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Assessing Thermal Comfort and Energy Efficiency in Partially Glazed Classroom Environments: Implications for Climate-Resilient Educational Spaces

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ABSTRACT

Ensuring thermal comfort in educational spaces is crucial for creating climate-resilient buildings that can adapt to and mitigate the effects of climate change. This study aims to analyze the thermal comfort level and energy consumption in partially glazed classrooms at a university in Semarang, Indonesia, which predominantly uses air conditioning. The research involved 31 students, with data collected on personal factors and environmental parameters over a four-week period. Measurements included indoor and outdoor air temperatures, relative humidity, and air velocity, while thermal comfort was assessed using the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). The results showed average indoor and outdoor temperatures of 25.52℃ and 32.71℃, respectively, with a PMV of 0.63, indicating a slightly warm environment. The highest energy consumption occurred in the third week, reaching 2.420 kWh. These findings highlight the need to optimize energy use while maintaining thermal comfort in educational spaces to enhance climate resilience and ensure conducive learning environments despite rising urban temperatures.

1. INTRODUCTION

Climate change is expected to increase the risk of extreme weather conditions [1]. In particular, the duration of high temperatures in tropical and dry climates has increased with climate change and rapid urbanization. Notable consequence of urbanization is the alteration of heat balance, which adversely affects the quality of life for urban inhabitants [2]. In recent years, Indonesia has experienced an increase in the frequency of severe climate related hazards with floods and windstorms accounting for 70% of these disasters; and droughts, landslides, forest fires, heat waves, storms and others climatic events accounting for the remaining 30% [3]. Java is one of the most studied areas in terms of mega-urban formation and urban development, as it is home to over 60% of the country's population. Semarang, one of the cities in Java, experienced the highest urbanization growth between 1990 and 2010 compared to its surrounding areas [4]. The city government is currently planning to expand green spaces by planting 58,000 tree seedlings, aiming to help mitigate the heat in the urban area. With midday summer temperatures in Semarang already peaking between 33℃ and 36℃, these green initiatives are expected to contribute to cooling the city [5]. Factors contributing to climate change, including industrial waste, deforestation, and buildings with excessive electrical energy consumption, further exacerbate these temperature increases [6]. Buildings serve to protect occupants from extreme heat and cold, but the extent of heat received by the earth's surface is influenced by the area exposed to solar radiation. The challenges of climate change are expected to affect the adaptation life and comfort of the community in adapting to the environment.

Thermal comfort in buildings is influenced by several factors, including air temperature, mean radiant temperature, relative humidity, clothing insulation, metabolic rate, and air velocity [7]. In educational and office buildings, providing an environment that supports optimal learning and working performance for students and employees is crucial, alongside maintaining thermal comfort [8]. The position and design of buildings, particularly the use of materials like glass, significantly impact human thermal comfort during activities [9]. Glass is widely used as a building skin material, and its application in the campus buildings has led to partially glazed classrooms [10]. These partially glazed classrooms can increase indoor temperatures due to enhanced solar heat gain, impacting thermal comfort and energy consumption.

The classroom serves as a space where students, lecturers, and teaching staff engage in various activities. To enhance thermal comfort, classrooms are equipped with air conditioning (AC) systems. The modes of air circulation, including natural ventilation (NV) and AC, impact the actual thermal sensation and the occupants thermal comfort acceptance [11]. While the exclusive use of air conditioning could ensure 100% thermal comfort, it may be impractical due to the high electricity costs associated with it [12].

Thermal comfort refers to individuals' perceptions of comfort or discomfort in their environment [13]. According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards, thermal comfort conditions are defined by human responses indicating their level of satisfaction with the environment [14]. Factors influencing thermal comfort include outdoor climate, season, and indoor environment [15]. The predicted mean vote (PMV) model, developed by Fanger in 1967, is widely used for thermal comfort assessment and is integrated into international standards such as ISO 7730 and ASHRAE Standard 55-2017 [14]. The International Energy Agency projects a substantial rise in the use of cooling units, which is expected to significantly drive global electrical energy consumption by 2050 [16]. Indonesia's energy consumption is generally distributed across the industrial (50%), transportation (34%), residential (12%), and commercial (4%) sectors. Additionally, government projections indicate that the residential sector will account for 59% of total electricity consumption, while the commercial, industrial, and public sectors are expected to comprise 22%, 12%, and 7% of electricity demand, respectively [17, 18]. Adjusting the temperature setting of AC units by just 1°C can significantly impact energy consumption [15].

A preliminary survey conducted in the classrooms of Industrial Engineering in Diponegoro University, Semarang, Indonesia, revealed that 90.9% of 33 students believed thermal comfort influenced their learning activities. However, 33.3% of students felt the classroom conditions were neutral, and only 9.1% thought the conditions were cold. Prolonged exposure to indoor air temperature can significantly affect workers' performance [19]. Air temperature and humidity can alleviate several symptoms of Sick Building Syndrome (SBS), such as fatigue and headaches [20]. The survey also found that 69.7% of students were unsure about the optimal AC temperature settings.

Given the significant role of thermal comfort in educational environments, this study aims to evaluate thermal comfort, determine the neutral and comfortable temperatures for students in classrooms, and assess the electrical energy consumption associated with AC usage. By optimizing thermal comfort and energy efficiency, this research seeks to enhance the climate resilience of educational spaces, ensuring they remain conducive to learning amid rising urban temperatures.

2. MATERIAL AND METHODS

2.1 Subjects

This study involved 31 undergraduate students from the Industrial Engineering at Diponegoro University, located in Semarang, Central Java. The participants consisted of 11 males and 20 females, aged between 18 and 22 years, all of whom were residents of Semarang. A purposive sampling technique was employed alongside field survey research methods, selecting participants based on specific criteria and considerations.

