THE EFFECTS OF FAÇADE DESIGN AND BUILDING ORIENTATION ON INDOOR AIR TEMPERATURES IN CAMPUS BUILDING: CASE STUDY

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ABSTRACT

As it serves as the outermost layer directly exposed to the surrounding climate, building façade is one of the key factors influencing thermal comfort. Glass is a commonly used facade material in building design due to its ability to allow natural light into indoor spaces and enhance aesthetic appeal. However, if the proportion of glass is not carefully considered in relation to the local climate—particularly the building's orientation to the sun— it can lead to increased indoor temperatures, negatively impacting thermal comfort. This study examines the impact of facade design, specifically the window-to-wall ratio (WWR) and building orientation, on indoor air temperatures in two case study buildings at Institut Teknologi Sumatera: Building E and the General Lecture Building (GKU). Field measurements conducted over six consecutive days, with hourly temperature recordings, showed that GKU consistently maintained lower indoor temperatures than Building E. This was attributed to GKU's north-south orientation and its brick facade with shading elements, which helped minimize solar heat gain. In contrast, Building E, characterized by an east-west orientation, a high WWR, and insufficient shading, experienced higher indoor temperatures and thermal discomfort, even with air-conditioning. These findings highlight the crucial role of facade design in optimizing thermal performance in tropical climates, offering valuable insights for sustainable architectural practices worldwide.

Keywords: *Façade Design, Building Orientation, Indoor Air Temperature, Thermal Comfort, Window-to-Wall Ratio*

INTRODUCTION

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE, 2010) defines thermal comfort as "a state of mind in which an individual feels satisfied with the thermal environment, based on subjective evaluation"

(Hamzah *et al.*, 2018). Based on these definitions, thermal comfort can be understood as an individual's psychological perception of their surrounding environment, where they do not feel excessively hot or cold. (Md Din *et al.*, 2014). Even though staying in the same room, thermal sensations are different among people. People staying in a very similar room condition which having the same climate and have the same culture, issuing different feelings on thermal comfort due to the combination of a several factors which affecting perception (Djongyang, Tchinda and Njomo, 2010).

Although thermal comfort is defined as a state of mind, its assessment is influenced by physical, physiological, psychological, and environmental factors. Since subjective perception of thermal comfort is inconsistent, emphasis is placed on environmental factors to ensure occupant comfort. Various environmental elements influence thermal load, including air temperature, radiant temperature, relative humidity, and air velocity (Marin Restrepo *et al.*, 2023).

The tropical region, situated between the Tropic of Cancer (23°27'N) and the Tropic of Capricorn (23°27'S), is characterized by a hot and humid climate, as illustrated in Figure 1. This area experiences intense solar radiation, extended periods of sunshine throughout the year, high temperatures, and elevated relative humidity levels.

Figure 1. Map of Tropical Countries in Southeast Asia
Source: Google Earth

Based on the 2001 Indonesian National Standard (SNI) (Table 1), the thermal comfort limits effective temperature (TE) for equatorial conditions (are 19℃ (the lower limit) - 26℃ (the upper limit). At 26℃, people start to sweat. Meanwhile the humans' work ability begins to decline at the temperature of 26.5℃ - 30℃. Environmental conditions began to be difficult for humans at a temperature of 33.5℃ – 35.5℃ and no longer possible at a temperature of 35℃ - 36℃.

Table 1. Thermal Comfort Limit

Conditions	Effective Temperature
Cool Comfortable	20,5℃-22,8℃
Threshold	24,0℃
Optimal Comfort	22,8℃-25,8℃
Threshold	28,0℃
Warm Cozy	25,8℃-27,1℃
Threshold	31,0℃

Source: SNI 03-6572-2001

The thermal comfort of a building, which influences energy consumption, is shaped by several factors, including building orientation, ventilation, and the thermo-physical properties of the materials used in the building envelope (Latha et al., 2015; Andhy and Citraningrum, 2019). The building envelope functions not only as a barrier between the indoor and outdoor environments but also as a protective shield against climatic elements such as solar radiation, outdoor air temperature, wind, and precipitation (Ralegaonkar and Gupta, 2010; Kumar and Suman, 2013; Latha et al., 2015). The climatic-responsive design of the building envelope plays a crucial role in optimizing thermal performance, which in turn impacts energy consumption (Al-Saadi and Budaiwi, 2007).

