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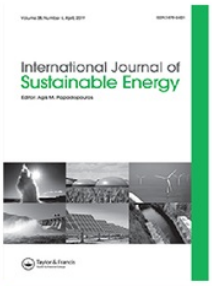

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Design of energy efficient and thermally comfortable air-conditioned university classrooms in the tropics

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ABSTRACT
This study aims to design energy efficient and thermally comfortable air-conditioning system in university classrooms. The research has been conducted in two steps. The first step was a survey of students' thermal comfort under air-conditioning classrooms, which collecting 175 questionnaires from 92 students. The second step was the calculation of cooling energy consumption using the EnergyPlus software. With the air temperature ranged from 23.0 to 24.0°C about 53% of respondents felt uncomfortable (cold or cool). The neutral temperature of students was found to be 27.0°C, which is higher than the classrooms' temperature. The energy simulation results show that the most significant factors affecting energy use is the temperature setting. Therefore, there is a possibility to reduce the cooling energy while improving the thermal comfort of students. To this end, it is recommended to raise the air temperature setting from 25.0°C to a minimum of 26.0°C.

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KEYWORDS
Thermal comfort; energy efficiency; air-conditioned classrooms; university classrooms; tropical area

Introduction

The crisis of electrical energy has stimulated the government of Indonesia to promote energy saving programmes since 1982. The government issued a Presidential Instruction (*Inpres*) No. 9 the year 1982 on energy conservation. This Presidential Instruction is primarily intended to save energy of lighting and air-conditioning in state-owned buildings (Presiden RI. 1982). It then followed by a Presidential Decree (*Keppres*) No. 43 the year 1991 on energy conservation, which includes energy conservation in buildings (Presiden RI. 1991). Lastly, the government issued an *Inpres* No. 10 the year 2005 on energy efficiency (Presiden RI. 2005). This *Inpres* is primarily intended to use fuel (oil) and electrical power efficiently and appeal to all levels of society to make fuel savings for motor vehicles and the use of electrical energy in buildings. Based on the *Inpres* No. 10 the year 2005, the Ministerial of Energy and Natural Resources (ESDM) issued a Ministerial Regulation No. 31 the year 2005, which stipulated that the air-conditioned of commercial buildings, as well as state-owned buildings, must provide a minimum indoor air temperature of 25°C (ESDM 2005).

Buildings consume about 40% of primary energy worldwide (Yang, Yan, and Lam 2014). In Indonesia, commercial buildings consumed about 47–65% of electricity for air conditioning (Hilmawan and Said 2009). According to Yang, Yan, and Lam (2014), several measures can be used to reduce the energy use in buildings. These are including the design and construction of building envelopes which include the thermal insulation, sensitivity and optimisation, and life cycle analysis; technical and economic analysis of renovation of existing buildings; and the control of heating, ventilating, and air-conditioning (HVAC) and lighting system. For existing buildings, higher indoor temperature set-points (thermostat settings) remains a potential energy savings measure (Fang et al. 2018).

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The control system of HVAC has a significant influence on the energy consumption while maintaining the thermal comfort of occupants (Mathews et al. 2001). However such indoor temperature should not exceed the range of occupants' thermal comfort (Karyono 2000). A study in China shows that an increase of 1°C of indoor temperature has an excellent opportunity to reduce the electrical energy use by about 6% (Yang and Zhang 2008).

Mathews et al. (2001) investigate different control strategies for retrofit techniques including air-bypass on cooling coils, reset and set back control, improved HVAC system start-stop times, and economising on outside air intake. They found that improved HVAC system start-stop times together with air-bypass, reset and set back control to be the most effective techniques (Mathews et al. 2001). Avci et al. (2013) show that the model predictive control (MPC) strategy can lead to significant reductions in overall energy consumption. There are several efforts to correlate the energy efficiency with the thermostat settings. For example, Karunakaran, Iniyan, and Goic (2010) study the application of combined variable refrigerant volume (VRV) and variable air volume (VAV) air-conditioning (AC) systems with the aim at achieving improved energy conservation, good thermal comfort and better IAQ for air conditioning spaces. Tzivanidis, Antonopoulos, and Gioti (2011) have developed a model for predicting the behaviour of buildings thermal under the influence of all possible thermal loads and the cooling control system in conjunction with thermal comfort requirements.

The indoor environmental quality (IEQ) including thermal comfort has a significant impact on occupants' well-being and comfort (Al horr et al. 2016). In educational buildings, thermal comfort is becoming an essential requirement for enabling students to learn and work productively (Haverinen-Shaughnessy et al. 2015; Jiang et al. 2018). Therefore, providing a comfortable and healthy environment in school is necessary for students well-being and productivity (Bellia et al. 2010). An extensive literature review by Mendell and Heath (2005) showed a good correlation between indoor school environments (which include thermal comfort) and the performance and attendance of children.

Many researchers have carried out studies on the thermal comfort of students in the tropical areas. These studies include the analysis of thermal comfort in schools in Singapore (Wong and Khoo 2003), Malaysia (Hussein and Rahman 2009), Hawaii (Kwok 1998), Brazil (de Abreu-Harbich, Chaves, and Brandstetter 2018), and in Madagascar Island (Nematchoua, Ricciardi, and Buratti 2017, 2018). Based on the survey carried out in the secondary schools in Singapore, Wong and Khoo (2003) found that none of the thermal performances of classrooms was within the thermal zone of the ASHRAE standard. However, more than 70% of students found these conditions acceptable. The neutral temperature found in this study was 28.8°C. Hussein and Rahman (2009) carried out field measurements in elementary and secondary schools in Johor Bahru found that even though the thermal conditions did not satisfy the ASHRAE standard, more than 80% of students accept the classrooms' thermal environment. Kwok (1998) found that the majority of classrooms failed to meet the ASHRAE standard. However, more than 80% of students accepted this thermal condition. The neutral temperature values in these tropical classrooms were 26.8 and 27.1°C for NV and AC classrooms, respectively. Based on the investigation of thermal comfort in the three thermal situations, i.e. natural ventilation, air-conditioning, and evaporative cooling, de Abreu-Harbich, Chaves, and Brandstetter (2018) found that the natural ventilation was the most unfavourable in comparison to the air-conditioning and the evaporative cooling. However, using air-conditioning system requires the high expenditure in cooling energy (Nematchoua, Ricciardi, and Buratti 2018). compared the thermal performance of residential and school buildings in Madagascar. They found that the thermal comfort of the residential was better than the thermal comfort in school buildings. The comfort temperature varied from 24.6 to 28.4°C during both seasons in residential and school buildings. Nematchoua, Ricciardi, and Buratti (2017) studied the thermal comfort in the four building types, i.e. hospitals, shopping centres, traditional buildings, and school buildings. They found that air temperature and relative humidity have the significant impact on the thermal comfort. More than 80% of respondents felt comfortable in the temperature ranges between 22.9 and 27.2°C and the relative humidity from 45.2 to 70.5%.

