Adaptive thermal comfort of naturally ventilated classrooms of elementary school in the tropics

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Abstract. Thermal comfort is one of the very important factors in enhancing the human quality of life, including students who spent a lot of times learning in schools. This article intended to analyze the students' adaptive thermal comfort in naturally ventilated classrooms of the elementary school in the tropical city of Makassar. The study analyzed data gathered from 33 surveyed classrooms in six primary schools. The recorded data consists of the personal and adaptive behavior of 1,111 students, and the thermal environments of the classrooms. At the same time, students filled out the questionnaires asking their thermal sensation, comfort level, and thermal preferences against the classrooms' thermal environments. The results of measurements showed that the indoor mean air temperature, air humidity, and air velocity were 30.4 °C, 68%, and 0.1 m/s, respectively. This indicated that the classrooms had the hot temperature, high humidity, and low air velocity. The calculated PMV based on these parameters showed that about 90% of students felt either warm (+2) or hot (+3). The PMV overestimated the actual students' thermal comfort where more than 85% of students voted slightly cool (-1), neutral (0), and slightly warm (+1). In addition, the neutral temperature predicted by PMV was 25.5 °C. This neutral temperature was very low in comparison to 30.2 °C calculated by using thermal sensation vote (TSV). These suggest that students of elementary schools in the tropic are tolerant to the hot environment. Adaptive behavior of students might be the best way to explain this phenomenon.

Keywords: adaptive model, air temperature, neutral temperature, thermal comfort, elementary schools

1. Introduction

Thermal comfort is one of the very important factors in enhancing the human quality of life, including students who spent a lot of times learning in schools. Pepler and Warner in 1968 discovered that there was a positive influence of the classrooms' thermal quality on students' performances [1]. Mendell and Heath [2] carried out an extensive literature review and found that a good correlation between indoors' school environments and the students' performance and attendance records. It is necessary to provide a healthy and comfortable environment in school to enhance students' productivity and well-being [3].

A number of articles have analyzed and discussed the thermal comfort of students in the classrooms worldwide. For examples, the thermal comfort analysis of students in classrooms in the United Kingdom [4-6] as the temperate climate. Several studies have also been conducted in the Mediterranean climate, such as in Italy [7-9], in the subtropical climate in, Japan [10,11], Taiwan [12], and Australia [13]. A number of thermal comfort studies carried out in the tropical area including Malaysia [10], Singapore [14], Indonesia [15-18] and Hawaii [19]. Most of these thermal comfort studies were based on the heat balance models using the indicator of predicted mean vote (PMV) model. Fanger [20] developed the PMV model in 1970, which later on adopted by ASHRAE as ASHRAE 55 standard [21]. The PMV model is calculated using six variables i.e. air temperature, mean radiant temperature, relative humidity, air velocity, clothing index, and the metabolic rate of respondents' activity. A number of studies found that the predicted mean voted (PMV) model mostly overvalued the respondents' actual vote in the naturally ventilated classrooms in the hot regions such as in Singapore [14] and Indonesia [16-18]. Wong and Khoo [14] found the neutral temperature in the secondary school in Singapore predicted by PMV was 26.1 °C. It was 2.7 °C lower than the neutral temperature calculated from thermal sensation vote (TSV). Several studies done by Hamzah et al [16-18] found a neutral temperature predicted by PMV were lower than the TSV. For example, Hamzah et al [16] found the neutral temperature of students were 23.0 °C (PMV) and 29.0 °C (TSV) for secondary schools in Makassar, Indonesia. A big discrepancy of 6 °C was found in this study [16].

Another thermal comfort model is an adaptive thermal comfort model. The model is especially established for predicting the thermal comfort in naturally ventilated buildings located in the hot environment. Based on the worldwide thermal comfort data collected from 1935 to 1975, Humphreys [22] proposed a linear regression between neutral temperature (T_n) and mean outdoor temperature (T_{out}) as follows:

$$T_n = 11.9 + 0.534T_{out} \quad (1)$$

The equation has subsequently been revised to increase the precision of the relationship as follows [23]:

$$T_n = 13.2 + 0.534T_{out} \quad (2)$$

Auliciems [24] tried to reanalyze Humphreys' data [22] by eliminating some conflicting data, integrating of more recent field studies results, and uniting data from buildings with passive and active climate control. Auliciems proposed the relationship between neutral temperature (T_n) with average indoor air temperature (T_a) and outdoor monthly temperature (T_{out}):

$$T_n = 9.22 + 0.48T_a + 0.14T_{out} \quad (3)$$

According to Roaf et al. [25], there are three categories of thermal comfort adaptation i.e. physiological, behavioral, and psychological. Among these three adaptation categories, behavioral adaptation is definitely the most common way to do for the people in adjusting their thermal comfort [25]. The behavior adaptations include changing the activity and the clothing levels, closing or opening the windows, switching the fans, switching the air conditioning, etc.