Generally, building envelope systems are classified into two main types: opaque and transparent. The opaque system consists of elements such as walls, roofs, floors, and insulation, while the transparent system includes windows and skylights (Mirrahimi *et al.*, 2016). In reality, the opaque envelope surfaces, such as walls and roofs, constitute the largest portion of the building envelope and are directly exposed to external environmental conditions (Sadineni, Madala and Boehm, 2011). The heat gain over the opaque envelope surface contained 30% of the overall power consumption for the air conditioning in the building, with 11% through roof and 19% through walls.

Solar radiation is the primary source of heat transferred through the building envelope, influencing the thermal sensation of occupants indoors. The amount of heat transmitted through elements such as walls and roofs varies depending on climate conditions and the properties of the materials used (Al-Obaidi, Ismail and Abdul Rahman, 2014b). The wall acts as a thermal storage element during the day and can be used to warm the room at night. Meanwhile, windows can allow penetration during the day (Ozel and Ozel, 2020). Direct solar heat gain through glazing and indirect heat gain from reflected, diffused, and re-radiated solar energy absorbed by surfaces contribute to the rise in air mass temperature, ultimately impacting indoor air temperature (Al-Obaidi, Ismail and Abdul Rahman, 2014a).

Previous studies have extensively investigated the role of building envelopes in maintaining thermal comfort. Andhy and Citraningrum (Andhy and Citraningrum, 2019) examined the impact of facade engineering on room temperatures in a university building in Indonesia and emphasized the importance of optimizing material selection to mitigate heat gain. Similarly, Al-Obaidi et al. (Al-Obaidi, Ismail and Abdul Rahman, 2014b) highlighted the effectiveness of passive cooling strategies, such as reflective and radiative roofs, in reducing energy consumption in Southeast Asia. Mirrahimi et al. (Mirrahimi *et al.*, 2016) further explored how building envelopes, particularly the balance between opaque and transparent materials, influence thermal performance in high-rise buildings located in hot and humid climates. These studies collectively demonstrate the critical influence of facade design on indoor thermal conditions.

The use of glass as a facade material has grown in popularity due to its aesthetic appeal and functionality, including natural lighting and visual connectivity. Glass is is often used in the building design due to its simple shape and is a functional (Furqon, S. and P, 2015). However, as Latha et al. (2015) and Irfan et al. (2023) pointed out, excessive use of glass, particularly in climates with high solar radiation, can lead to increased indoor air temperatures and higher energy consumption for cooling. Ozel and Ozel (2020) examined the effect of window-to-wall ratio (WWR) on thermal performance and found that higher WWRs often exacerbate indoor overheating when not paired with adequate shading or proper building orientation. Despite these findings, research gaps remain in understanding the combined influence of high WWR and suboptimal orientation on thermal comfort, particularly in educational buildings where consistent indoor conditions are critical for productivity.

This study aims to bridge these gaps by focusing on two university buildings at Institut Teknologi Sumatera. The analysis emphasizes how facade design and building orientation impact indoor air temperatures, particularly in tropical climates. Building E, characterized by its high WWR and east-west orientation, serves as a case study for examining the drawbacks of excessive glass use in facade design. In contrast, the General Lecture Building (GKU), with its brick facade, shading devices, and north-south orientation, provides a comparison to emphasize effective strategies for reducing heat gain.

THEORY / RESEARCH METHODS

Case Studies

Building E and the General Lecture Building (GKU) were chosen as the case study of this research (Figure 2). These buildings are located at Institut Teknologi Sumatera (ITERA) in Lampung, Indonesia (5°21'36.3"S, 105°18'55.5"E). Being in a hot and humid tropical climate, they are exposed to intense solar radiation and extended periods of sunshine throughout the year (Arminda *et al.*, 2021). From January to October 2021, Bandar Lampung has the maximum temperature of 34.8℃ on October, the minimum temperature of 19.6℃ on July and the average temperature of 28.9℃ (BMKG, 2021).