Most thermal comfort studies in Indonesia were focused on residential and office buildings. A study by Feriadi and Wong (2004) was concentrated in residential buildings in Yogyakarta, while Karyono (2000) in office buildings in Jakarta. Just recently, four studies were concentrated in the thermal comfort of students in the classrooms in Indonesia (Karyono, Heryanto, and Faridah 2015; Hamzah, Mulyadi, and Amin 2017; Hamzah et al. 2016, 2018). Karyono, Heryanto, and Faridah (2015) focused on the thermal comfort of students in the air-conditioned university classrooms. They found that the neutral temperature based on air temperature (T_a) 24.1°C in the Tarumanegara University (Untar) and 24.9°C in the University of Mercu Buana (UMB). Hamzah et al. (2016) studied the thermal comfort of students in the naturally ventilated university classrooms, while Hamzah, Mulyadi, and Amin (2017) and Hamzah et al. (2018) in the naturally ventilated elementary and secondary schools classrooms, respectively. Hamzah et al. (2016) found that the neutral temperature of university students in the naturally ventilated classroom was 29.6°C T_a. The neutral temperatures of students in the naturally ventilated elementary and secondary schools were 30.2°C T_o and 29.0°C T_o, respectively (Hamzah, Mulyadi, and Amin 2017; Hamzah et al. 2018).

The current standards, international (ASHRAE 2013) or national (BSN 2011) are only focusing on providing the indoor temperature, which is regarded as comfortable ranges. The ASHRAE standard specifies the operative temperature, humidity and the clothing for a thermally comfortable room. While the national standard SNI 03-6390-2011 specifies that the design working area should provide room temperature ranging from 24.0 to 27.0°C or 25.5°C ± 1.5°C (BSN 2011). This national standard applied for the buildings located in the area with the maximum outdoor air temperature of 34.0°C. However, these standards might provide a cooler thermal environment than the one preferred by occupants in the air-conditioned classrooms in the warm and humid tropical region.

Previous researches were mostly focused on the thermal comfort of students either in the naturally ventilated or air-conditioned classrooms. Except for the study carried out by de Abreu-Harbich, Chaves, and Brandstetter (2018), they have no attention to correlating the thermal comfort and the energy efficiency in the classrooms. However, according to Allab et al. (2017), educational buildings including university campuses are especially concerned by the issues of energy and indoor environmental quality (including thermal comfort). Thermal comfort in educational buildings needs more attention than other buildings because of their specific character compared to other buildings. Educational buildings represent a particular case due to their specific occupants, activities and occupancy pattern. This study intended to integrate the students' thermal comfort and preferences into the design of energy efficient air-conditioning systems for university classrooms that located in the hot-humid tropical area. The outcome of this article is to provide comfortable learning environments for students while reducing the energy use for cooling the classrooms. The specific objectives of this article are as follows:

(1) To analyse the thermal sensation and thermal preference of students based on the measured thermal environmental conditions of air conditioning classrooms and the response of students to their thermal environment.
(2) To find the best strategy for reducing the cooling energy consumption used based on the thermal responses and thermal preferences of students.

Materials and methods

The research was carried out in two steps. The first step was a thermal comfort survey and measurement in air conditioning classroom to determine the comfortable air temperature for students. The second step was energy simulation to find out the best energy efficiency strategy for air-conditioned university classrooms, which accommodate the thermal comfort of students.

Data collection and generation

Survey and measurement

The surveys and measurements have been carried out in a classroom that located in the Classroom Building and a computer laboratory located in Architecture Building, Faculty of Engineering, Hasanuddin University Gowa Campus. The surveys have been conducted over four days in May 2017 involving 92 students from the Department of Architecture. The students' ages were ranging from 18 to 24 years old. Most students filled out the questionnaires twice, which were resulted in 175 answered questionnaires.

The data has been collected through survey and questionnaire methods. The collection of data was carried out as follows:

(1) Survey on objective measurement was conducted to collect the personal and the thermal environment data. Personal data was gathered by collecting the clothing and the activity of each respondent. The measurements have been carried out using several instruments. The LSI-Lastem Thermal Comfort Multi Logger (marked as LSI TC) is a set of apparatus, which consists of several sensors and a data logger. The arrangements of LSI-Lastem applied in this survey including one data loggers and two sensors. The sensors including a globe thermometric probe (BST131) for measuring mean radiant temperature (MRT) and a portable psychometric forced ventilation probe (BSU102) for measuring air temperature and relative humidity. The four basic HOBO loggers, which only measure air temperature and relative humidity (marked as HOBO-1), and two HOBO with external air velocity sensors (marked as HOBO-2). One classroom at 2/F in Classroom Building and one laboratory at 2/F Architecture Building were selected for the measurements (Figure 1). The sensors were attached at 100 cm above the floor level (Wong and Khoo 2003). Because of the limitation of equipment, the MRT only recorded at one point that was in the centre of the room, while the air velocity recorded at two points (A, B). The specifications of instruments used in this research are listed in Table 1.