Most of the state-owned schools in Makassar or in Indonesia were planned and constructed as a prototype building. Usually, no consideration is paid to the condition of local climate and environment. The schools have been built to the same models regardless of the thermal sensation and preference of occupants. During daytime, the classrooms are experiencing the hot thermal environment. The temperature mostly varied from 28 °C in the morning to 33 °C in the afternoon [18]. These temperatures are laid outside the comfort zone of ASHRAE [21] or local standards [26]. However, most studies in Makassar show that despite the hot temperature, still more than 80% of students voted in the comfortable region and more than 80% of students accepted the hot thermal environment. To explain this phenomenon, a further study based on analysis of adaptive thermal comfort in the elementary schools is necessary to be undertaken.

2. Methods

2.1. Data collection

The study was carried out at the 33 classrooms in the six chosen primary schools in different locations in Makassar tropical city. The data collection was carried out in two protocols as follows:

- The objective measurement survey was carried out to collect the thermal environment and the personal data. Several instruments have been used for the measurement and collection of indoor environmental data. The main instrument used in the study was the Thermal Comfort Multi Logger (LSI TC) from LSI-Lastem, Italy. The LSI TC consists of three sensors that collected and recorded in one data logger. The three sensors including a portable psychometric forced ventilation probe (BSU102), a globe thermometric probe (BST131), and a wet bulb temperature probe (BSU121). The BSU102 sensor was used to collect air temperature and relative humidity, the BST131 sensor for globe temperature, and BSU121 for wet bulb temperature. In addition to the LSI TC, measurements of the thermal environments of classrooms were also recorded by Hobo Loggers from Onset, US. Two types of loggers were used in the survey, namely a standard Hobo, which only measured and recorded the air temperature and relative humidity, and the Hobo logger with the external sensor. There were four standard Hobo and two Hobo with external sensors were used in the surveys. The external sensors attached in the Hobo loggers were used to measure the air velocity inside the classrooms. The equipment was placed in the six points in the classrooms, with the sensors attached in the pole at about 1 m above the floor level [14]. Because of the number of instruments is limited, two environmental parameters could not be measured at the six points. The MRT was only measured and recorded at point A, and the air velocity at points A and B. The position of instruments in the classrooms are similar to that shown in Hamzah et al [18]. The students' clothing data were written in details in the questionnaires, and the students' activities were recorded by the surveyors.
- The subjective measurement survey was carried out to collect the students' responses level. This was collected by questionnaire method. The questionnaire was developed and modified based on the questionnaire used by Wong and Khoo [14]. This modified questionnaire has also been used in the naturally ventilated classrooms in Makassar [16-18]. The questionnaire has been adapted to include seven questions. Among the seven questions, four questions correlated to the thermal aspects that are the thermal sensation, comfort level, preference, and thermal acceptance. The following two questions asked about the students' votes on the air velocity. The last question intended to get the students' votes on the humidity. This questionnaire asked the TSV of respondents in seven scales, namely: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2), and hot (+3). The TCV also in seven scales: much too cool (-3), too cool (-2), comfortable cool (-1), comfortable (0), comfortable warm (+1), too warm (+2), and much too warm (+3).

2.2. Data analysis and processing

Data were processed and analyzed by using spreadsheet software and a statistical package. The spreadsheet MS Excel has been used to calculate the mean, minimum, and maximum values of environmental data and to generate graph illustrating the proportion of PMV, TSV, and TCV. The availability of two personal variables for each respondent and four environmental variables is required for calculating the PMV of each student. The calculation of PMV was completed using MS Excel spreadsheet template developed by Farina [27]. The PMV calculator was developed based on the ASHRAE standard 55 [21]. Statistical analysis of SPSS (statistical package for social science) software has been used to show the scatterplots of respondents' actual votes (TSV and TCV) and the PMV against the operative temperature (T_o). The linear regressions of the three pairs were also been calculated using the SPSS software. The validity of linear regression equations was evaluated by the two criteria. Firstly, the test of linearity of regression to make sure that the regression is linear, and second is the test of significance of the equation coefficient. Before analyzing, the data have been verified by examining the normality and reliability of data.