The criteria for selecting the respondents included active undergraduate students of Industrial Engineering at Diponegoro University, students currently engaged in classroom learning activities, students who are physically and mentally healthy, and students who are willing to participate as respondents and follow the research procedures.

The population was represented by one class of 31 students, ensuring a balanced representation of both male and female students. This approach allowed for a comprehensive analysis of thermal comfort and energy consumption in the classroom environment.

2.2 Instruments

The research utilized a variety of sophisticated instruments to gather comprehensive data as show Table 1. The Elitech GSP data logger was employed to accurately measure indoor air temperature ($T_{a\ in}$) and relative humidity ($R_{h\ in}$), ensuring precise monitoring of the classroom environment. For air velocity (A_v), the Benetech hot wire anemometer GM8903 provided reliable readings through indoor logger data. To capture physiological responses, a core body temperature monitor was used to record both core body temperature (T_{core}) and skin temperature (T_{skin}). Electrical energy consumption was meticulously tracked using a Micro power monitor, which measured power usage in watts. Additionally, the outdoor conditions were monitored with a Wireless weather station MISOL-2320, capturing outdoor air temperature ($T_{a\ out}$) and relative humidity ($R_{h\ out}$).

2.3 Research procedure

The campus building of the Department of Industrial Engineering at Diponegoro University, located at 7°03'04.1"S 110°26'29.3"E, faces southeast. The 4th floor classrooms were chosen because they are adapted to the direction of sunlight, air velocity conditions, and the room type is included in the glass building. Data collection for this study took place every Thursday over a span of four weeks from November to December 2023, between 11:00 am and 12:30 pm. This research is included in the survey field study, so there is no control in the implementation of data collection. Temperature air conditioner adjustment is in accordance with the preferences comfort of the occupants' conditions with a range of 20°C-26°C. The condition of the clothing used does not specify the type and material that should be used. Conditions of classroom windows and doors are closed. The wall materials in classroom almost used bricks. This process involved two data collection methods: subjective Thermal Comfort questionnaires capturing are Thermal Sensation Vote (TSV), Thermal Preference (TP), Thermal Comfort (TC), and Thermal Acceptability (TA), and objective measurements of the physical environment. Measurements were taken by distributing the ASHRAE thermal comfort questionnaire [14] after the class was completed. The resulting data included 121 entries related to thermal comfort factors.

Table 1. The specification of instrument research

Instrument	Measured Parameter	Valid Range	Accuracy	Unit of Measurement
Elitech GSP Data Logger	Air temperature (in)	-20°C-40°C	± 0.5°C	°C
	Relative humidity (in)	20%-90%	± 3%	%RH
Benetech Hot Wire GM8903	Air velocity	0.0-30.0	± 0.1 m/s	m/s
Core Body Temperature	Core body and Skin temperature	20°C-42°C	± 0.5°C	°C
Micro Power Monitor GM86	AC-Electricity consumption	0.00-99.999	-	kWh
Wireless Weather Station MISOL -2320	Air temperature (out)	-20°C-40°C	± 0.5°C	°C
	Relative humidity (out)	20%-90%	± 3%	%RH

Various tools are illustrated in Figure 1. Caption A highlights the Benetech Hot Wire Anemometer GM8903, installed at a height of 1 to 1.2 meters from the floor, measuring air velocity (A_v). Caption B shows the Elitech GSP Temperature and Humidity Data Logger, which records indoor air temperature ($T_{a\ in}$) and relative humidity ($R_{h\ in}$). Caption C displays the position of the respondents, while Caption D shows the installation of the Micro Power Monitor GM86, used to gauge the energy consumption in watts.

To ensure comprehensive data, core body temperature measurements were taken from two respondents seated in the front and back rows of the classroom. Indoor physical environment data, including air temperature, relative humidity, and air velocity, were collected at 60-second intervals. Concurrently, outdoor physical environment data were gathered using a wireless weather station to monitor outdoor air temperature ($T_{a\ out}$) and relative humidity ($R_{h\ out}$).

For energy consumption data, the average power (watt) used by the AC was measured. The data were analysis to determine the electrical energy consumption costs incurred. Power measurements were taken before and after using the AC with a GM86 micro power monitor, a non-logger instrument, to accurately capture energy usage.

During these measurements, students engaged primarily in sedentary activities such as sitting and reading, with a metabolic rate of 1.0. This thorough approach to data collection ensured a robust dataset for analysis thermal comfort and energy consumption in the classroom environment.

Figure 2 is the condition of data collection when students are participating in class learning. Tool installation and data collection were carried out during class learning until completion. The process is also in accordance with the procedure and initial research design.

The data collection procedure was meticulously planned and executed in several stages: preparation, pre-class setup, in-class monitoring, and post-class evaluation, as show in Figure 3. During the preparation stage, participants were briefed on the data collection process, and their consent was obtained for participation in the research. Before class began, the indoor and outdoor physical environments were set up, and individual conditions were assessed using a core body temperature monitor. This step ensured that all necessary equipment was in place and functioning correctly.