(2) Survey on subjective measurement, which was conducted to measure the level of thermal comfort of respondents. The survey carried out by using the questionnaire technique, which was adapted from Wong and Khoo (Wong and Khoo 2003). The questionnaire included six questions as listed in Table 2, which captured the thermal sensation, thermal comfort, thermal preference and thermal acceptance of respondents. In addition to them, the questionnaire also intended to obtain the respondents' votes on the air velocity as well as the humidity of classrooms. The TSV responses were measured based on a seven-point scale to measure the thermal sensation of respondents (ASHRAE 2013). This seven-point scale is originally developed by Fanger (1970). The seven-point TSV scales are: hot (+3), warm (+2), slightly warm (+1), neutral (0),

Figure 1. Measurement and survey situation at the classroom (left) and the laboratory (right).

Table 1. The specification of instruments used in the surveys.

No.	Instrument Name	Range	Accuracy	Resolution
1.	Black Globe Radiant temperature (EST131)			
	- Radiant temperature	−40 to + 80°C	NA	0.01°C
2.	Psychrometer Sensor (ESU102)			
	- Air temperature	−5 to + 60°C	NA	0.01°C
	- Relative humidity	0 to 100%	NA	1%
3.	HOBO Temp/RH logger (UX100-011)			
	- Air temperature	−20 to + 70°C	± 0.21°C	0.024°C
	- Relative humidity	5 to 95%	± 2.5%	0.05%
4.	HOBO Temp/RH/Light/External (U12-012)			
	- Air temperature	−20 to + 70°C	± 0.21°C	0.024°C
	- Relative humidity	5 to 95%	± 2.5%	0.05%
	- Air velocity	0.15 to 10 m/s	± 0.05 m/s	NA

Note: NA = Not available.

slightly cool (−1), cool (−2), and cold (−3). The TCV responses were measured based on Bedford scale (Bedford 1936), which measures the thermal comfort of respondents. TCV scale also uses the seven-point scale, namely: much too warm (+3), too warm (+2), comfortably warm (+1), comfortable (0), comfortably cool (−1), too cool (−2), and much too cool (−3). The thermal comfort can also be measured by asking the thermal preference and acceptance of occupants. Thermal preference related to the question of whether the occupants prefer to be warmer or cooler or no change.

Table 2. Thermal comfort questionnaire (adapted from Wong and Khoo (2003)).

1. How do you feel about the temperature in the classroom at this moment?
   - ☐ cold (−3)
   - ☐ cool (−2)
   - ☐ slightly cool (−1)
   - ☐ neutral (0)
   - ☐ slightly warm (+1)
   - ☐ warm (+2)
   - ☐ hot (+3)
2. Do you feel comfortable now?
   - ☐ much too cool (−3)
   - ☐ too cool (−2)
   - ☐ comfortably cool (−1)
   - ☐ comfortable (0)
   - ☐ comfortably warm (+1)
   - ☐ too warm (+2)
   - ☐ much too warm (+3)
3. What do you like to be?
   - ☐ cooler (−1)
   - ☐ no change (0)
   - ☐ warmer (+1)
4. How do you rate the overall acceptability of the temperature at this moment?
   - ☐ acceptable (0)
   - ☐ not acceptable (−1)
5. How do you feel about the air velocity in the classroom at this moment?
   - ☐ too still (−2)
   - ☐ slightly still (−1)
   - ☐ just right (0)
   - ☐ slightly breezy (+1)
   - ☐ too breezy (+2)
6. How do you feel about the humidity in the classroom at this moment?
   - ☐ much too humid (−3)
   - ☐ too humid (−2)
   - ☐ slightly humid (−1)
   - ☐ just right (0)
   - ☐ slightly dry (+1)
   - ☐ too dry (+2)
   - ☐ much too dry (+3)

In addition to those, the questions related to the air velocity and the humidity had also been included in the questionnaire.

Computer simulation for energy calculation

The second step of the study was to carry out computer simulation to find out the best energy efficient strategy. The computer simulation used for energy calculation was EnergyPlus version 8.7. The software was developed based on the BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 programmes. EnergyPlus is energy and thermal simulation software that can be used to size appropriate HVAC (Heating, Ventilating, and Air Conditioning) equipment, develop retrofit studies for life cycling cost analyses, optimise energy performance, etc. (U.S. Department of Energy 2016).

Three classroom models have been developed and simulated. Each model was simulated with three different ceiling heights, i.e. 2.7, 3.0, and 3.5 m. The models were based on the existing classrooms taken from the classrooms of Faculty of Engineering; Hasanuddin University (Classroom Building) consists of three sizes (Figure 2):

- Small classroom (7.2 m × 7.2 m = 51.84 m^2)
- Medium classroom (9.0 m × 7.2 m = 64.80 m^2)
- Large classroom (9.0 m × 10.80 m = 97.20 m^2)

The material used in the simulation is more straightforward to get a reasonably accurate result. The material used in the computer models is a brick wall with plasterboard on both sides of the wall, concrete floor, and the roof deck with fibreglass quilt insulation, and plasterboard underneath. The technical properties of the building materials are listed in Table 3.

The windows located in the North and South walls. The single pane windows used 6 mm clear glass, while the construction of double pane windows uses two layers of 6 mm clear glasses with air in between. The characteristics of the glass materials used in this study can be seen in Table 4.

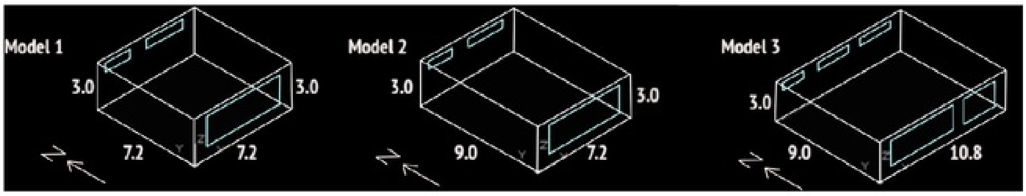

Figure 2. The geometry of classrooms models.

Table 3. Material of building models for simulation.

