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Original Research Article

Thermal Comfort and Cognitive Performance under Glass Facade Buildings

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Abstract
Glass is one of the most adaptable modern materials. However, the use of glass can have unfavorable effects such as glare, heat, and discomfort. This study focuses on the issue of designing contemporary glass buildings and facades in humid tropical environments to evaluate the thermal comfort of building occupants and assess its effects on the completion of cognitive tasks. The Wet-Bulb Globe Temperature (WBGT) parameter was used to measure thermal comfort, and the ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) scale was used to assess thermal comfort perception. The Montreal Cognitive Assessment was used to assess eight female respondents' cognitive abilities, and the cut-off point was 26. The WBGT has a temperature range of 25, 54°–28, 83°C, in terms of thermal sensation, 54% of respondents feel hot and 62% are uncomfortable. In the completion of cognitive tasks, 75% received a score of less than 26. The results show that there is an effect of thermal comfort on cognitive performance. Due to respondents feeling uncomfortable in high-rise buildings with glass facades, as well as with cognitive outcomes that are below the cut-off point, recommendations for improvement are needed to increase thermal comfort, such as double glass facades.

Keywords: Glass facade; tropical humid; internal environment; thermal comfort; cognitive performance

1. Introduction

Glass achieves the highly desired freedom from enclosed space by virtually integrating the outdoors into the interior. Glass connects the space, enhances the quality of the space, and transmits enough light whether it used for windows, facades, or interior partitions (Savi et al., 2013). The use of glass influenced by the climate: in hot climates, too much sunlight is undesirable; in cold climates, winter heat control is an imperative factor (Butera et al., 2014). Appropriate glass selection, raising the sky angle, modifying the shape and position of the windows, or selecting very light colors for the walls and ceiling are essential considerations. Higher infiltration and exfiltration rates through the building envelope, increased air movement across thermal flow channels, and low occupant comfort levels can all be caused by poorly performing facades (Cammelli & Mijorski, 2016). The low thermal conductivity due to thinner walls and the use of non-local building materials such as concrete in modern homes create higher temperature variations (Ariffin et al., 2018). Studies have shown that when people are dissatisfied with their indoor environment, it has an impact on their comfort, health, and productivity (Al et al., 2016). The thermal comfort of building occupants will be impacted by the local climate. Individual differences are explored using causal factors such as gender, age, and so on. There are no clear and consistent results about the magnitude and relevance of inter-group differences in thermal comfort between females and males, or the young and the old (Z. Wang et al., 2018).

Since occupants expend energy and concentration striving to compensate for a lack of environmental comfort rather than concentrating on their core activity (Roskams & Haynes, 2019). Thus, improving Indoor Environmental Quality (IEQ) can boost productivity by 0.5% to 5% (Lamb & Kwok, 2016). Aside from offering comfort to its residents, buildings must also be energy efficient and environmentally conscious (Bellia et al., 2020). In addition to saving energy, indoor thermal environments can maximize worker productivity and thermal satisfaction (Kawakubo et al., 2023). It is difficult to accomplish energy savings without compromising acceptance of the indoor environment since people from diverse climates cannot share a consistent perception, expectation, or acceptance of the thermal environment.

The air temperature in Semarang City, Central Java, reaches 34.1°C, and in 2021 Semarang will become the hottest city in Indonesia according to the Meteorology, Climatology and Geophysics Agency (Harmoko & Putri, 2021). There is little attention shown to designing modern buildings that has glass facades according to the climate, or the architectural character of a country, especially countries that are different from European countries, as the concept of using glass facades in buildings will have an impact on the internal environment of the building (Ahmed et al., 2019). Current research is only on the thermal comfort of occupants of buildings that have glass facades, but little has measured the cognitive function of occupants of these buildings, especially buildings whose purpose is as places of learning such as universities. The studies of thermal comfort in educational facilities are completed for various reasons, including those related to energy use, learning processes, well-being, and health. Where As previously stated, the concept of using glass facades in buildings will have an impact on the internal environment of the building, and an uncomfortable indoor environments have an impact on participants' motivation and learning process, as well as their ability to focus, learn, memorize, and think until completing test (Guevara et al., 2021).