2.3. Research Sample

The surveys and measurements have been carried out in six selected elementary schools in Makassar, which represented six sub-districts in the city. The elementary school in Indonesia is known as

Sekolah Dasar (SD). The selected schools are situated in the dense area in the city center to the less dense area in the suburban. The first surveyed school was SD Inpres Nipa-nipa. The selected school is situated in a suburban area, which far away from the settlements concentration. The second surveyed was in SD Negeri Sudirman 1. This school is located in the opposite of the town square in the city center. The school shares its location with three other elementary schools. In the third day, the survey was carried out in the SD Inpres Tamalanrea 4. The school was located in the dense area of a residential complex of Bumi Tamalanrea Permai (BTP), which is bordering with the road environments. The fourth day of the survey was carried out in the SD Inpres Daya. The school is located in the local commercial area. It is adjacent to arterial roads about 13 Km away from the city center. The fifth school to be surveyed was SD Inpres Hartaco Indah. The school is located in the medium density of the residential area. The last survey was carried out in the SD Unggulan Toddopuli. The school is situated in the medium density of residential and commercial regions. The characteristics of the samples are illustrated in Table 1.

Table 1: Characteristics of samples and date of survey (adapted from [18])

No.	School name	School location	Number of classes	Number of students	Date of survey
1	SD Inpres Nipa-nipa	Manggala	5	157	21 April 2016
2	SD Negeri Sudirman 1	Ujung Pandang	6	205	29 April 2016
3	SD Inpres Tamalanrea 4	Tamalanrea	5	160	30 April 2016
4	SD Inpres Daya	Biringkanaya	6	239	3 May 2016
5	SD Inpres Hartaco Indah	Tamalate	5	126	7 May 2016
6	SD Unggulan Toddopuli	Panakkukang	6	224	12 May 2016
Total			33	1,111	

3. Results and Discussion

3.1. Outdoor and indoor microclimate conditions

The outdoor microclimate condition recorded in the Vaisala Station located at the rooftop of Department of Architecture Building, Faculty of Engineering, Gowa Campus. The monthly average outdoor temperatures were 30.2 °C and 30.6 °C in April and May 2016, respectively.

The indoor microclimatic conditions recorded during the measurements can be seen in Table 2. The table shows that the average air temperature was 31.4 °C with minimum and maximum temperatures were 28.3 °C and 34.3 °C, respectively. The air temperature condition shows the excessive heat in the classrooms. This average air temperature was higher than the temperature specified in the national standard SNI [26] and international ASHRAE standard [21]. The average of air humidity of 68% was within the comfort zone of SNI [26].

Table 2. The average indoor thermal environment measured at the six schools (adapted from [18])

Schools name	Air Temp (°C)	RH (%)	MRT (°C)	Air Velocity (m/s)
SD Inpres Nipa-Nipa	30.9	66.50	30.9	0.13
SD Negeri Sudirman 1	30.0	71.35	29.7	0.10
SD Inpres Tamalanrea 4	30.9	70.48	30.7	0.06
SD Inpres Daya	32.1	67.97	32.1	0.13
SD Inpres Hartaco Indah	32.6	64.11	32.5	0.08
SD Unggulan Toddopuli	32.1	67.73	32.0	0.10
Total	**31.4**	**68.02**	**31.3**	**0.10**

3.2. Students response to the thermal environment based on the thermal balance

This sub-section presents the results that have been explained in Hamzah et al. [18]. Figure 1 demonstrates the response of students to the air temperature in the classrooms. In terms of TSV scale, the majority of respondents (more than 85%) voted the center points (-1, 0 and +1). In details, less than 30% respondents voted the neutral (0) point, about 12% voted the hot regions (+2 and +3), and 2% voted the cold regions (-2 and -3). In the Bedford scale, more than 87% of respondents voted the central region (-1 to +1), about 10% in hot regions (+2 and +3), and only about 2% in the cold regions (-2 and -3). Interestingly, about 50% of respondents felt comfortable (0) in comparison to less than 30% voted neutral (0) in the TSV scale.