Materials	Thickness (m)	Conductivity (W/m-K)	Density (kg/m3)	Specific heat (J/kg-K)
Wall				
Plasterboard	0.012	0.16	950	840
Brick-fired clay	0.102	1.02	2080	790
Plasterboard	0.012	0.16	950	840
Floor				
Concrete	0.1015	1.7296	2243	837
Roof				
Roof deck	0.019	0.14	530	900
Fibreglass quilt	0.1118	0.04	12	840
Plasterboard	0.01	0.16	950	840

Table 4. Glazing material properties.

Construction	Glass U-Factor (W/m2-K)	Glass SHGC	Glass Visible Transmittance
Single Pane Window (Clear 6 mm)	5.778	0.819	0.881
Double Pane Window (Clear 6 mm + air 3 mm + clear 6 mm)	3.61	0.697	0.781

Data processing and analysis

Data analyses were carried out by spreadsheet software MS Excel. The spreadsheet has been used to calculate the mean value of indoor environmental variables and to generate a bar chart showing the percentage of TSV and TCV. The environmental variables including air temperature, relative humidity, mean radiant temperature (MRT), and the air velocity.

For the statistical analyses, a statistical software SPSS version 16 has been used to calculate the regression equation, which is based on Pearson correlation. The regression analysis examines the correlation and the linearity of data between TSV and air temperature (T_a) and also between TCV and air temperature (T_a). The criteria for accepting the linear regression analysis were determined based on the test of linearity of regression (*F*-test) and the significance of the equation coefficient (*t*-test). The equation is statistically linear if the absolute value of F is higher than F_{table} and *sig.* value is lower than its probability (0.05). The F_{table} for the case is 3.844. The equation coefficients are significant if the absolute value of t is higher than t_{table} and the *sig.* value is lower than half of its probability (0.025 for two tails).

The TSV and TCV were gathered from the respondents' votes written in the questionnaire. The TSV votes were grouped according to ASHRAE scale, while the TCV was grouped using Bedford scale. Also, the regression analysis was used to analyse the correlation and the linearity of data between room volumes and the energy consumptions. Before analysing the data using statistical analyses, the data should be verified. One method of verification is to check their normality and reliability. The checking required making sure that the results are valid for concluding. All data have been checked for their normality and reliability.

Results and discussion

Thermal environmental condition

The measurements have been carried out in May 2017. The outdoor thermal condition recorded in the Vaisala Station located at the rooftop of Architecture Building at the Faculty of Engineering, Gowa Campus. The monthly average outdoor temperature during daytime (8:00 am to 4:00 pm) was 29.5°C with a maximum of 33.8°C and a minimum of 21.9°C. At the same time, the monthly relative humidity was 63.1% with a maximum of 90.4% and a minimum of 40.1%. This indicates that the daytime temperature was hot.

The indoor thermal environment conditions of classrooms during measurements are shown in Table 5. As seen in the table, the air temperatures in the classrooms were in the ranges of 22.9 to 26.9°C with the average of 24.8°C (≈25°C). The relative humidity (RH) values were ranging from 41% to 68% with an average of 49.9% (≈50%). By using the formula of operative temperature $(T_o) = (T_a + MRT)/2$ (ASHRAE 2013), then the operative temperatures (T_o) were ranging from 20.2 to 25.2°C (T_o) with an average of 22.5°C (T_o). In general, the air temperature and the relative

Table 5. The indoor thermal environment conditions of surveyed classrooms.

Statistic	Air Temperature (T_a) (°C)	Relative Humidity (RH) (%)	MRT (°C)	Airflow (m/s)
Average	24.8	49.9	20.1	0.1
Minimum	22.9	41.1	17.5	0.0
Maximum	26.9	68.4	23.5	0.7

humidity have already laid in the thermal comfort zone according to SNI 03-6390-2011 (BSN 2011), and ASHRAE standard (ASHRAE 2013). This thermal condition can be achieved because the classrooms were cooled by air conditioning (AC) system. In the naturally ventilated university classrooms, the air temperature is ranging from 30.75°C in the morning to 31.96°C at 11.45 am (Hamzah et al. 2016). However, supplying cold air to the classrooms will increase the energy use. Therefore, there is a need to analyse the energy use to cool the classroom and balance with the thermal comfort perceived by respondents. For the energy analyses, the air temperature 25°C and relative humidity 50% were selected as the references setting. These settings are also relevant to the recommendation from the Ministry of Energy, Natural Resources, and Mineral (ESDM 2005).

Students' responses to the air temperature of classrooms

Students' responses to the air temperature in the classrooms based on indicators of thermal sensation vote (TSV) and thermal comfort votes (TCV) are illustrated in Figure 3. Regarding TSV, Figure 3 shows that the majority of respondents (almost 80%) voted in the cool region (−3 to −1) where more than 35% felt cool (−2) and about 18% felt cold (−3). There were only about 15% of respondents felt neutral (0). These indicate that most of the students felt cool in the classrooms' air temperature. Interestingly, there were about 8% of respondents felt slightly warm (+1) or warm (+2).

Regarding the TCV, Figure 3 shows that more than 60% of respondents voted the cold regions (−3 to −1) and only less than 10% vote the hot region (+1 to + 2). There were about 30% of respondents felt comfortable in these surveyed classrooms. The percentages of respondents who voted comfortable (0) in the TCV scale were more than those who voted neutral in the TSV scale. The percentage of respondents who voted 0 (comfortable) in TCV scale is higher than those who voted 0 (neutral) in the TSV scale. A similar result was found in Feriadi and Wong (2004), where about 40% of respondents voted 0 (comfortable) in the TCV, and only less than 20% voted 0 (neutral) in the TSV.

Figure 4 illustrates the distribution of respondents based on the air temperature conditions recorded in their positions. The temperatures are classified into four groups i.e. (Group 1) 23.1–24.0°C, (Group 2) 24.1–25.0°C, (Group 3) 25.1–26.0°C, and (Group 4) 26.1–27.0°C. The numbers of respondents in each group were: (Group 1) 19 respondents (11%), (Group 2) 77 respondents (44%), (Group 3) 45 respondents (26%), and (Group 4) 34 respondents (19%).