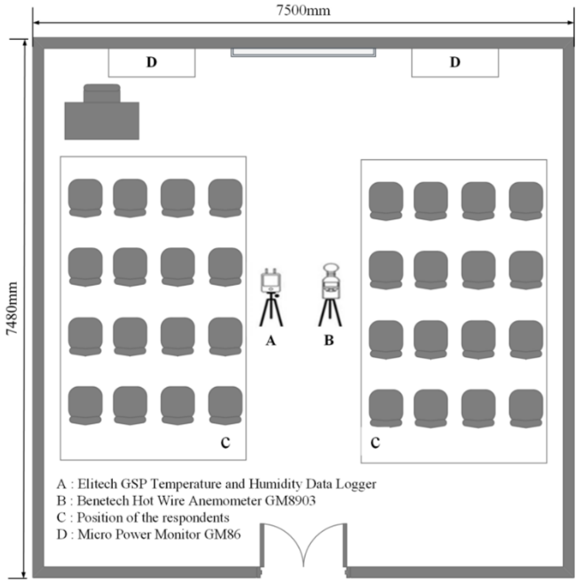

Figure 1. Layout measurement for data collection in classroom

Figure 2. Data collection conditions in classroom

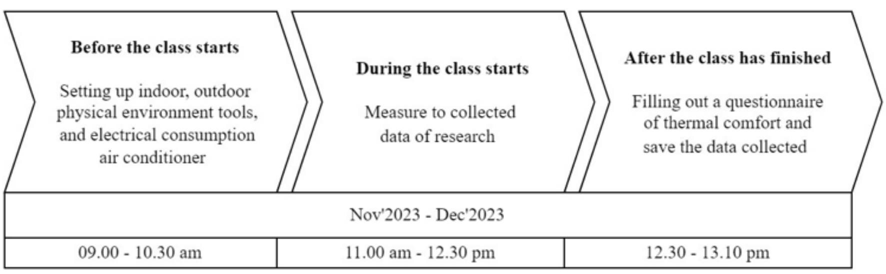

Figure 3. Procedure of data collection

During the class, continuous monitoring of environmental parameters was conducted to gather accurate data on thermal comfort. After the class, participants completed a detailed questionnaire on their thermal comfort experiences. Data collected were then securely stored for analysis. Figure 3 provides a technical illustration of the data collection process, offering a visual guide to the various stages and methods employed.

2.4 Analysis of data

The Griffiths method is a calculation used to determine the level of comfortable temperature. The coefficients used in this method are 0.25, 0.33, 0.40, and 0.5 [6]. This calculation finds the minimum, maximum, average, and standard deviation values. To predict the thermal comfort temperature for each participant based on TSV votes, we used the Griffiths method with Eq. (1) [21]:

$$Tc = \mathrm{T}_a + \frac{0 - \mathrm{TSV}}{\propto} \quad (1)$$

where, TSV – Thermal Sensation Vote, TC – thermal comfort, Ta – thermal acceptability. The Griffiths method in the calculation process uses indoor air temperature ($T_{a\ in}$) and TSV in the regression model to correlate the results of the Thermal Sensation Vote with $T_{a\ in}$.

The Predicted Mean Vote (PMV) was calculated based on ASHRAE standards using a Microsoft Excel spreadsheet [22] PMV and Predicted Percentage of Dissatisfied (PPD) calculations are performed using Microsoft Excel, incorporating six key thermal comfort factors: indoor air temperature ($T_{a\ in}$), indoor relative humidity ($R_{h\ in}$), indoor air velocity ($A_{v\ in}$), metabolic rate (met), clothing insulation (Clo), and mean radiant temperature (MRT). The ASHRAE scale is utilized, which includes the following categories: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (1), warm (2), and hot (3). These factors and scales provide a comprehensive framework for evaluating thermal comfort levels and predicting occupants' satisfaction within indoor environments.

Regression analyses were conducted to examine the correlation and linearity between TSV, TP, TC, TA, and indoor physical environment factors such as indoor air temperature ($T_{a\ in}$), relative humidity ($R_{h\ in}$), air velocity ($A_{v\ in}$), and individual conditions of clothing insulation (Clo). Probit regression was used to determine the neutral temperature (T_n) [21]. This analysis was performed in Microsoft Excel utilizing the XL-STAT add-in tool [22].

3. RESULTS

3.1 Thermal Sensation Vote (TSV)

The subjective thermal comfort variables in this research include Thermal Sensation Vote (TSV), Thermal Preference (TP), Thermal Comfort (TC), and Thermal Acceptability (TA). Measurements were taken by distributing a thermal comfort questionnaire after each class session. A total of 121 data points were collected for these thermal comfort factors.

Based on individual conditions, the mean clothing insulation was 0.52 Clo. For respondents seated in the front of the class, the average core body temperature (T_{core}) was 36.98°C, while the average skin temperature (T_{skin}) was recorded. For those in the back row, the average core body temperature was 33.07°C and the average skin temperature was 34.14°C. The mean radiant temperature (MRT) measured each week was 29.16°C, 29.18°C, 29.10°C, and 29.27°C, respectively.

Thermal Sensation Vote (TSV) scale ranges from hot (+3) to cold (-3). The results show in Figure 4 indicated that 3 respondents (2%) voted hot, 4 (3%) voted warm, 14 (12%) voted slightly warm, 20 (17%) voted neutral, 41 (34%) voted slightly cool, 28 (23%) voted cool, and 11 (9%) voted cold. Thermal Preference (TP) was assessed on a scale with three indicators: prefer to decrease (+1), just right (0), and prefer to increase (-1). The results show in Figure 5 that 14 respondents (12%) preferred to decrease the temperature, 33 (27%) felt the temperature was just right, and 74 (61%) preferred an increase. Thermal Comfort (TC) was measured on a scale from very comfortable (+3) to very uncomfortable (-3). The results show in Figure 6 revealed that 7 respondents (6%) felt very comfortable, 69 (57%) felt comfortable, 27 (22%) felt slightly comfortable, 15 (12%) felt slightly uncomfortable, 3 (2%) felt uncomfortable, and none felt very uncomfortable. Thermal Acceptability (TA) had two main scales: acceptable (0) and unacceptable (+1). The results show in Figure 7 that 116 respondents (97%) found the conditions acceptable, while 5 (3%) found them unacceptable. The way that section titles and other headings are displayed in these instructions, is meant to be followed in your paper.