The concept of modern architecture has been applied in various sectors, one of which is in the construction of lecture buildings that have begun to adapt modern architecture. The research was conducted at industrial engineering buildings, Diponegoro University, Semarang, Indonesia. The building adapt modern architectural designs, where the walls of the building use glass. The building has a facade that is dominated by glass, so it is necessary to measure the thermal comfort and performance of the occupants of the building. The construction of buildings with glass walls will reflect heat radiation from the sun so that the area around the building will experience increased heat (Butera et al., 2014). Glass has become one of the most important innovations in human history related to building technology. Climatic considerations influence the usage of glass; in cold climates, winter heat control is critical, but in warm ones, much sunlight is undesirable. Based on the results of a preliminary study on an industrial engineering building that has a glass dominant façade, WBGT measurements were taken from 8 a.m. to 4 p.m. on weekdays. The WBGT value obtained is 24°C-29.9°C with a temperature of 30,2°C-36,9°C. Where the temperature increases from 11 a.m. to 2 p.m. The highest WBGT value occurred at 2 p.m. As a result, the goal of this study is to evaluate thermal comfort in buildings with glass dominant facades by measuring WBGT as an objective measurement and using the ASHRAE scale to determine thermal comfort perception. In addition to thermal comfort, it's imperative to know if the occupants of modern buildings affect cognitive function, which was measured using the Montreal Cognitive Assessment in this study. The performance decreased by around 1% for every 1°C increase in temperature in the 24-32°C range (Wargocki et al., 2019). The performance decreased by around 1% for every 1°C increase in temperature in the 24-32°C range (Wargocki et al., 2019).

The MoCA assesses a variety of cognitive domains. Visuospatial/Executive, Naming, Memory, Attention, Language, Abstraction, Delayed Recall, and Orientation are among them about time and place (Hobson, 2015). On the other hand, the MoCA test has high sensitivity and specificity for MCI screening. This is because usually a sensitive test requires examination for a long time, which is unpleasant for

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respondents. Meanwhile, the time needed to complete the MoCA test is only about 10 minutes. The conclusion that can be drawn is that the MoCA test is an easy, fast, and accurate cognitive examination for screening. The MoCA test comes from a different culture than Indonesia, so in Husein et al.'s (2010) research, they conducted validity and reliability tests using WHO (World Health Organization) rules so that they could be used in assessing cognitive awareness in the general public in Indonesia. The WHO rules contain the steps that must be taken in validating an intercultural test so that the test can be accepted to be carried out in a country with a different language and culture. Several factors cause MoCA to be superior for detecting MCI (Mild Cognitive Impairment) compared to MMSE (Mini-Mental State Examination). Another study demonstrates that MoCA reflects cognitive reserve and that the MoCA score reflects cognitive reserve more sensitively than the MMSE score (Kang et al., 2018). MoCA has more words in the memory domain, and the ability to recall has a longer duration compared to MMSE. This study is expected to provide recommendations for students on how to increase thermal comfort during the learning process, as well as contribute to students' thermal comfort investigation in the tropics.

2. Methods

Evaluation of thermal comfort is carried out by measuring it objectively and subjectively, as well as the influence of the classroom environment on cognitive task performance. Objective measurements were carried out, including Dry bulb temperature (Tdb), Wet bulb temperature (Tw), black globe temperature (TG) and relative humidity (RH). WBGT is a comprehensive index for assessing heat stress in people exposed to heat. The WBGT index is reported to be simple to learn, and use, and valid for organizing work-recovery regimens (Alfano et al., 2014). This is supported by the findings of Ghani et al, who studied numerous thermal indices and discovered that WBGT is the best index for measuring heat stress in hot and dry environments (Ghani et al., 2021). Beside physical measurements, the subjective response were collected using ASHRAE Scale, such as thermal sensation, thermal preference, thermal comfort, and thermal acceptance (Schweiker, 2019). According to Sun et al., when analyzing the influence of indoor environmental conditions on performance, subjective responses are a useful supplement to objective evaluation (Sun et al., 2020). In addition to the thermal comfort-related questions, a background section gathered information on the participants' country, city, and place of residence. As mentioned before, this research using MoCA to determine student cognitive performance. The MoCA score is calculated by combining points from each finished task ranging from 0 to 30. A higher score suggests better cognitive performance. The highest score is 30, and a score of 26 or more is deemed normal (Hobson, 2015).