The detail distributions of thermal sensation vote (TSV) for each group are shown in Figure 5. In Group 1 (23.1–24.0°C), the TSV of respondents was dominated by the cold (−3) and cool (−2). More than 87% of respondents felt slightly cool (−1) to cold (−3). The majority of them (36%), felt cool,

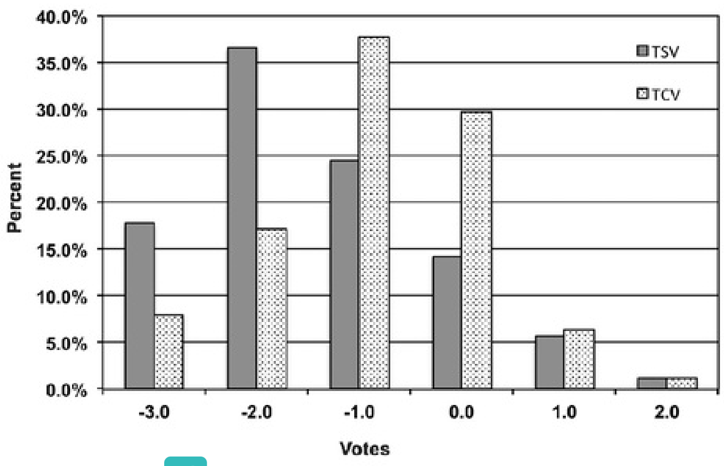

Figure 3. Response of students based on thermal sensation votes (TSV) and thermal comfort votes (TCV).

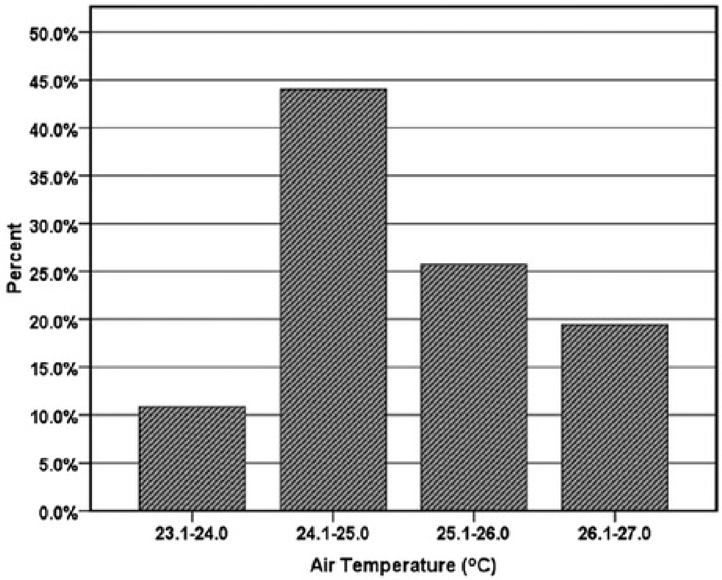

Figure 4. The distribution of TSV based on the four groups of air temperature.

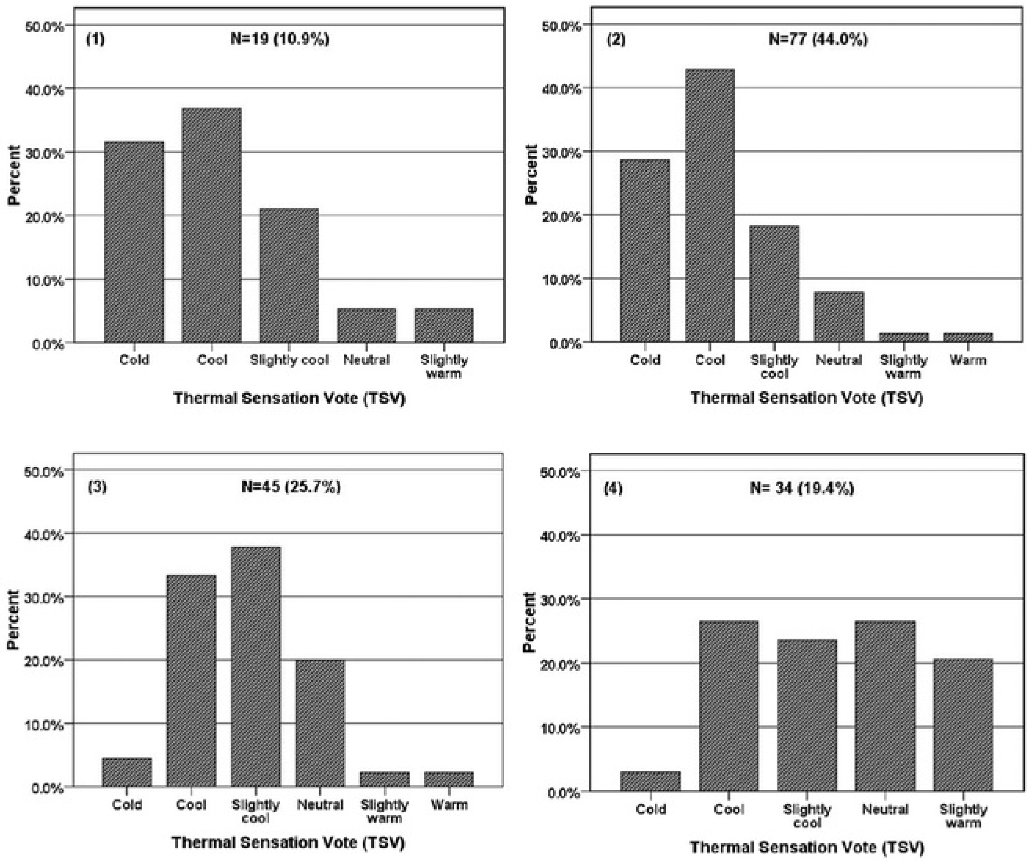

Figure 5. The detail TSV of respondents based on the four groups of air temperature: (Group 1) 23.1–24.0°C, (Group 2) 24.1–25.0°C, (Group 3) 25.1–26.0°C, and (Group 4) 26.1–27.0°C.

followed by 31% felt cold (−3) and 20% felt slightly cool (−1). The results show that only about 5% of respondents felt neutral (0). This indicated that most of the students felt uncomfortable in the air temperature range of 23.1 to 24.0°C. Therefore, the air temperature ranges from 23.1 to 24.0°C might not be the comfortable temperature for the students.