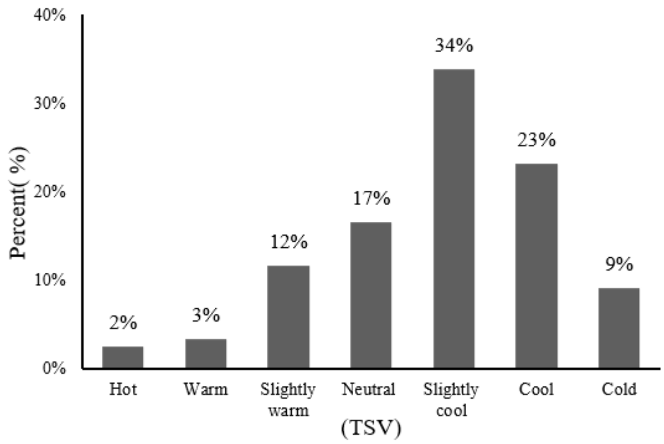

Figure 4. Thermal Sensation Vote

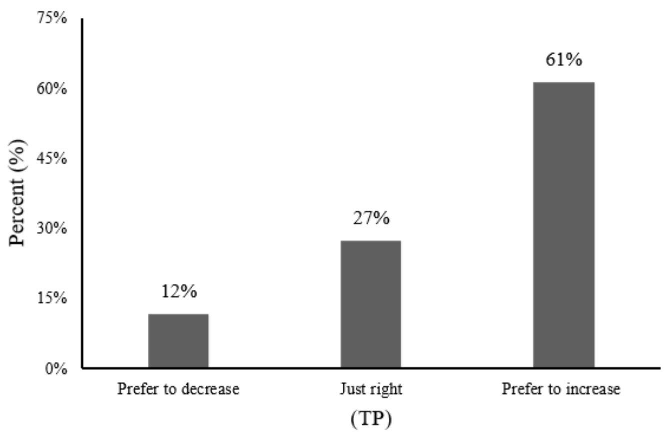

Figure 5. Thermal preference

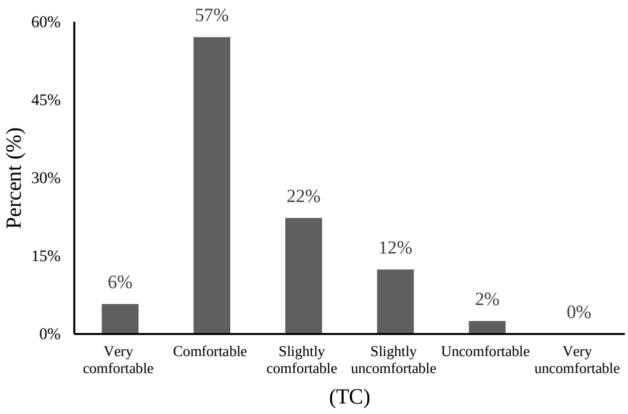

Figure 6. Thermal comfort

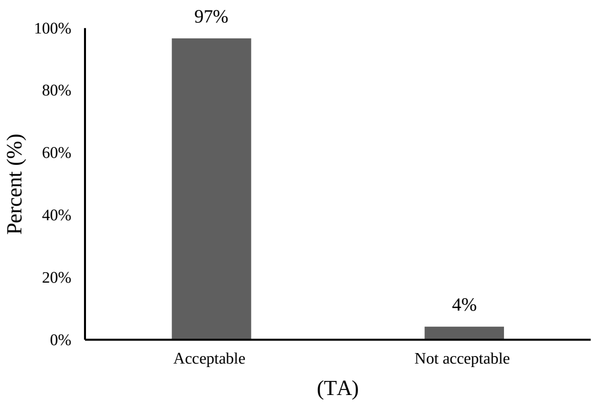

Figure 7. Thermal acceptability

3.2 Physical environment

The indoor physical environment measurements included air temperature ($T_{a\ in}$), relative humidity ($R_{h\ in}$), and air velocity ($A_{v\ in}$). For the outdoor physical environment, air temperature ($T_{a\ out}$) and relative humidity ($R_{h\ out}$) were recorded. The measurement results can be seen in Table 2. A total of 72 data points were collected for both ($T_{a\ in}$) and ($T_{a\ out}$), 70 data points for ($R_{h\ in}$), 72 data points for ($R_{h\ out}$), and 85 data points for ($A_{v\ in}$). Clothing insulation measurements were obtained from respondents by having them complete a questionnaire at the end of the lesson. Additionally, core body temperature and skin temperature were measured for two respondents seated in the front and back rows of the classroom.

Table 3 reveals insights into how the physical environment impacts thermal comfort perceptions among students. The analysis highlights several significant correlations. Notably, indoor air temperature ($T_{a\ in}$) has a positive relationship with Thermal Sensation Vote (TSV), with a coefficient of 0.279 and a significance level of 0.002, indicating that as the indoor temperature increases, students tend to perceive it as warmer. Conversely, there is a negative correlation between indoor air temperature and thermal comfort with a coefficient of -0.186 and a significance level of 0.041, suggesting that higher temperatures might reduce students' comfort levels.

Furthermore, indoor air temperature also negatively correlates with Thermal Acceptability (TA), with a coefficient of -0.348 and a highly significant p-value of 0.000, indicating that higher temperatures are less likely to be deemed acceptable by students. Additionally, indoor relative humidity shows a positive correlation with Thermal Sensation Vote (TSV), with a coefficient of 0.190 and a significance level of 0.037, suggesting that increased humidity levels are perceived as contributing to the warmth.