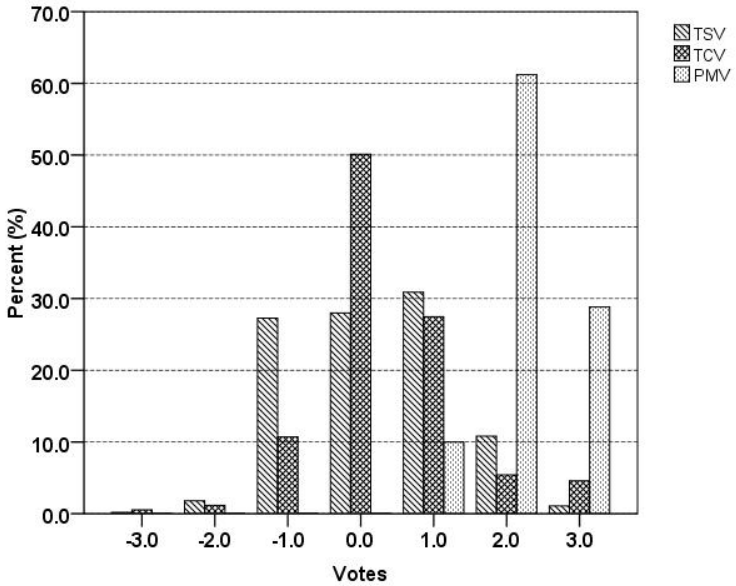

Figure 1. The percentage of thermal sensation votes, thermal comfort vote, and the predicted mean vote of elementary school students (source: [18])

As expected, the percentage of the predicted vote was very different with the TSV and TCV. In the predicted model, almost 90% of students were predicted to have voted in the hot regions (+2 and +3), and only 10% respondents were predicted in the central line vote (-1 to +1). The figure suggests that the percentage of votes by the PMV model overestimated the respondents' actual votes. In the PMV model, only small number of students will be predicted to feel slightly warm (+1), and no students to be predicted neutral (0), while in the TSV and TCV, there were almost 30% and 50% of students felt neutral and comfortable, respectively. This result agrees with several studies conducted in Makassar [16,17] and Singapore [14]. This indicates that the PMV model may not be suitable for estimating the students' thermal comfort in the naturally ventilated classrooms in the tropical area.

Figure 2 demonstrates the scatterplots and the linear regressions of the operative temperature (T_o) against the predicted PMV, TSV, and the TCV. With operative temperatures were ranging from 28.5 °C to 34.0 °C the neutral temperature (T_n) obtained from the PMV model is 25.5 °C (T_o). This predicted T_n is lower than that one resulted from actual votes (TSV or TCV). The neutral temperature (T_n) obtained from the relationship between actual votes (TSV and TCV) and the operative temperature (T_o) are 30.2 °C (T_o) and 29.4 °C (T_o) for TSV and TCV, respectively. The neutral temperature calculated based on the TSV is very similar to the study conducted in Makassar [16,17] and Singapore [14]. The neutral temperatures obtained from Makassar studies are 29.0 ºC and 29.6 °C, respectively for secondary school [16] and university students [17]. While the Singapore study found the neutral temperature of 28.8 °C for secondary school students [14].