In Group 2, the respondents' votes also dominantly (more than 89%) laid in the cool region (−3 to −1). About 43% of respondents felt cool (−2), 28% slightly cool (−1), and 18% cold (−3). Even though the percentages of respondents who felt neutral increased in comparison to group 1, the percentage of them was still less than 10%. This also indicated that most of the students felt uncomfortable in the air temperature range of 24.1 to 25.0°C. Therefore, the air temperature ranges from 24.1 to 25.0°C might not also suitable for the students' thermal comfort requirement.

The increase of air temperature from the range of 24.1–25.0°C to 25.1–26.0°C (Group 3) reduces the percentages of respondents who felt cold (−3) to slightly cool (−1). About 75% of respondents had thermal sensation votes in the cool region (−3 to −1), which was 14% less than the previous group. In the details, the percentage of respondents who felt cold (−3) reduced from 18% in the Group 2 to 5% in this group. Also, the percentage of respondents who voted cool (−2) decreased from 48% to 33%. In comparison to the two other groups (Group 1 and Group 2), the percentages of people who felt neutral increased from less than 10% to about 20%. This is a good indication that most of the students preferred a little bit higher temperature.

In the Group 4, with the temperature ranges from 26.1 to 27.0°C the percentages of respondents who felt cool (−2) to slightly warm (+1) are quite similar. The percentage of respondents who felt neutral increases from 20% in the Group 3 to 28% in this group. The percentage of the respondent who felt cold were significantly reduced from more than 30% in Group 1 to less than 5% in this group.

The students' responses to the air temperature show that there was a significant correlation between the provided air temperature in the classrooms and the percentage of students felt comfortable. The data analysis showed that the higher percentage of students who felt discomfort were in the temperature range between 23.1 and 24.0°C, while the higher percentage of students felt comfortable was in the air temperature ranges between 26.1 and 27.0°C. This fact suggests that the classrooms temperature setting may be increased from 25.0°C in the current setting to 26.0°C to accommodate the students' thermal comfort and preference.

Neutral temperature

Figure 6 demonstrates the relationship between the air temperature (T_a) with a value of TSV and TCV. The relationship between the air temperatures with the value of thermal sensation votes (TSV) analysed by using a statistical approach. Using the answers from 175 questionnaires, the obtained value of TSV ranges from cold (−3) to warm (+2), with the percentage as shown in Figure 3. The linear regression analysis with R^2 0.227 provides the following equation:

$$\mathrm{TSV} = 0.613\mathrm{T_a} - 16.796 \tag{1}$$

By using equation (1), the value of TSV = 0 will be obtained when the air temperature is 27.4°C. This result is higher than the neutral temperature found in the air-conditioned university classrooms in Jakarta (Karyono, Heryanto, and Faridah 2015), which was range from 24.1 to 24.9°C. This neutral temperature is also higher than the neutral temperature found in the air-conditioned classroom in the tropical country of Brazil which was 25.9°C (de Abreu-Harbich, Chaves, and Brandstetter 2018). This fact might indicate that students in Makassar prefer hotter air temperature than students in Jakarta (Karyono, Heryanto, and Faridah 2015) and Brazil (de Abreu-Harbich, Chaves, and Brandstetter 2018). One reason why the students' neutral temperature is high might be because students have acclimated the higher temperature in the naturally ventilated classrooms (Hamzah et al. 2016, 2018; Hamzah, Mulyadi, and Amin 2017). Similar to this phenomenon is also occur in the office, government and educational buildings in Thailand (Busch 1992; Yamtraipat, Khedari, and Hirunlabh 2005).