Table 4 presents a comprehensive overview of the average comfort temperatures calculated using various Griffiths constants. With a constant of 0.25, the mean comfort temperature was higher at 28.79℃, but with a much larger standard deviation of 5.30℃, indicating greater variability. Similarly, a constant of 0.33 yielded a mean temperature of 28.00℃ with a standard deviation of 4.00, while a constant of 0.40 resulted in a mean of 27.56℃ and a standard deviation of 3.29. Using a Griffiths constant of 0.50℃, we found that the average comfortable temperature was 27.16℃, accompanied by the smallest standard deviation of 2.64 among all the constants tested. The calculation of comfortable temperature initially uses a Griffiths constant of 0.5℃. Fanger's experiments also explain that when the Griffiths constant is 0.33℃ for regression (Thermal sensitivity), all other variables are considered the same for occupants with a clothing insulation value of 0.6 Clo. Clearly, the 0.50 constant not only provides the most accurate mean temperature but also ensures the least variation, making it the optimal choice for assessing thermal comfort.

Table 2. Thermal environment conditions of the surveyed classroom

	$T_{a\ in}$ (℃)	$R_{h\ in}$ (%)	$A_{v\ in}$ (m/s)	$T_{a\ out}$ (℃)	$R_{h\ out}$ (%)
Mean	25.53	61.29	0.04	32.72	59.43
Maximum	26.58	65.57	0.07	33.91	67.88
Minimum	24.31	57.28	0.05	29.1	54.79
SD	0.26	2.13	0.01	1.12	5.12

Notes: 1. $T_{a\ in}$: Indoor air temperature, 2. $R_{h\ in}$: Indoor relative humidity, 3. $A_{v\ in}$: Indoor air velocity, 4. $T_{a\ out}$: Outdoor air temperature, 5. $R_{h\ out}$: Outdoor relative humidity.

Table 3. The relationship correlation

Variable	Coefficient	Sig.	Description
$T_{a\ in}$: TSV	0.279**	0.002	Significant relationship
$T_{a\ in}$: TC	-0.186*	0.041	Significant relationship
$T_{a\ in}$: TA	-0.348**	0.000	Significant relationship
$R_{h\ in}$: TSV	0.190*	0.037	Significant relationship

Notes: 1. * means p < 0.05, 2. ** means p < 0.01

Table 4. Average comfort temperature (℃)

Constanta	Min	Max	Mean	Standard Deviation
0.25	14.42	38.55	28.79	5.30
0.33	17.33	35.64	28.00	4.00
0.40	18.92	34.05	27.56	3.29
0.50	20.42	32.55	27.16	2.64

Table 5. Percentage of thermal sensation in probit regression

TSV	Equation*	Indoor Air Temperature $T_{a\ in}$ (°C)					
		Mean	S.D	N	R^2	SE	P
≤ -3	$P(\leq -3) = -0.321\,Ta(in) + 6{,}798$	21.17	3.11	121	0.535	0.099	< 0.001
≤ -2	$P(\leq -2) = -0.321\,Ta(in) + 7{,}712$	24.02					
≤ -1	$P(\leq -1) = -0.321\,Ta(in) + 8{,}614$	26.83					
≤ 0	$P(\leq 0) = -0.321\,Ta(in) + 9{,}165$	28.55					
≤ 1	$P(\leq 1) = -0.321\,Ta(in) + 9{,}855$	30.70					
≤ 2	$P(\leq 2) = -0.321\,Ta(in) + 10{,}281$	32.02					

Notes: 1. P(≤) is the probit of proportion of the votes that are 1 and less, and so on, 2. S.D: standard deviation, 3. N: number of sample, 4. R^2 (*cox and snell*), 5. Determination coefficient, 6. SE: Standard error of the regression coefficient, 7. * means regression coefficient is significant ($p < 0.001$)

3.3 Neutral Temperature (T_n)

Table 5 presents the calculation results using probit regression for various Thermal Sensation Vote (TSV) thresholds. For example, to calculate the mean air temperature (°C) for TSV (< -3), we use the formula |6.798/-0.321|, resulting in a mean temperature of 21.17°C. To determine the standard deviation (SD), which is the reciprocal of the probit regression coefficient within a cumulative normal distribution, we use the formula |1/-0.321|, yielding a standard deviation (SD) of 3.11°C. These calculations provide crucial insights into the relationship between air temperature and thermal sensation, facilitating a better understanding of thermal comfort levels.

3.4 Regression of predicted mean vote (PMV)

The PMV equation provides an assessment according to the ASHRAE thermal sensation scale, where a PMV value of zero (0) represents the optimal condition for occupants as shows Figure 8. A negative PMV value indicates that the environment feels cool to cold, while a positive PMV value suggests a warm to hot environment. The average PMV values were 0.48 in the first week, 0.55 in the second week, 0.90 in the third week, and 0.59 in the fourth week. Correspondingly, the PPD values were 10.8%, 12.1%, 22.8%, and 16.3%. The PMV and PPD calculations indicated a consistent increase from the first week to the third week, followed by a decline in the fourth week. These variations highlight the dynamic nature of thermal comfort perceptions over time.

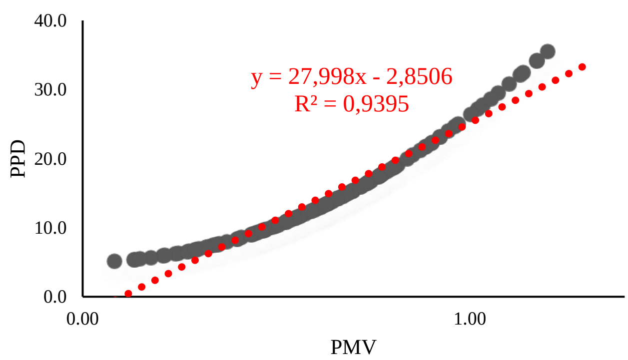

Figure 8. Linear regression PMV and PPD

3.5 Energy consumption of AC usage

Power consumption (in watts) was measured every Thursday over a four-week period. Data collection involved recording power usage both before and after each class session, followed by calculating the average consumption for each day. The average power consumption over the four-week period was as follows: 1604.75 watts during the first week, 1552.25 watts during the second week, 1613.65 watts during the third week, and 1526.7 watts during the fourth week.