Data collection in classrooms on the 2nd floor and 4th floor without using air conditioning (free-running). The determination of the sample was performed using purposive sampling due to the fact that there are inclusion and exclusion criteria in this study. The inclusion criteria in this study were active students, respondents had not traveled of the city in the previous 14 days. Generally, it takes 7 to 14 days for humans to adapt to heat; 75% of physiological adjustments occur in the first 4-6 days of heat exposure (Taylor, 2014). Then the exclusion criteria in this study are students who have CIPA disease. An inherited condition called congenital insensitivity to pain with anhidrosis (CIPA), two characteristics of CIPA include diminished or absent sweating and the inability to feel pain and temperature. Type IV heredity sensory and autonomic neuropathy is another name for this condition. In addition, this study did not select respondents who have a bad lifestyle, such as sleeping less than 7 hours a day and drinking less water.

This research, which is related to physiology, biomechanics, and anthropometry (human physics), generally does not require a large number of samples, and the research results are not much different. Based on several studies that have been conducted, the number of research respondents related to thermal comfort is between eight and eighteen (Sun et al., 2020). Therefore, the number of respondents in this study was eight, as shown in Table 2. A field study conducted in a Doha discovered significant gender differences in thermal comfort (Indraganti & Humphreys, 2021). In Doha, approximately 34% of females voted uncomfortably cold. Females in Doha are 97% more likely than males to say that the thermal environment has an impact on their self-reported productivity. So, this study only included female respondents as previous research has shown that male and female have significantly different thermal comfort.

In this study, the respondents has between 7 and 9 hours of sleep, had no history of illness, and did not smoke. If the respondents experience sleep deprivation, it will affect cognitive function. Activities carried out by respondents in the evening before data collection included doing assignments, having dinner, and playing cellphones. As for activities in the morning before data collection, there are breakfast and online lecture activities. Research conducted by Schrumacher and Sipes states that students who get between seven and eight hours of sleep each night will achieve higher scores on tests related to cognitive functions such as critical thinking, problem solving, and short-term memory (Schumacher & Sipes, 2015). Then the respondents consumed about 1.5 to 2 litres of water per day. According World Health Organization (WHO) guidelines, it is explained that the requirements for fluid replacement in the tropics are equivalent to 4.1 to 6 litres per day. Adequate water intake is determined by age and sex.

Data collection was carried out at peak temperatures, from 11 a.m. to 2 p.m. Based on a preliminary study conducted at the Diponegoro University industrial engineering building with WBGT measurements taken from 8 a.m. to 4 p.m. on weekdays. WBGT value of 24°C–29.9°C with a temperature of 30.2°C–36.9°C Where the highest WBGT value occurs from 11 a.m. to 2 p.m. Therefore, this research was conducted at the highest temperature. The research location and orientation of the Diponegoro University industrial engineering building can be seen in Figure 1.

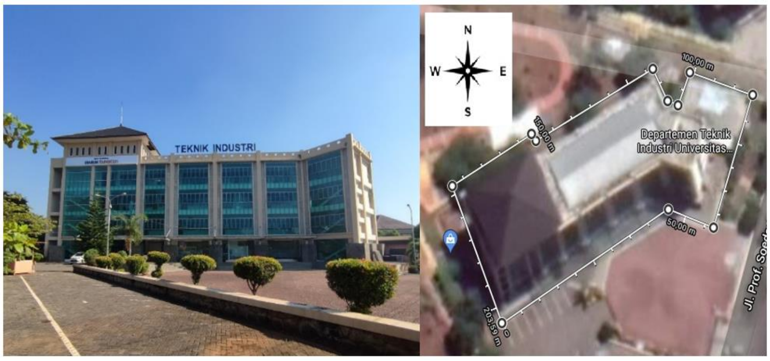

Figure 1. Industrial engineering Diponegoro University building and orientation

Figure 2. Layout of the building on the 2nd and 4th floors

According to other studies, classroom temperature affects students' academic performance (Kwabena & Baafi, 2020). So, this research was conducted on the classroom at the 2nd floor (201 and 204), namely on the west and east sides of the building, because the flat surface facing east or west of the building receives sunlight without wind (Nugroho et al., 2022). Otherwise, conducted in classrooms on the fourth floor (401 and 404) that facing east and west. Observation of objects with different height is due to thermal differences in the height of a building, which have an important role in ventilation performance. This is supported by the findings of Nugroho et al. (2022) that there is a thermal difference with altitude.

