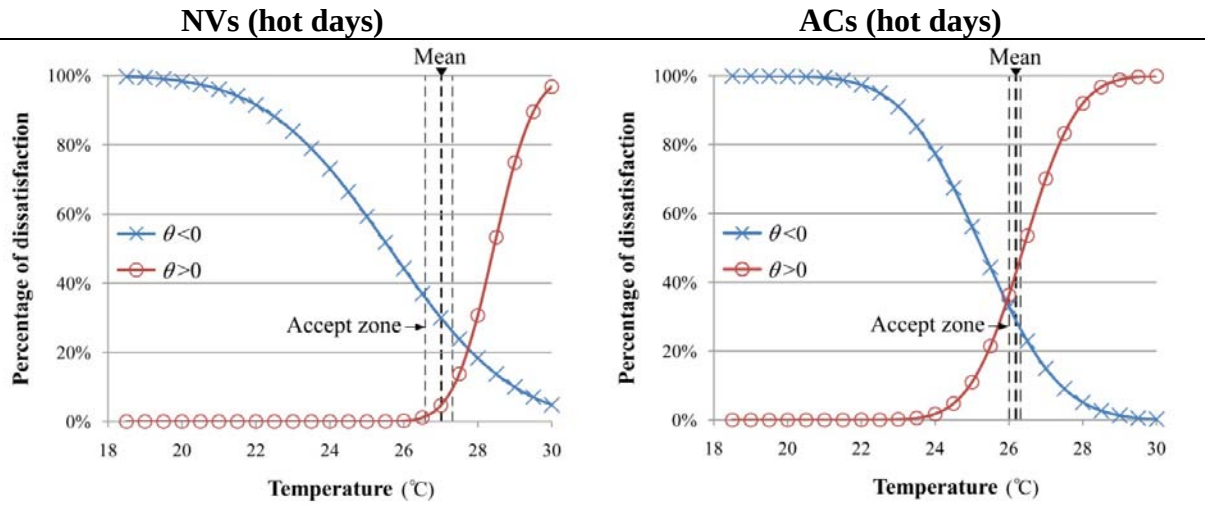

Fig. 7a, b Thermal sensation votes in hot days

Table 4. Acceptable range of temperature and relative humidity during the hot days (clo.≧0.7)

Ventilation type	Samples	Operative temperature (℃)	Relative humidity (%)
Natural ventilation	146	Neutral temperature = 23℃ Standard deviation = 2.1℃	Neutral humidity = 55.3% Standard deviation = 6.7%
Air-condition	134	Neutral temperature = 23.7℃ Standard deviation = 1.7℃	Neutral humidity = 55.6% Standard deviation = 6.5%

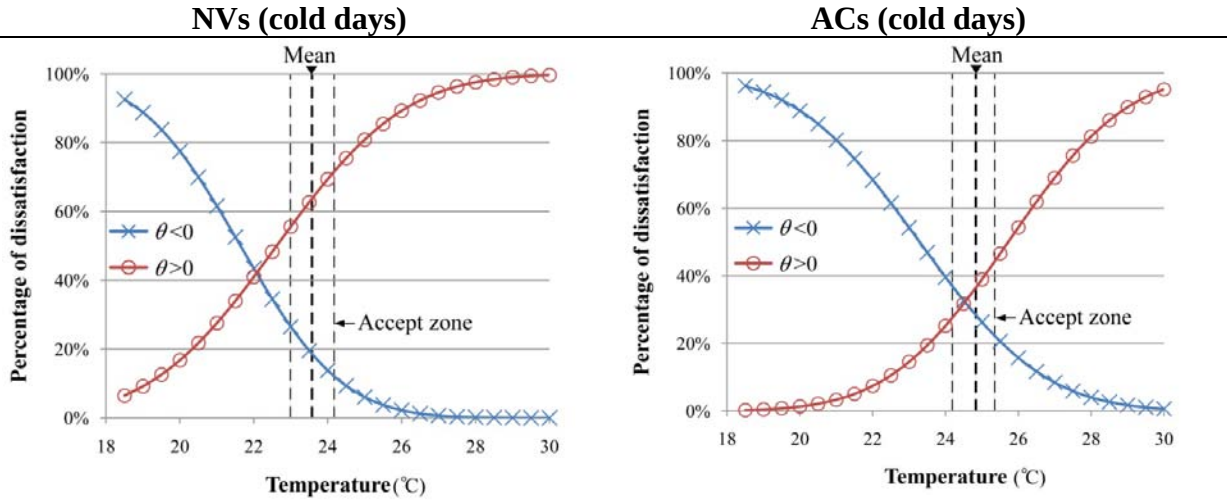

Fig. 8a, b Thermal sensation votes in cold days

DISSCUSSION

Thermal comfort zone

Taiwan belongs to the subtropical climate zone and is surrounded by the ocean, causing a high temperature and high humidity climate. Especially summer (hot day) is usually raining in the wet season and winter is usually in dry season. As Taiwan students can accept a higher temperature and humidity for fitting local climate than the ASHRAE Standard 55.