4. DISCUSSIONS

Based on the subjective thermal comfort conditions, 74% of respondents rated their thermal sensation from neutral (0) to slightly cool (-2), while 12% and 9% of respondents felt slightly warm (+1) and cold (-3), respectively. Less than 5% of respondents reported feeling hot (+3) or warm (+2). Similar studies have shown that about 87% of respondents chose the three central options (-1 to +1), indicating that despite higher temperatures in the classroom, most students still felt comfortable [22]. As indoor air temperature ($T_{a\ in}$) increases, fewer occupants report cold sensations, while more report warm sensations [23]. According to Guevara et al. [24], 51% of occupants indicated their situation as comfortable, and over 71% the slightly cooler. Although most respondents preferred slightly cool conditions, they still felt comfortable in the classroom environment.

The results of Thermal Preference (TP) suggest that the air temperature needs to be adjusted, as most respondents preferred a cooler room. In a related study, 78% of occupants felt comfortable, while 47% felt slightly warm, and 37% felt no change [24]. Another study found that more than 80% of respondents found the room conditions acceptable, with only 20% finding them unacceptable [22].

The physical environment conditions revealed that the overall average indoor air temperature ($T_{a\ in}$) was 25.52°C. The average ($T_{a\ in}$) varied from 24°C to 26°C, but in the first and third weeks, it exceeded the threshold value, though the deviation of less than 1.0°C was still acceptable [25]. In contrast, the average outdoor air temperature ($T_{a\ out}$) was 35°C and can impact to discomfort reduce performance [26]. The average relative humidity outside ($R_{h\ out}$) ranged from 54% to 67%, within the maximum limit of 70%. However, high relative humidity can affect human health, contributing to allergies and respiratory issues [27].

Comfort level criteria for air velocity (A_v) are categorized into three indicators: comfortable (0.00-0.50 m/s), less comfortable (0.50-1.00 m/s), and uncomfortable (1.00-1.50 m/s) [27]. In this study, the indoor air velocity ($A_{v\ in}$) remained within comfortable limits, below 0.50 m/s. Clothing insulation measurements showed that 8% of respondents were in the 0-0.3 Clo (slimmer doming) category, 41% in the 0.31-0.5 Clo (summer doming) category, 41% in the 0.51-0.70 Clo (spring clothing) category, and 9% in the 0.71-1.30 Clo (winter clothing) category. The optimal clothing combination includes long pants, t-shirts, jackets or shirts, and shoes.

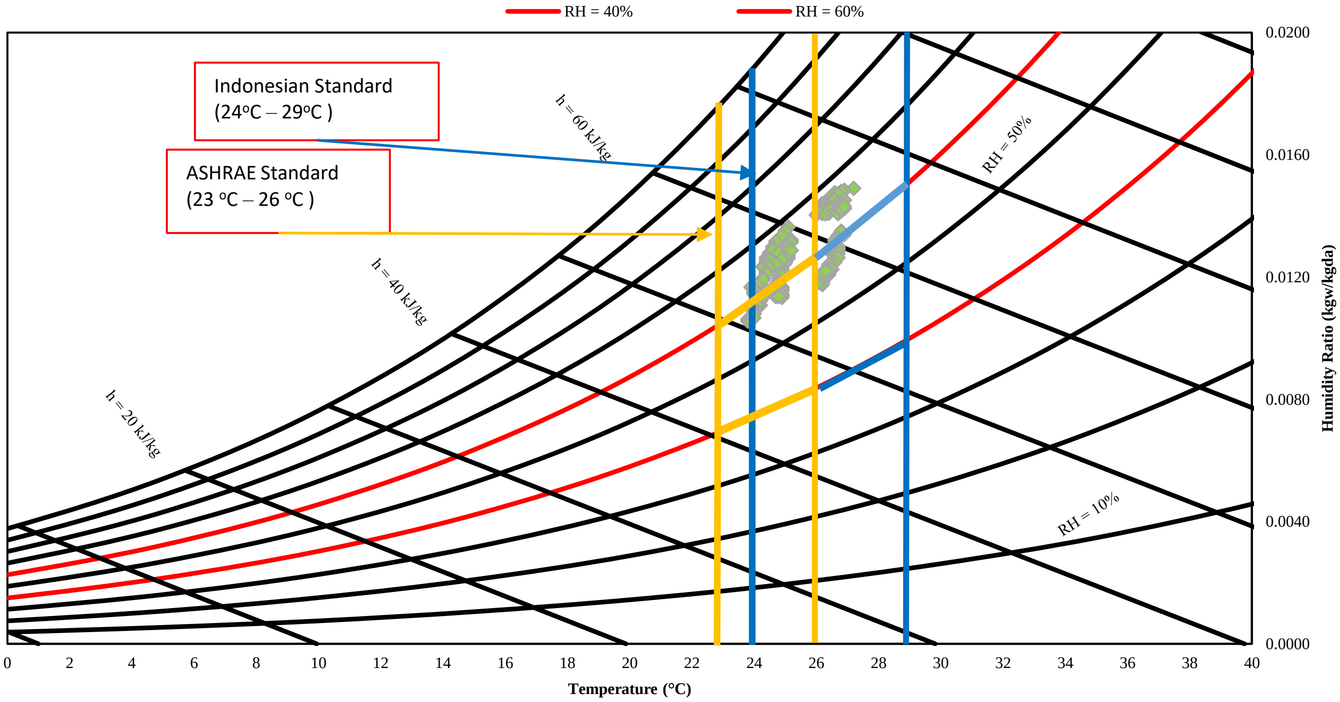

Figure 9. Psychometric chart

The Griffiths method has been widely used to calculate comfort temperatures in various studies [28]. This method employs indoor air temperature ($T_{a\ in}$) and Thermal Sensation Vote (TSV) in a regression model to correlate thermal sensation results with ($T_{a\ in}$). The average classroom air temperature was 25.52℃, which is 1.64℃ lower than the Griffiths constant comfort temperature of 27.16℃. These findings align with [29], who found a preference for a comfortable air temperature of 24.5℃, 2.8℃ lower than the measured comfortable temperature of 27.3℃. This discrepancy is attributed to occupants' preference for cooler temperatures due to the use of AC, even though they may feel comfortable at higher temperatures [30]. When the neutral condition TSV (≤ 0) was considered, the average temperature was 28.55℃, within the thermal comfort standard range of 24-29℃ [31]. Probit regression analysis in identifying neutral temperature is crucial for understanding thermal comfort assessment, analyzing occupant adaptation, and assessing external influences on building thermal comfort [29].