Objective data collection uses the Lutron WBGT-208 Meter Heat Index WBGT Meter. Then subjective data is used using the ASHRAE Scale (Table 1). The measurements were parallel by filling out a thermal comfort questionnaire. After that, the respondents were guided to fill out the MoCA to determine the students' cognitive performance. Data collection was carried out in the hot summer, when the dry season and the sun were shining brightly. Because in hot summer, the risk of overheating caused by the greenhouse effect will cause a significant increase in cooling load if the cavity is not ventilated sufficiently or the solar radiation is too heavy. Extremely uncomfortable and will affect the cognitive function of students. The heat transmission that buildings gain in summer is undesirable, especially during the day with high external temperatures (Y. Wang et al., 2020). The schedule for data collection in this study can be seen in Table 2. There were 8 respondents, consisting of respondent 1 (R1), respondent 2 (R2), as well as others.

Table 1. Scale of thermal comfort

Scale	Thermal sensation (TS)	Thermal comfort (TC)	Thermal preference (TP)	Thermal acceptability (TA)
-3	Cold	Very uncomfortable	Much cooler	
-2	Cool	Uncomfortable	Cooler	
-1	Slightly cool	Slightly uncomfortable	Slightly cooler	Completely unacceptable
0	Neutral	Neutral	No change	Just Acceptable
1	Slightly warm	Slightly comfortable	Slightly warmer	Completely Acceptable
2	Warm	Comfortable	Warmer	
3	Hot	Very comfortable	Much warmer	

Table 2. Schedule of Thermal Comfort Measurements

Day	Time	Room 201	Room 204	Room 401	Room 404
Day 1	11.00 a.m. - 14.00 p.m	R1	R2	R3	R4
Day 2	11.00 a.m. - 14.00 p.m	R2	R3	R4	R5
Day 3	11.00 a.m. - 14.00 p.m	R3	R4	R5	R6
Day 4	11.00 a.m. - 14.00 p.m	R4	R5	R6	R7
Day 5	11.00 a.m. - 14.00 p.m	R5	R6	R7	R8
Day 6	11.00 a.m. - 14.00 p.m	R6	R7	R8	R1
Day 7	11.00 a.m. - 14.00 p.m	R7	R8	R1	R2
Day 8	11.00 a.m. - 14.00 p.m	R8	R1	R2	R3

Table 3. MoCA Instrument (Panentu & Irfan, 2013)

Cognitive Domain	Value	MoCA Test
Visuospatial abilities	5	Participants follows the number sequence and draws an object or cube.
Naming	3	Participants say the name of the animal in the picture.
Short-Term Memory	0	Participants repeat some of the words requested two times in a period of five minutes.

Cognitive Domain	Value	MoCA Test
Attention	6	Participants read a list of numbers, tapping their hands whenever the letter "A" appeared in the letters being read out and subtracting operations.
Language	3	Repeat the two prepared sentences. Say as many words as possible that start with the letter S (a minimum of 11 words).
Abstraction	2	Mention the fruitiness of objects such as bananas and oranges.
Working Memory	5	Participants must remember the words mentioned without getting a clue.
Spatial Orientation	6	Participants state the date, month, year, day, place, and city.

The scope of the MoCA-INA (Indonesia) instrument and the points for each task function are explained in Table 3. The MoCA test originates from Canada. This test comes from a country and culture that is different from Indonesia, so Panentu and Irfan (2013) tested it for validity and reliability before being used in the wider community in Indonesia. The MoCA test is very sensitive for screening for mild cognitive impairment. The tests at MoCA include visuospatial abilities, naming, short-term memory, attention, language, abstraction, working memory, and spatial orientation (Panentu & Irfan, 2013).