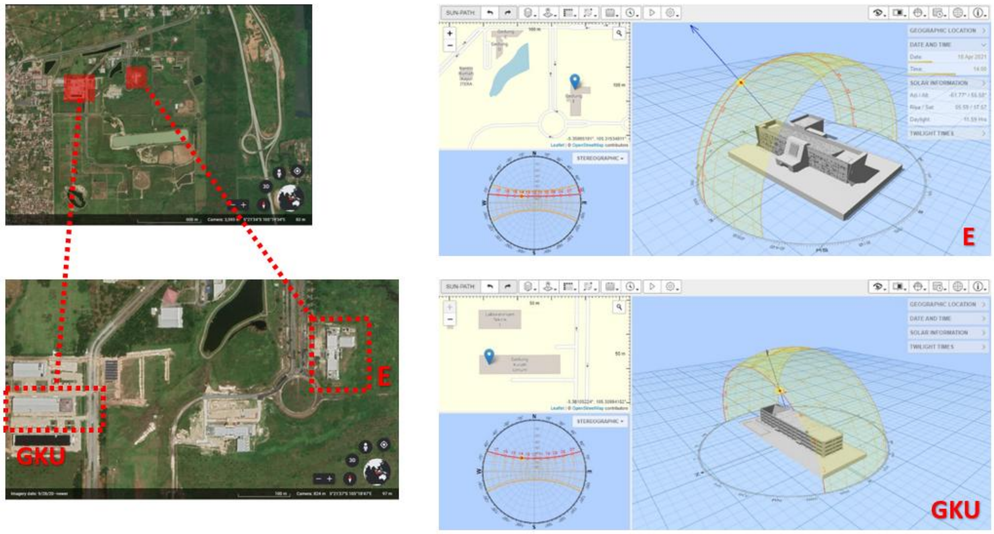


Figure 2. Location And the Sun Path of Case Studies

Building Details

Building E consists of three above-ground floors and a semi-basement level. Its facade is entirely covered with metal-framed single clear-glazing windows, resulting in a 100% window-to-wall ratio (WWR), with only a few sections that can be opened (Figure 3). The glass walls are 6 mm thick and have a U-value of 6.0 W/m^2K (Steven Szokolay, 2008). Some windows are coated with a glass film, but over time, the coating has deteriorated and developed cracks in several areas. Since using glass as the building envelope material, the east-west orientation and the absence of shading devices that can reduce exposure to sunlight into the room, building E has a problem with high air temperature. These conditions cause the teaching and learning activities are not conducive and reduce concentration of the students. Even though there is an air conditioning system inside the room, it is unable to overcome this thermal problem.

Figure 3. Building E, ITERA

To evaluate different conditions, the General Lecture Building (GKU) was chosen as a comparison (Figure 4). The GKU building has an orientation facing north and south. This building is surrounded by a balcony (cantilever) with a width of ± 100 cm on each floor which functions as a maintenance line and the placement of the AC machine. Indirectly this balcony can also be a shading to reduce sun exposure.

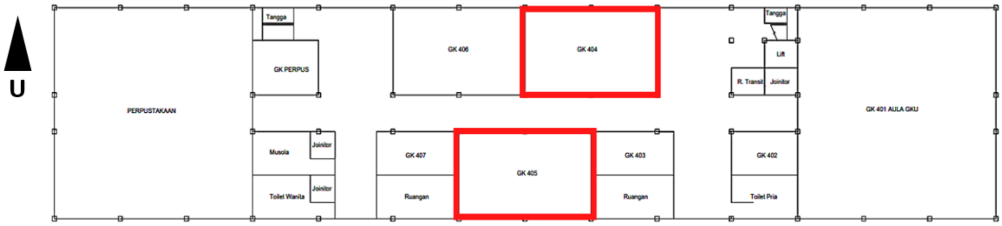
Figure 4. The Lecture Building (GKU), ITERA

Data Collection

The data was collected using quantitative methods (Raco, 2018) by measuring the indoor air temperature and surface temperature of the sample rooms. There are two rooms that were selected from building E and GKU, respectively. The rooms were chosen according to several criteria such as the position in the building (located on the top floor, directly above the roof). The sampling criteria include the material used for opening materials on the door facade, room orientation, functional similarities and activities, floor level, and room area. From these criteria, the selected room located in Building E, which includes Room E308 and E309. Meanwhile, for GKU building, the selected rooms are GK404 and GK405 as shown in Figure 5.