The psychrometric chart is a standard tool for designing and evaluating thermal comfort systems according to ASHRAE standards [32]. The x-axis represents the indoor air temperature ($T_{a\ in}$) data collected over four weeks, while the y-axis shows the humidity ratio calculated from indoor relative humidity ($R_{h\ in}$) and ($T_{a\ in}$). As depicted in Figure 9, the red curved line indicates the maximum tolerance limit for *r*(40-60%) as per Indonesian standards [31]. The yellow vertical lines mark the ASHRAE standard temperature range (23-26℃), and the blue vertical lines represent the Indonesian standard temperature range (24-29℃). Despite some data points exceeding the 60% humidity limit, the overall trend remains within the optimal temperature ranges, highlighting effective climate resilience in the classroom environment.

Based on Figure 8, there is a strong positive relationship between Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD). This is supported by thermal comfort research using AC ventilation, which shows a strong positive correlation between PMV and PPD with a coefficient of R^2 = 0.992 [33]. Additionally, studies with a neutral temperature of 25.5℃ have an R^2 value of 0.940, indicating that 80%-90% of thermal acceptance falls within the ranges of -0.5 to 0.5, and -1 to 1 [24]. The timing of data collection also impacts PMV and PPD values; PMV tends to be neutral to slightly warm in the morning and slightly warm in the afternoon and evening. Therefore, the PMV and PPD results in this study still represent ideal conditions, as the data collection duration accounts for temperature variations between morning and afternoon.

The correlation between physical environment variables and thermal comfort questionnaire results indicates that lower air temperatures decrease perceived thermal comfort. Previous research has shown that outdoor temperature and relative humidity has an indirect impact on occupant's comfort [34]. Geographical location and urbanization also play a role, as exposure to air temperatures and clothing styles impact thermal comfort [35].

The effectiveness of electrical energy consumption is generally influenced by the air conditioning load [8]. The cooling load, defined as the heat flow rate required to maintain desired indoor conditions, increases with higher cooling demands. Previous research indicates that effect of change in based on outdoor temperature result in increased heat absorption by the evaporator, leading to heavier refrigerant circulation and increased electrical energy consumption [36]. The weekly energy consumption of the AC system was 2.407 kWh in week-1, 2.328 kWh in week-2, 2.420 kWh in week-3, and 2.290 kWh in week-4. Corresponding electrical energy costs were IDR 22,848, IDR 21,067, IDR 21,900, and IDR 20,720, respectively. Mixed-mode ventilation, combining AC with natural ventilation, can achieve energy savings of 3.1-70.6% [37]. These findings highlight the potential for energy-efficient and climate-resilient building designs that optimize energy consumption while maintaining thermal comfort. For comparison, in many tropical countries, buildings often consume a significant portion of their energy for air conditioning due to the hot and humid climate. For instance, in Malaysia, office buildings typically have air conditioning systems consuming between 40% and 60% of the building's total energy consumption. Similarly, studies in Singapore and Thailand reveal substantial energy use attributed to air conditioning, often accounting for up to 50% of a building's total energy consumption [38].

Calculation of thermal comfort levels in this study used PMV and PPD approaches. PMV calculation model assumes that standardized individuals with metabolic rate, body composition, and a sensitivity to heat. Despite this, individuals show marked physiological variation [25]. For example, people with a higher basal metabolic rate, which is the energy the body uses at rest, tend to generate more heat and may feel the temperature in the same environment is cooler compared to people who have a lower metabolic rate. Environmental factors as a parameter of thermal comfort assessment have a very significant role. Equatorial climate conditions can result in consistently high temperature increases throughout the year, with typical averages ranging from 25℃ to 33℃ and minimal seasonal fluctuations [39]. The effect will indirectly affect human thermal comfort conditions, especially when indoors. Research related to calculations using comfort temperature with FR mode shows the following results 24.5℃ (standard deviation 2.7℃; 95% confidence limits were 24.3℃ and 24.6℃), This similar to previous studies for natural ventilation during the off-season. However, the results of the CL model show an increase of 27.4℃ (SD=3℃; 95% confidence limits were at 27.1℃ and 27.7℃) [40]. When compared to this study, the results of the comfort temperature calculation mode show 27.16℃. The comfort temperature value has almost the same result as the cooling mode (CL). This indicates that differences in climate conditions with either FR or CL mode settings will result in significant thermal comfort levels. The difference between TSV and PMV is smaller, ranging from 1 point for the lowest operating temperature to 0.1 point for the highest operating temperature. Although a greater similarity between the average PMV and the average TSV is observed when considering CL mode conditions, the PMV index is still not a good predictor of the actual TSV [40]. Thermal comfort assessment from quantitative calculations shows that the objectivity of comfort levels is still not clearly predictable, the results explain that although there is a tendency towards cooler environments regarding preferences, the conditions of flexibility are greater regarding indoor conditions. In addition, the consideration of higher outdoor classroom temperatures does not necessarily indicate that individuals do not want a change in indoor temperature or only want it to change slightly. This fact can be proven in warmer regions, individuals can easily adapt to a wider range of indoor temperatures during the unheated season or with variations in indoor temperature [41].