3. Result

3.1. WBGT Measurements

According to the measurement results, the classroom's highest WBGT value was 28.83 °C. The classroom is located on the fourth floor and faces east. Then for the lowest WBGT value, which is in the classroom on the 2nd floor at 25.54°C, with the orientation of the classroom facing north. As we can see in Figure 1, it can be seen that the average value of WBGT measurements in each classroom, and the highest average WBGT value is in room 404 as the roofs in industrial engineering buildings are flat, so they are different from multistage roofs with ventilation, which can increase indoor comfort in tropical climates (Zune et al., 2020). The average humidity value can be seen in Figure 2, the humidity values obtained ranged from 38.2% to 57.42%, with temperatures ranging from 30.9°C to 35.46°C (Figure 3). The results of these measurements are supported by research conducted by Nugroho et al which concluded that there are thermal differences according to altitude (Nugroho et al., 2022). According to other studies, building height has a significant impact on ventilation performance(He et al., 2019).

Based on the results of the measurements of thermal comfort, respondents felt uncomfortable at a WBGT of 26.05°C–28.83°C due to the temperature exceeds the respondent's comfort WBGT value. According to ASHRAE (Guide for Building in Hot and Humid Climates), comfort for humid tropical areas like Indonesia ranges from 24°C to 29°C (Karyono, 2015). The temperature inside the building ranges from 30.9°C to 35.46°C. Where the average temperature of class 201 is 31.9°C, class 204 is 32.69°C, room 401 is 32.76°C, and room 404 is 34.30°C. The results show that the temperature in the east room (rooms 204 and 404) is hotter than the classroom to the west (201 and 401). Because classrooms 204 and 404 have scads of glass on the walls of the room so that the room temperature becomes higher. Then the room on the 4th floor is hotter than the 2nd floor because the 4th floor is closer to the roof. The roof will absorb a lot of heat so the roof must have good insulation to reduce the heat factor on the top floor of a building (Limb & Balton, 2019).