The indoor air temperatures of rooms in both Building E and GKU were measured using a handheld WeatherHawk WindMate (WM-300) wind meter (Arminda and Kamaruddin, 2021; Arminda *et al.*, 2021). The measurement tools were placed inside the building with occupants level following the ASHRAE standard 55 (ASHRAE, 2010). Measurements were conducted at one-hour intervals from 8:00 AM to 5:00 PM (during working hours) over six consecutive days in April 2021. Results of the data taken were converted into tables and graphs to analyse the thermal conditions of each room and descriptively analysed. In analysis part, the data taken was divided into 3 time zone, i.e. morning (8.00 am – 10.00 am), afternoon (10.00 am – 2.00 pm) and evening (2.00 pm – 5.00 pm).

(a) Floor Plan of Room E308 (west) and Room E309 (east) in Building E, ITERA



(b) Floor plans of Room GK404 (north) and Room GK405 (south) at GKU, ITERA

Figure 5. Testing room (a) Building E, (b) GKU

RESULTS AND DISCUSSION

In the morning, the temperature obtained is the result of the average temperature from 08.00 am - 10.00 pm and for daytime temperatures obtained from the average results from 12.00 am - 02.00 pm, also in the afternoon where the results of the temperature figures are obtained from the average temperature 03.00 pm - 05.00 pm.

Table 2. Comparison of Room Temperature of Building E and GKU

Building	Room	Room Temperature (°C)		
		Morning (08.00-10.00)	Afternoon (12.00-14.00)	Evening (15.00-17.00)
Building E	E308	30,1	31,1	30,9
	E309	29,8	31,5	31,5
The Lecture Building	GK404	28,3	28,2	26,8
	GK405	29,0	28,6	27,6

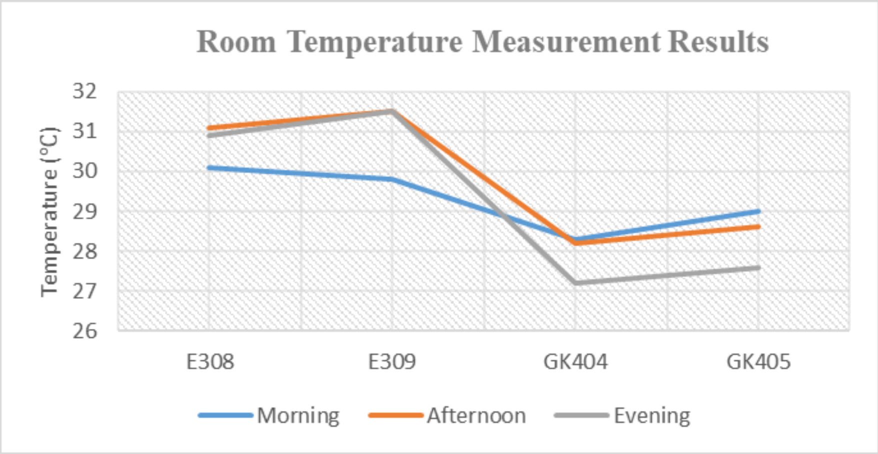


Figure 6. Indoor Air Temperature Measurements of Room Sample in Building E and GKU

The indoor air temperature in Building E at all times and all rooms have a higher value than the temperature in GKU. Based on Table 3, the thermal conditions in the GKU which have an average temperature value of 30.8 °C are in the category of optimal comfort and the thermal conditions at Building E which has an average temperature value of 28.15°C is in the threshold category warm boundaries that cause building users to feel uncomfortable.

Table 3. Comparison of Thermal Comfort Conditions of Building E and GKU

Buildings	Rooms	Room Temperature (°C)		
		Morning (08.00-10.00)	**Afternoon (12.00-14.00)**	**Evening (15.00-17.00)**
Building E	E308	Threshold	Threshold	Threshold
	E309	Threshold	Threshold	Threshold
The Lecture Building	GK404	Optimal comfort	Optimal comfort	Optimal comfort
	GK405	Optimal comfort	Optimal comfort	Optimal comfort

The room in Building E that directly faces the direction of the sun's path with facade material in the form of glass directly adjacent to the outer space is a factor thermal discomfort created in the room. The use of this glass material is less considering the orientation of Building E.

Based on Table 3, in the morning the room in Building E has reached the threshold warmth, as well as in the afternoon and evening. The room becomes less effective for activities because building users tend to sweat with these conditions. This causes ineffectiveness to respond to it, for example some building users add layers to glass walls and rely on assistive devices air conditioning in the form of fans as well as Air Conditioning (AC) which is used in one unit room to reduce indoor heat all the time.