Figure 10 compares the comfortable temperatures from this study with similar research in Indonesia. Two classroom studies reported comfortable temperatures of 26.5℃ and 27℃ [42, 43]. Office building studies reported comfortable temperatures of 23.61℃ and 26.4℃ [23, 34], while one residential study reported 23.1℃ [44]. This study found a comfortable temperature of 27.16℃, slightly higher than some studies but consistent with others, particularly office buildings using similar ventilation types.

These findings emphasize the importance of adaptive thermal comfort strategies and energy-efficient designs in creating climate-resilient educational buildings. By optimizing indoor temperatures and humidity levels, we can create environments that not only enhance thermal comfort but also improve energy efficiency. This approach ensures that educational spaces remain conducive to learning despite the challenges posed by climate change. The use of adaptive methods such as the Griffiths method allows for precise adjustments to indoor environments, fostering resilience and sustainability in building design. By prioritizing thermal comfort and energy efficiency, we can better prepare educational institutions to withed the impacts of a changing climate while promoting the health and productivity of occupants.

Climate change in Indonesia has been marked by an increase in surface air temperatures, precipitation change, sea surface temperature rise, sea level rise, and extreme climatic events. This risk is further magnified by changing weather patterns, which extend the length of the wet season and increase the intensity of the dry season, which results in more frequent droughts. The previous analysis provides a broad overview of hazard risk across Semarang [3]. Developing a comprehensive response to climate change vulnerability, however, requires more than examining the geography of hazard risk. It also requires a closer examination of what vulnerability looks like in those areas that have the highest risk for particular hazards.

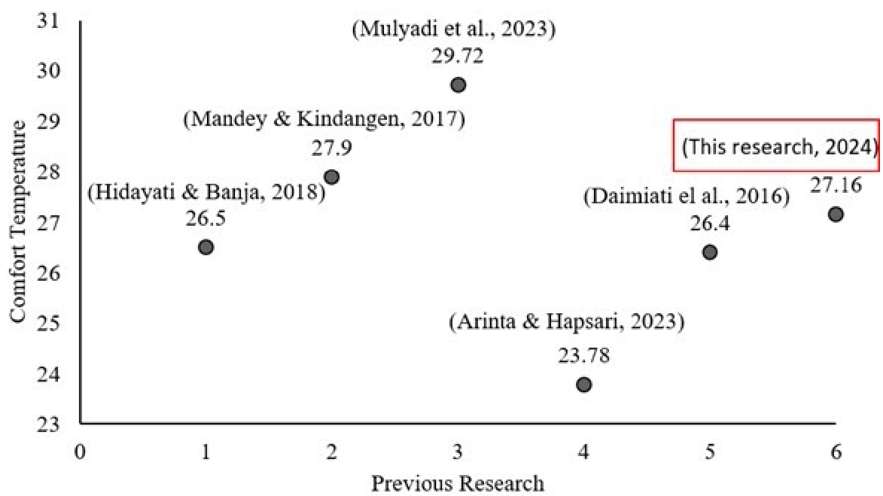

Figure 10. Previous research comfort temperature (℃) with current research

This study, the geographical conditions of Semarang City indicate a consistent change and increase in temperature that affects the adaptation of individual life adjustments. Air temperature conditions that are outside the control limits make individuals will adjust their environment by using various alternatives such as the use of natural ventilation or indoor air conditioners. This condition is also influenced by the physical properties of the building that is occupied. Research in the Industrial Engineering Building, Diponegoro University contains glass material as the main component. The use of glass material makes an increase in indoor air temperature associated with solar heat gain which will affect thermal comfort and expenditure of electrical energy consumption. The challenge of climate change that is consistently increasing year by year has a significant effect on thermal comfort to be the main factor of individual satisfaction regarding thermal comfort.

5. CONCLUSIONS

This study, conducted in focus on evaluation thermal comfort classroom, determine the neutral and comfortable temperature, and assess the electrical energy consumption associated with AC usage. The main findings are summarized as follows.

Evaluation of thermal comfort in this study showed that 93.95% of room occupants feel comfortable conditions through the calculation of PMV and discomfort conditions felt by the occupants of the room is an average of 10%. Calculation of PMV and PPD is not fully the final result in evaluating thermal comfort because there are other factors that can not be controlled, believing that although residents feel comfortable conditions at higher temperatures, there is a preference for cooler temperatures due to the use of air conditioning.

The measurement of comfortable temperature reaching 27.16℃ shows that the subjective calculation is different from the reality of the occupants in the classroom. In conditions where the air temperature outside the room is hotter, indoor occupants will make adjustments to regulate comfortable temperature conditions using air conditioning, while probit regression is used to determine how the correlation between TSV and air temperature. The results of the neutral temperature are quite different from the comfortable temperature, when the TSV ≤ 0 condition the average neutral temperature is 28.55℃. The difference is because the neutral temperature measurement considers aspects of the physical environment and subjectivity related to the Thermal Sensation Vote. Further calculations related to the correlation test were also carried out in this study. The findings explain the indication that when indoor air temperature increases, residents tend to think it is warmer. Conversely, when the temperature is higher, it turns out to reduce the comfort level of residents.

Energy consumption findings highlight the potential for energy-efficient and climate-resilient building designs that optimize energy consumption while maintaining thermal comfort. The importance of adaptive thermal comfort strategies and energy-efficient design in creating climate-resilient educational buildings.

Limitations in this study are the duration of data collection and the use of measurement tools. In future research, researchers can consider a longer duration of data collection and the addition of research focus not only to evaluate, but also to simulate more continuous improvement. In addition, researchers can also develop by conducting real measurement related to the calculation of thermal comfort levels using the application.

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