Optimising Thermal Comfort in The Classroom:

High schools in the hot and humid tropical climate of Indonesia

A Thesis

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Statement of Originality

This is to certify that to the best of my knowledge the content of this thesis is my own work.

All the assistance received in preparing this thesis and sources have been acknowledged.

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Signed

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Abstract

Provision of a thermally comfortable learning environment is crucial as thermal comfort significantly impacts students' health, cognitive performance, and academic performance. An uncomfortable classroom can lead to reduced attention and concentration, ultimately hindering students' learning outcomes. This thesis proposes strategies to optimise thermal comfort for students in Indonesian classrooms. This focus is particularly important given that previous studies have highlighted dissatisfaction among Indonesian students with the thermal conditions in their classrooms.

Indonesian public-school classrooms are typically designed for natural ventilation, relying heavily on the outdoor climatic resources to provide a thermally comfortable indoor climate. Designing thermally comfortable naturally ventilated buildings in Indonesia's hot and humid tropical climatic context presents challenges due to consistently intense solar radiation, limited wind resources, and high humidity throughout the year. These challenges are compounded by the lack of occupant-centric guidelines for school design and the absence of scientifically based thermal comfort standards that are relevant to local climatic and cultural context. Currently the typical classroom design is applied nationwide, regardless of the variation in local climates. This approach is suboptimal because it neglects the principle of thermal history, which plays a crucial role in shaping thermal comfort expectations.

In naturally ventilated classrooms, students have limited personal control over their indoor microclimate. Consequently, adjusting clothing insulation remains one of the most important mechanisms for attaining individual comfort preferences. However, the Indonesian classroom setting does not permit clothing adaptations, as students are required to wear specific uniforms during school hours. Therefore, the design of Indonesian school uniforms assumes an even greater importance than usual. The uniform must not only reflect community values and culture, but also permit adaptations to the climate to optimise each student's thermal preference. Currently, Indonesia applies the same school uniform design for public school

students nationwide. Designing climate-responsive school uniforms for female Muslim students is particularly challenging due to the requirement for stringent modesty, which means covering most of the body surface apart from the face and palms. Almost complete covering by clothing inevitably exacerbates thermal discomfort in Indonesia’s hot and humid tropical climate.

The overarching goal of proposing optimised strategies for thermal comfort in Indonesian classrooms was addressed through three distinct phases of research. The first was aimed at assessing the impact of Indonesian Muslim school uniforms on thermal comfort. This objective was accomplished by performing thermal manikin measurements of eleven configurations of Indonesian school uniforms. These configurations were based on the official Indonesian school uniform, with variations in wearing style (tucked-in or untucked shirt) and the inclusion of leggings as an extra layer worn under the skirt. Manikin results provided insight into the thermal comfort of designs in the context of naturally ventilated classrooms in Indonesia while complying with Islamic cultural requirements.

The second phase of the research assessed the indoor microclimate of Indonesian classrooms and evaluated the relative influence of various building design and construction features. This was achieved using Computational Fluid Dynamics (CFD) and thermal performance simulations of classroom configurations based on architectural drawings of Indonesian typical classroom, as outlined in the Appendix 4 of the Operational Guidelines for the Procurement of Buildings and Educational Facilities in Indonesia (Kementrian Pendidikan dan Kebudayaan Republik Indonesia, 2018). The simulation models included variations in natural ventilation mode (single-sided and cross-ventilation), first versus second floor location, eight different window orientations ranging from north (azimuth angle 0°) to northwest (315°), and six combinations of wall and roof construction materials (Autoclaved Aerated Concrete (AAC) and brick walls; concrete tiles, clay tiles, and corrugated aluminium roofs). The simulated classroom building models were concrete structures with top-hung windows having a 30° opening, combined with clerestory openings. Fans were not incorporated into the model, as Indonesian design regulations do not mandate their inclusion in classrooms. Climate data for use the building simulation studies were drawn from the lowland coastal area of Surabaya and highland Ruteng. These two sites were selected as representative of the main climate types of Indonesia.

The third phase of the research assessed the thermal comfort responses of students in the simulated Indonesian classrooms. In this phase, the Standard Effective Temperature (SET) was used as the thermal comfort index, and yearly percentages of comfortable occupied hours were calculated as a metric of performance.