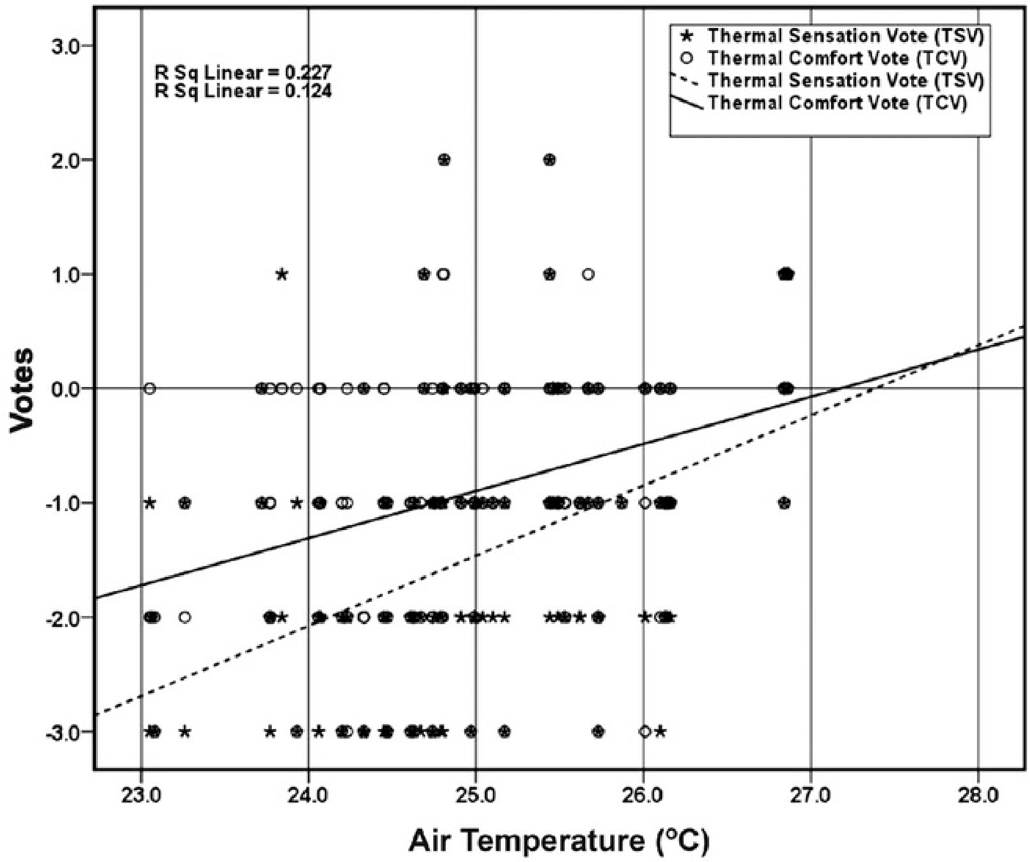

Figure 6. The regression between the air temperature (T_a) and TSV and TCV, respectively.

The relationships between the air temperatures with the value of thermal comfort vote (TCV) were analysed using a statistical method. The linear regression analysis with R^2 0.124 gives the equation as follows:

$$TCV = 0.412T_a - 11.201 \quad (2)$$

The neutral temperature calculated from this equation (2) is 27.2°C (T_a). This neutral temperature is slightly smaller than the neutral temperature based on the TSV and significantly higher than the neutral temperature found in the air-conditioned university classrooms in Jakarta (Karyono, Heryanto, and Faridah 2015) and classrooms in Brazil (de Abreu-Harbich, Chaves, and Brandstetter 2018) as mentioned before.

The energy consumption for cooling

The results of thermal comfort studies have been integrated into the energy simulation processes. The results of simulations show that the integration of thermal comfort studies has the opportunity to reduce the energy use while maintaining the comfort of occupants. The following sections will explain the results of the simulations.

Cooling energy consumption for the different type of classrooms

The yearly cooling energy consumption of three different types of classrooms (small, medium and large) and the three different ceiling heights (2.7, 3.0, and 3.5 m) have been calculated using the EnergyPlus software (U.S. Department of Energy 2016). These combinations make nine different room volumes. With the same ceiling height, the size of classrooms plays an important effect on cooling energy consumption. Bigger classroom, of course, will use more energy to cool the entire space. The regression analysis between the room volumes and the cooling energy consumption can be seen in Figure 7.

The linear regression between the room volumes and the cooling energy consumption is statistically significant (R^2 0.98 and sig 0.000 < 0.05) is explained in the following formula:

$$E = 9.44V + 1{,}124.8 \tag{3}$$

where E is cooling energy in kWh/year, and V is room volume in m^3. The increase of 1 m^3 of room volume will require around 9.44 kWh of energy annually. Therefore, according to this result, the room volume should be minimised to reduce the energy consumption.

The effect of air temperature settings

Room air temperature setting is one of the main important factors that affect the use of energy for cooling. As mentioned before, the Government of Indonesia has set a minimum temperature set-point of 25°C for working spaces in the government and institutional buildings (ESDM 2005). Therefore, the temperature of 25°C serves as the reference temperature in the calculation of energy efficiency in the classroom.

Small classroom. Table 6 shows the annual cooling energy consumption required for various room temperature settings for the small classroom. An increase of 1°C from the reference temperature of 25°C may provide a considerable energy saving. Equally, a decrease of 1°C gives a considerable burden on the energy use in the classroom. It shows that the use of 27°C as a room temperature setting according to the student's neutral temperature may reduce the use of energy by 26%. The highest efficiency of about 37% can be achieved at a temperature setting of 28°C. The problem,

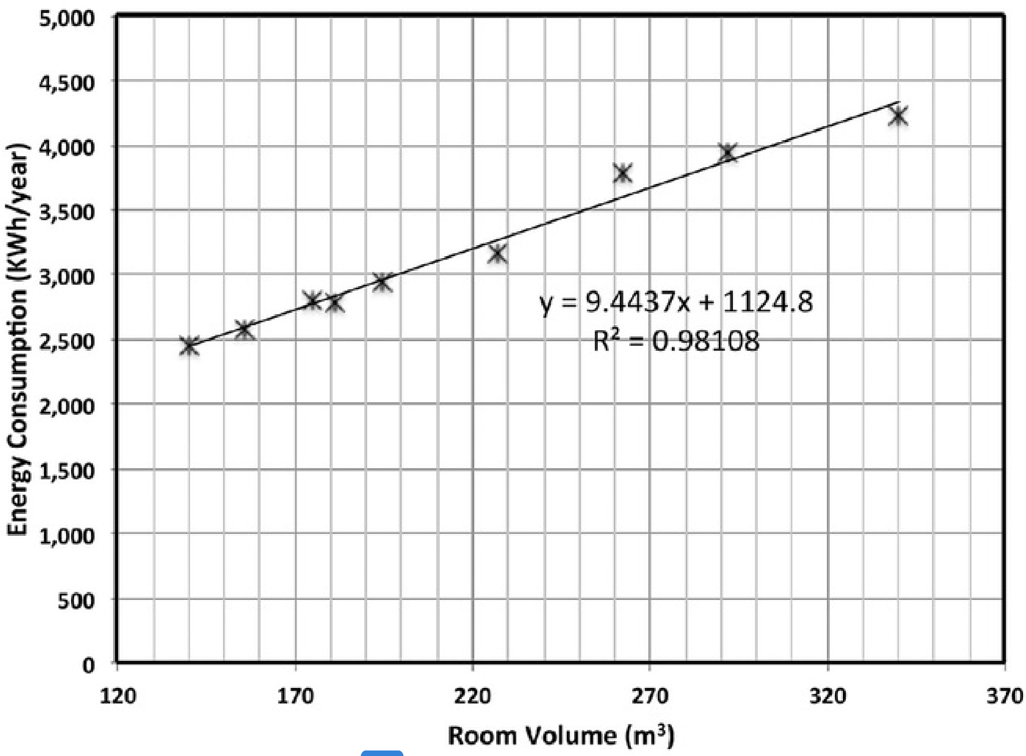

Figure 7. Regression between room volumes and cooling energy consumption for three types of classrooms with three ceiling heights.