Meanwhile, in GKU, which has a facade of brick walls and glass windows, sufficiently indicates the temperature that falls into the optimal comfort category for building users. The temperature in the rooms at GKU shows the same number comfortable because the incoming heat is reduced well. In addition, the orientation of the buildings that face north becomes a factor of not too much incoming heat. This can also reduce electricity waste in the use of air conditioning aids.

Looking at the analysis of the comparison graph of room temperature in Building E and GKU, this shows that the room in Building E is quite uncomfortable. The air that enters the room is also hot and makes building users sweat quickly so it is not comfortable to use for activities. Meanwhile, GKU is classified as having room which is comfortable to use for activities and can adjust to the hot climate of the city Lampung.

The findings for Building E align with Latha et al. (2015), who emphasized the challenges posed by extensive glass facades in hot climates. The lack of shading devices and the building's east-west orientation exacerbated solar heat gain, resulting in thermal discomfort. In contrast, GKU's north-south orientation and use of brick facades with shading devices reflect the recommendations of Mirrahimi et al. (2016) for optimizing thermal performance through balanced opaque and transparent envelope materials.

The results also diverge from certain findings in Andhy and Citraningrum (2019), which suggested that glass facades can achieve thermal comfort when paired with advanced cooling technologies. In the case of Building E, air-conditioning systems were insufficient to offset the high heat gain, indicating the limitations of active cooling solutions without complementary passive strategies. This highlights a significant research gap: the need for integrated facade designs that combine shading, material selection, and orientation to achieve sustainable thermal comfort.

Each finding in this study contributes to the broader understanding of sustainable facade design. For example, the temperature disparity between Building E and GKU during peak afternoon hours supports the argument that orientation significantly influences solar heat gain. This is consistent with theoretical models and empirical studies, such as those by Al-Obaidi et al. (2014), which advocate for north-south orientations in tropical architecture. Furthermore, the study's findings on the inadequacy of single-glass facades with high WWR align with Ozel and Ozel (2020), reinforcing the importance of shading and material optimization.

The use of brick facades and shading devices in GKU demonstrates the effectiveness of passive cooling strategies in maintaining thermal comfort. This aligns with Mirrahimi et al. (2016) and expands on their findings by providing specific data on tropical educational buildings. By comparing these results with prior research, this study not only validates existing theories but also identifies opportunities for improving facade design, such as integrating double-skin facades or advanced glazing technologies.

Unlike many studies that examine only one aspect, this study considers multiple factors, providing a comprehensive perspective on façade performance. This finding is particularly important for tropical climates, where passive cooling strategies play a significant role in minimizing energy consumption. Furthermore, this study highlights the drawbacks of relying solely on the air conditioning systems for thermal comfort in buildings with inefficient façade designs. This highlights the need for an integrated approach that combines passive and active strategies, supporting global sustainability goals.

CONCLUSIONS

The study revealed that Building E, with its high glass-to-wall ratio and lack of shading devices, experiences significantly higher indoor temperatures compared to GKU, especially during afternoon hours. This results in thermal discomfort, reducing occupant productivity. The east-west orientation of Building E further contributes to increased solar heat gain, while the north-south orientation of GKU mitigates this issue and helps maintain optimal thermal comfort. Additionally, the absence of a double-skin facade or appropriate shading devices in Building E exacerbates heat retention, whereas GKU's use of brick walls and functional balconies provides effective passive cooling, thereby reducing reliance on air conditioning systems. As a result, GKU demonstrates superior energy efficiency, which is particularly valuable in tropical climates where minimizing active cooling is crucial.

Future research should focus on incorporating passive cooling strategies, such as green facades, double-skin facades, and optimized shading devices, to improve the thermal performance of Building E. It is also essential to analyse personal comfort factors, including clothing insulation, activity levels, and metabolic rates, to gain a holistic understanding of thermal comfort. Further studies should explore the potential of alternative and sustainable facade materials with lower thermal conductivity to enhance energy performance and occupant comfort in tropical climates. Long-term thermal monitoring across different seasons is recommended to capture comprehensive data on building performance and seasonal variations. Additionally, simulation-based validation using advanced tools can model the thermal performance of retrofitted facades and orientations, ensuring that proposed interventions are both practical and effective. Lastly, conducting cost-benefit analyses of design modifications will help balance upfront investments with long-term energy savings and improved occupant productivity.

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