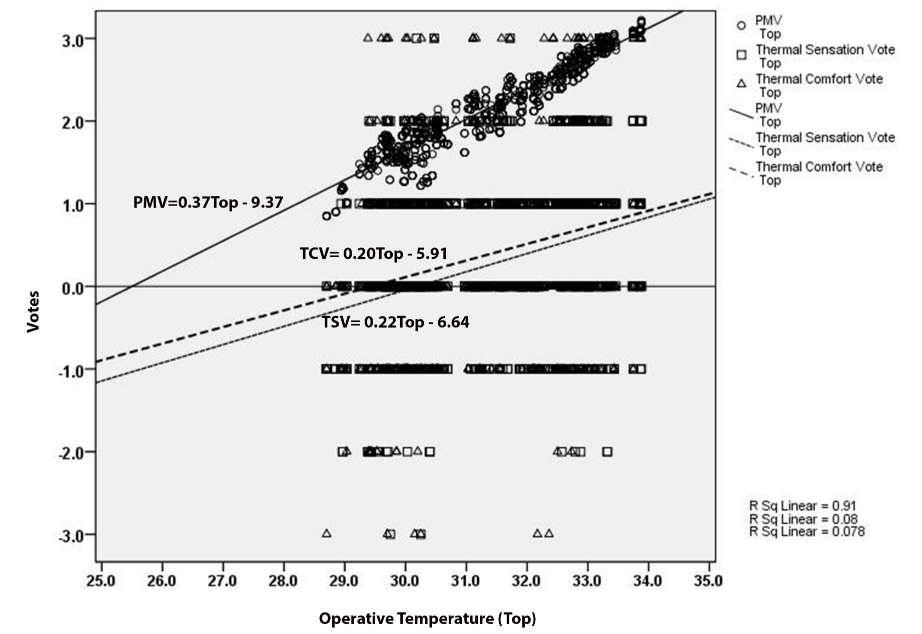

Figure 2. The scatterplots and the linear regressions of the operative temperature (T_o) versus the PMV, TSV, and TCV (source: [18])

3.3. Adaptive thermal comfort

The neutral temperatures (T_n) of each school have been calculated using Humphrey's model (eq. 2) and Auliciems model (eq. 3). The results of the calculations are shown in Table 3. As seen in Table 3, the Humphreys model only produced two neutral temperatures for the six schools, while the Auliciems model produced more varied neutral temperatures. The reason for this is that because Humphreys only uses the outdoor temperature, while Auliciems uses the indoor and outdoor temperature. The Humphreys model gives very close to the neutral temperature calculated from actual votes. In average, Humphreys produces a neutral temperature of 29.4 °C, which is close to 30.2 °C resulted from actual votes. The neutral temperature predicted by Auliciems is almost 1 ºC below the Humphreys. This might be due to the Auliciems model also included the data gathered from buildings with active thermal control.

Table 3. The comparison of neutral temperature between Humphreys model and Auliciems model

Schools name	Air Temp (T_a) (°C)	Out Temp (T_{out}) (°C)	Neutral Temp (T_n) Humphreys model	Neutral Temp (T_n) Auliciems model
SD Inpres Nipa-Nipa	30.9	30.2	29.3	28.3
SD Negeri Sudirman 1	30.0	30.2	29.3	27.8
SD Inpres Tamalanrea 4	30.9	30.2	29.3	28.3
SD Inpres Daya	32.1	30.6	29.5	28.9
SD Inpres Hartaco Indah	32.6	30.6	29.5	29.2
SD Unggulan Toddopuli	32.1	30.6	29.5	28.9
Average	**31.4**	**30.4**	**29.4**	**28.6**

3.4. Adaptive behavior of students

The surveys discovered that most the students use handheld fans to adjust their thermal comfort. When they felt hot, they mostly used their books for this purpose. Very little students used the battery operated handheld fans. For the classrooms that equipped with electric fans, students have very limited access to this equipment. Students should ask permission or wait for instruction from their teachers to operate the fans. Students sitting next to the open-able windows can open or close the windows when needed. Because the open-able windows only located on one side of the classrooms, therefore only very small numbers of students have access to this.

The reason for good thermal sensation and acceptance of students to this hot environment may because students have acclimatized well to the hot thermal environment [16]. Another explanation about this phenomenon is that the students have more chance to modify their thermal environment (adaptable) through several activities such as increasing the air velocity by using fans or opening windows. Also, students that are learning in the non-air-conditioning classrooms have a different expectation with those in air-conditioning ones [28]. This expectation makes students still feel comfortable even in the hot environments. The implication of this finding requires more attention to the passive design strategies to improve the thermal comfort of classrooms.

4. Conclusion

It was found that the PMV model overestimates the thermal sensation and the acceptance of elementary schools' students. In the hot classrooms' condition, the PMV model predicted the students to have hot thermal sensation. However, the students' actual votes indicated that the majority of students felt comfortable, where more than 80% of students voted in the central line ('slightly cool' to 'slightly warm'), and more than 80% students accepted the thermal condition. Besides, the neutral temperature (Tn) predicted by the PMV model is shallow in comparison to the one resulted from actual votes. These all findings indicate that the PMV model cannot explain the thermal sensation and acceptance of students in the hot condition of classrooms in Makassar.

Students adapt to the thermal environment through several activities. This adaptation makes students still feel comfortable in the hot thermal environment. In an adaptive model, it was found that the neutral temperature of students presented similar results gathered from actual votes. The closest neutral temperature of actual votes is that one predicted by Humphrey's model. The evidence supports the more comprehensive studies in the application of passive design in the school building are needed to accommodate students' comfort and lower the energy consumption in the education sector.

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