Table 6. Annual cooling energy consumption for small size classroom.

Room Temperature (°C)	Cooling Energy (kWh)	Reduction (−) /Increase (+) (kWh)	Percent of Reduction (−) /Increase (+) (%)
23	3637.28	1057.62	29.08
24	3101.62	521.96	14.35
25	2579.66	0.00	0.00
26	2082.36	−497.30	−13.67
27	1624.79	−954.87	−26.25
28	1220.65	−1359.01	−37.36

however, is that many respondents might not feel comfortable at this room temperature. The trade-off between energy efficiency and the comfortable should be considered in designing air-conditioned classrooms.

Medium classroom. Table 7 shows the annual cooling energy consumption required for various temperature settings for the medium classroom. As in the small classroom, an increase of 1°C from the reference temperature setting of 25°C offers significant energy efficiency. Likewise, a decrease of 1°C from the reference temperature setting may give a considerable load on energy use in the classroom. As per simulation, the use of 27°C room temperature setting according to the students' neutral temperature may reduce the cooling energy use by approximately 27%. The highest efficiency of about 38% can be achieved at a temperature setting of 28°C. However, the problem is that many respondents do not feel comfortable at this temperature ranges.

Large classroom. Table 8 illustrates the cooling energy consumption required for various room temperature settings. As in small and medium classrooms, an increase of 1°C from a reference temperature setting of 25°C could provide important energy efficiency in this large classroom. Similarly, a decrease of 1°C from a 25°C temperature setting provides a considerable burden for indoor energy use. Table 8 shows that the use of the 27°C as classroom temperature setting, which accommodates the student's neutral temperature will reduce the use of energy by about 27%. The highest efficiency of about 39% could be achieved at a temperature setting of 28°C. However, as mentioned before, the problem is that many respondents do not feel comfortable at this temperature.

The effect of glazing on the cooling energy consumption

To analyse the effect of glazing on the energy consumption the use of single pane and double pane glass in the windows were simulated using the EnergyPlus software (U.S. Department of Energy 2016). The simulation shows that for the North and South oriented windows the effect of changing

Table 7. Annual cooling energy consumption for medium size classroom.

Room Temperature (°C)	Cooling Energy (kWh)	Reduction (−) /Increase (+) (kWh)	Percent of Reduction (−) /Increase (+) (%)
23	4200.34	1256.26	29.91
24	3564.67	620.60	14.77
25	2944.07	0.00	0.00
26	2352.24	−591.83	−14.09
27	1815.21	−1128.86	−26.88
28	1343.94	−1600.13	−38.10

Table 8. Annual cooling energy consumption for large size classroom.

Room temperature (°C)	Cooling energy (kWh)	Reduction (−) /Increase (+) (kWh)	Percent of Reduction (−) /Increase (+) (%)
23	5692.24	1745.35	30.66
24	4811.34	864.45	15.19
25	3946.89	0.00	0.00
26	3127.65	−819.24	−14.39
27	2387.86	−1559.03	−27.39
28	1741.24	−2205.66	−38.75

Table 9. The comparison of annual cooling energy consumption (kWh/year) between single pane window and double pane window at different room temperature.

Room temperature (°C)	Single pane window	Double pane window	Improvement (%)
23	5692.24	5581.27	1.95
24	4811.34	4711.34	2.08
25	3946.89	3855.10	2.33
26	3127.65	3046.82	2.58
27	2387.86	2320.73	2.81
28	1741.24	1689.18	2.99

glazing from single pane to the double pane did not result in significant improvements. The improvement of energy consumption was only ranging from 2% to 3% (see Table 9).

The implication of results

Based on the performance of three strategies, it was found that the air temperature setting has the largest impact on the cooling energy consumption in the classrooms. The temperature setting is mostly related to the thermostat system. Generally, there are two types of thermostat system, i.e. manually and automatically controlled. Occupants through a panel or remote control can access the manually controlled thermostat. The thermostat can be set up in low temperature at the beginning and then manually adjusted with an increase of 1.5°C for every 30 min to reach the comfort temperature at 23 to 26°C (Bourdakis, Simone, and Olesen 2018).

For the centrally controlled system, the use of smart or automation system that applied the information technology is necessary. This smart system is supported by technologies that include the programmable thermostats, smart metres and outlets, zone heating, automated sensors, and wireless communication infrastructures (Meyers, Williams, and Scott Matthews 2010). Designing of an effective controller in order to decrease the energy consumption of the devices while satisfying the thermal comfort demands in buildings are the most important goals of control designers (Behrooz et al. 2018).

Conclusion

In conclusion, the study found that the provided air temperature in the air-conditioned classrooms is colder than the students' thermal preferences. The temperatures were ranging from 23.0 to 27.0°C with an average of 25.0°C. In this thermal environments, about 53% of respondents felt uncomfortable (cool or cold). The regression analysis found that the neutral temperature of students in this air-conditioned (AC) classroom is 27.0°C. This evidence suggests that the increase in air temperature is needed to accommodate the thermal preference of students while reducing the cooling energy. In the cooling energy calculation, it was found that an increase of 1°C from this temperature setting may provide considerable cooling energy savings of more than 13%. Therefore, it is recommended to raise the room temperature setting from 25.0°C to minimum of 26.0°C. The article has a promising result that can be applied in reducing the cooling energy of air-conditioned classrooms in the warm and humid tropical climate. However, this study has several limitations, especially the number of data collected from the survey and the availability of equipment. This limitation may reduce the accuracy of the measurement and research results. The future studies shall employ more metres and sensors working simultaneously to collect data on thermal environments. The studies shall concentrate on the thermostat control system that can maximise the reduction of cooling energy while maintaining the thermal comfort of occupants should be carried out.

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