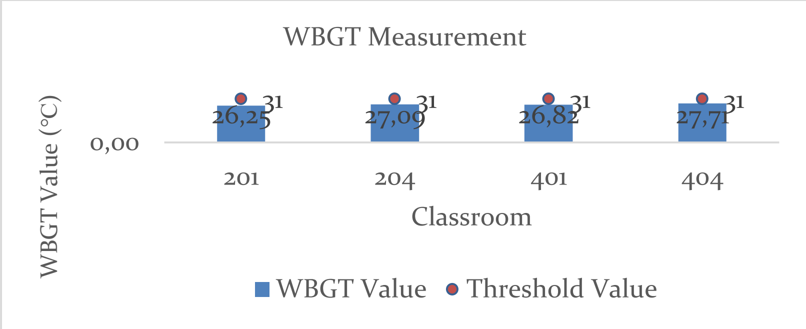

Figure 1. WBGT Measurements

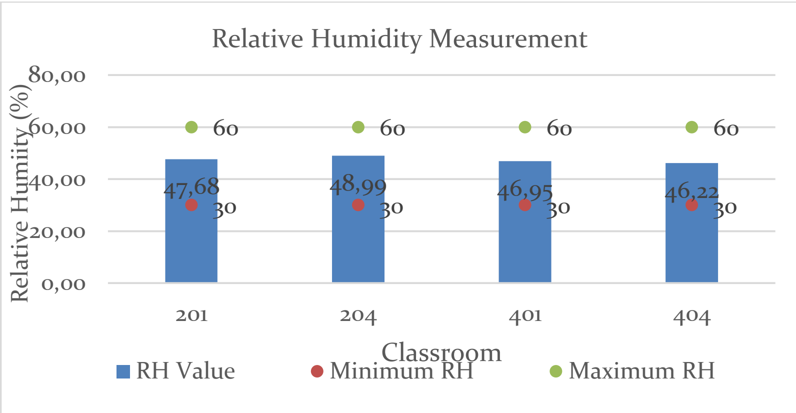

Figure 2. Relative Humidity Measurement

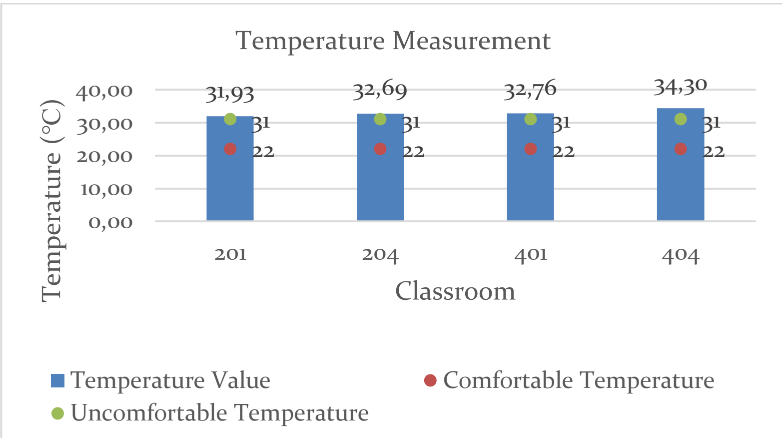

Figure 3. Temperature measurement

3.2. Thermal perception

In the thermal perception felt by respondents, the thermal sensation was obtained by 56% feeling hot, 25% feeling warm, 13% feeling neutral, and 6% feeling slightly warm. Then for thermal preferences, 47% of respondents chose much cooler, 34% cooler, 13% no change, and 6% rather cold. The thermal comfort of respondents in the classroom was rated as uncomfortable by 28%, 34% as very uncomfortable, 22% as slightly uncomfortable, and 16% as comfortable. According to perceptions of thermal acceptance, up to 50% of respondents do not accept thermal conditions in glass-dominated buildings, 28% strongly do not accept, and 22% accept. The neutral temperature range presupposes that the optimal thermal sensation is neutrality (not feeling warm or cold). Then, from the selection of actions taken by respondents, such as opening doors, opening windows, and turning on the air conditioner, they still felt uncomfortable. This is because the building has a dominant material of glass, so sunlight passes through the windows without being filtered, and the glazed facade significantly increases the air temperature in the summer(Freewan, 2014). The thermal adaptation behavior of building occupants, such as opening doors, opening windows, and turning on the air conditioner, is directly related to thermal comfort (Al-atrash, 2018). When occupants experience thermal discomfort, occupant behaviour tends to react to restore thermal comfort in the environment (Langevin et al., 2015). Personal adaptation, technological or environmental adjustment, and psychological adjustment are the three basic categories of thermal adaptive behaviour (Azizi et al., 2018).

3.3. Thermal comfort and cognitive function

The MoCA score is computed by combining the points granted for each task completed on a scale of 0 to 30, with higher scores indicating greater cognitive performance. The maximum score that can be achieved is 30, with a score of 26 or higher considered normal. According to numerous studies, the MoCA cut-off point is 26. The results obtained after carrying out the MoCA assessment were that as much as 75% obtained a score below 26 and as much as 25% obtained a score above 26. Respondents who obtained a score above 26 were in the 2nd floor classroom. Based on cognitive performance measurements, it was found that cognitive performance scores in the executive visuospatial, attention, language, and memory sections did not reach the minimum score. Whereas executive visuospatial consists of number sequences and drawing objects. This is supported by the research of Sukadarin et al. (2016) that there are several temperature differences that will affect performance in terms of the given task (Sukadarin et al., 2016). According to Varjo et al. (2015), sixty-five participants were tested in "Condition A" a neutral temperature (23.5°C) and in "Condition B", a high room temperature (29.5°C). This study provides strong evidence that a high room temperature and a low ventilation rate impair perceived working conditions and cognitive performance (Varjo et al., 2015). The results of this study not only provide insight into the environmental assessment of thermal indoor conditions but also provide some explanation for the importance of further studies on the topic of thermal comfort for both conditioned and free-running spaces. Understanding thermal perception and cognitive function in different classes makes it possible to improve building performance while increasing well-being and productivity.