Fig. 9a, b shows the thermal comfort zone of NVs and ACs in subtropical Taiwan. During the hot days, no occupant in NVs fell on the comfort zone of ASHRAE Standard 55 and they can tolerate the temperature range at 26.2℃-28.2℃ (relative RH=54.1%-65.2%). In ACs, 60% occupants fell on the comfort zone of ASHRAE standard 55 and the acceptable range of temperature was between 24.2℃-27.7℃(RH=43.9%-69.3%).

During the cold days, 68% occupants in NVs fell on the comfort zone of ASHRAE Standard 55 and the acceptable range of temperature was between 20.9-25.1℃(RH=47.5%-64.9%). 54% occupants in ACs fell on the comfort zone of ASHRAE Standard 55 and the acceptable range of temperature was between 22.0℃-25.4℃(RH=43.9%-67.1%). The recommended temperature setting of ACs in hot days is 27.3℃. Comparing with the ASHRAE Standard 55 (comfort temp.=23℃-26℃, RH=40%-60%), students in NVs have a higher acceptable range of temperature. The annual ambient humidity is high and therefore the comfort range of humidity in Taiwan is different from ASHRAE Standard during the cold days.

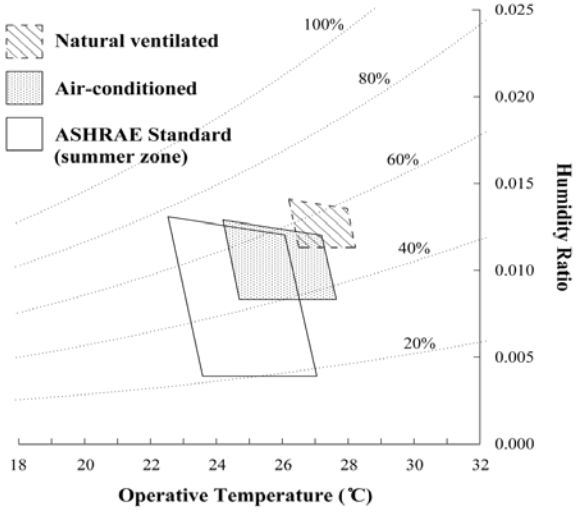

Fig. 9a thermal comfort zone in hot days

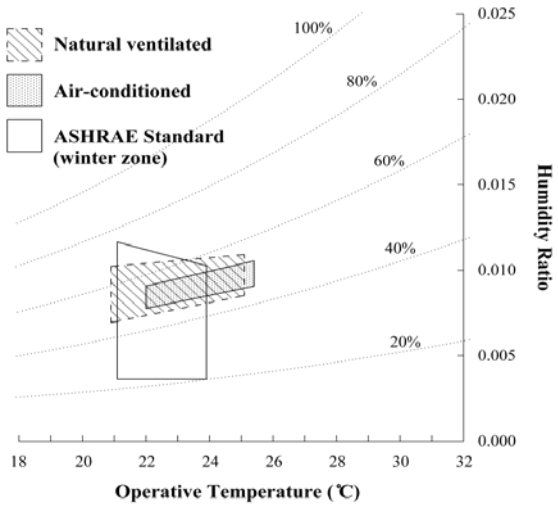

Fig. 9b thermal comfort zone in cold days

Energy efficiency

Students in NVs can accept 1℃ (mean temperature) higher than in ACs during the hot day. According to the previous experiences, energy consumption of an air-conditioner and a ceiling fan is approximately 0.13kWh/m^2 and 0.04kWh, respectively [14]. According to the field survey result, many classrooms were equipped with 3 air-conditioners and 6 ceiling fans. By the calculation of Equation 3, the total energy consumption of air-conditioning is 5.26kWh when the floor area is 80m^2 and the EER of a split type air-conditioner is 2.73. The energy consumption of ceiling fans is 0.24kWh. 3 air-conditioners or 1 air-conditioner with total 13,500 kcal/h is needed to support the whole classroom cooling. By the calculation of Equation 4, 5.02kWh (95%) energy consumption can be saved in natural ventilation classrooms. Students in Taiwan can accept 1.3℃ higher than the ASHRAE Standard 55 and

hence 7.8% (0.41kWh) energy consumption can be saved. In NVs, ceiling fan is suggested to control the indoor air speed and can improve the thermal environment during the hot days.

$$E_c = (A_t * K)/EER \quad (3)$$

where E_c is the energy consumption in air-conditioned classrooms, A_t is the total floor area, K is the constant with 0.13kWh/m^2, EER of split type air-conditioner is 2.73

$$E_E = \left(1 - \frac{E_N}{E_C}\right) * 100\% \quad (4)$$

where E_E is the efficiency of energy saving, E_N is the energy consumption of ceiling fans, E_C is the energy consumption of air-conditioners

CONCLUSIONS

This study aims at the thermal comfort of students in subtropical classrooms in Taiwan. 409 samples were received through field surveys. This study proposes the difference of thermal temperature range between the natural ventilated classrooms (NVs) and air-conditioned classrooms (ACs) via the clothing values and analyzes the efficiency of energy saving.

According to the result, 0.7clo is the boundary to distinguish hot days and cold days since students adjust their clothing value to resist the thermal environment. As students in Taiwan used to tolerate the hot and humid climate zone, most students can accept a high temperature and high humidity environment in a classroom. Hence, under the acceptable range of temperature, ceiling fan is recommended in natural ventilation classrooms to achieve the balance between the energy saving and comfortable environment.

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