3.4. Architectural Approach

According to Szokolay (2014), natural ventilation is the best approach in providing indoor thermal comfort for occupants. This strategy offers several advantages to the occupants. The benefits of naturally ventilated buildings include improved thermal comfort and lower operating costs due to changes in indoor air quality (Szokolay, 2014). The easiest effort to control climatic factors to obtain thermal comfort in buildings is by using a mechanical approach such as air conditioning (AC). The second approach is to condition the environment inside the building naturally with an architectural approach. However, as previously explained, mechanical approaches such as the use of air conditioners cannot fully provide comfort in the building, especially in rooms 204, 401, and 404. So an architectural approach is needed as a recommendation to obtain thermal comfort. According to Zheng et al. Indoor environmental indicators such as temperature, relative humidity, and global temperature can be utilized to forecast the opportunity for adaptive behaviour occurring. The implications of building occupant behavior on the use of electricity must be evaluated during the design or post-occupancy optimization phases (Du et al., 2020).

Hot air rising and cold air sinking is a common problem that causes the AC to not reach a cold temperature when the temperature is lowered. So the top floors have a natural tendency to be warmer than the bottom floors. In addition, the roof will absorb a lot of heat, so the roof must have good insulation to reduce the heat factor on the top floor of a building (Limb & Bolton, 2019). The type and color of glass used in the glass facade is an important condition in determining the thermal comfort of building occupants. besides that for visual comfort, indoor environment, and can help show the architectural characteristics of the local area (Ahmed et al., 2019). A double-glazed facade with shading devices reduces cooling energy usage by 2-5% while being 100% transparent. Due to the luminous factor, the glass has a light transmittance value of 1%, an outdoor reflectance of 53%, and an indoor reflectance of 20%. In addition to the energy factor, double glass has a 2% transmittance, a 39% outdoor reflectance, a 37% indoor reflectance, and a 59% absorbance. Glass facades that have multiple layers have an impact on the U value of the facade (Ahmed et al., 2019). Other research has found that using specific shade solutions can enormously reduce energy requirements for summer cooling, both in the entrance hall and indoors. Furthermore, the shade reduces overheating when the air conditioning system is not in use, thereby boosting indoor thermal comfort (Evola et al., 2017).

4. Conclusions

Based on the results of the measurements of thermal comfort, respondents felt uncomfortable at a WBGT of 26.05°C–28.83°C, which was in the industrial engineering building. The temperature in the industrial engineering building ranges from 30.9°C to 35.46°C. Then, from the selection of actions taken by respondents, such as opening doors, opening windows, and turning on the air conditioner, respondents still felt uncomfortable in classrooms 204, 401, and 404. However, the highest discomfort was in room 404, with a WBGT of 27.22 °C. The WBGT value that provides thermal comfort in industrial engineering buildings ranges from 23.18°C to 25.90°C, with a humidity value of 35.3% to 52.18%. The type or color of glass as a building facade plays an important role, especially in terms of thermal, visual, and environmental comfort in the building. The U value of the building facade is affected by the double-layered facade. The addition of shading to the double-facade will also reduce the use of cooling energy in the room by 2-5%. On the other hand, keep the building 100% transparent and viewable. However, in the implementation of the double-facade, it is advisable to face the north side with horizontal shading. This application will help save energy than double shading of no shading facades. The internal environment needs to be optimized by analyzing the sun's path at key times of the year and determining the best geometric configuration for the facade.

The easiest effort to control climate factors to obtain thermal comfort in buildings is by using a mechanical approach such as Air-Conditioning (AC). The second approach is to condition the environment inside the building naturally with an architectural approach. However, as previously explained, mechanical approaches such as the use of AC cannot fully provide comfort in the building. As a result, before making a suitable facade design decision and making a building comfortable for occupants, architects and researchers must carry out a thorough and holistic assessment of the surrounding environment. As a results, it concluded that the architectural approach have proposed as a recommendation to obtain thermal comfort for occupants of buildings that use glass as building walls. Climate analysis and interpretation should be incorporated into the design and fabrication process starting with the conceptual phase through to building construction. Future research and testing of effective shading mechanisms for radiation-susceptible urban buildings is suggested. Different types of glazing, shading devices and effective angles for different orientations should be investigated to develop standard city guidelines that assess prospective facade designs in the city before issuing building permits.

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