A school uniform comprising a loose-fitting, untucked long-sleeve shirt paired with long trousers and a hijab provides 0.39 clo less clothing insulation compared to the official female school uniform (a long-sleeve shirt tucked into a long skirt with leggings worn underneath). Consequently, the substitution of trousers in the uniform provides significantly better thermal comfort and a longer duration of comfortable classroom hours compared to the long skirt. This substitution in the school uniform for girls resulted in an increase in annual comfortable occupied hours by 21-66% (equivalent to 612 to 1,948 hours per year) in lowland Surabaya's classrooms and 45-83% (equivalent to 1,314 to 2,432 hours per year) in highland Ruteng's classrooms, depending on the modes of natural ventilation, floor level, and windows orientation applied.

The clothing insulation of ensembles with skirts is higher than that of ensembles with trousers for several reasons. The design of the skirt tends to trap more air, which impedes heat transfer and increases thermal insulation. Additionally, the leggings worn underneath the skirt add an extra insulating layer and further inhibit air circulation. In contrast, ensembles with trousers are lighter. The absence of leggings provides less insulation, reducing the risk of overheating and discomfort from excessive sweating. Moreover, the untucked style of trousers enhances air circulation, aids in sweat evaporation, and helps maintain dryness, thereby improving thermal comfort.

Variations in local climates in Indonesia, exemplified by the lowland coastal climate of Surabaya and the highland climate of Ruteng, affect the effectiveness of different school design strategies in achieving optimal thermal comfort for students.

Implementing single-sided ventilation in first-floor classrooms in coastal Surabaya, which experiences higher daily temperatures and humidity, would increase the number of yearly comfortable occupied hours by 11-38% (equivalent to 321-1,109 hours). In this local climate, cross-ventilation strategies in first-floor classrooms may inadvertently introduce warmer air and higher humidity, potentially reducing comfort. For classrooms on the top floor in such conditions, indoor operative temperatures would increase significantly, decreasing comfortable hours. Therefore, applying cross-ventilation systems on the top floor is essential to enhance air movement and improve heat dissipation. Conversely, in the highland climate with lower daily temperatures, the application of cross-ventilation—regardless of floor level—may result in greater comfortable occupied hours compared to single-sided ventilation. In Ruteng's classrooms, cross-ventilation could increase yearly comfortable hours by 3-12%, equivalent to 88-350 hours per year.

Prioritising building design strategies that enhance natural ventilation and reduce solar heat gain is crucial in a hot and humid tropical climate like Indonesia. Such approaches are essential for achieving lower indoor operative temperatures and increased air velocities, thereby enhancing thermal comfort. Specifically, orienting classroom windows at oblique 45° angles towards the prevailing wind direction is recommended to maximise ventilation performance. These findings highlight the importance of understanding local climate characteristics, including prevailing wind directions and velocities, when designing strategies for naturally ventilated buildings.

Typical Indonesian classrooms, especially those using single-sided ventilation, often experience very low indoor air velocities, which are insufficient for comfort. Therefore, this study recommends incorporating fans to improve natural ventilation in Indonesian classrooms, particularly when single-sided ventilation is the only viable option. Fans can increase air movement, enhance sweat evaporation, and improve heat dissipation, thereby improving thermal comfort.

The improvement in comfortable occupied hours achieved through clothing adjustments is significantly greater than that attained through modifications to building features. Adjusting clothing insulation led to a decrease in Standard Effective Temperature (SET) values by approximately 3°C, increasing the percentage of comfortable occupied hours in classrooms to as much as 80% annually. In contrast, the modifications to natural ventilation modes, floor levels, and window orientations resulted in a maximum SET reduction of less than 2°C, raising the annual percentage of comfortable occupied hours in classrooms by a maximum of 38%. These findings highlight the critical importance of clothing insulation in enhancing students' thermal comfort, especially in naturally ventilated classrooms.

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List of Abbreviations

AAC	Autoclaved Aerated Concrete
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
CAD	Computer-Aided Design
CBE	Centre for the Built Environment
CFD	Computational Fluid Dynamics
f_{cl}	clothing area factor
H	dry heat loss per square metre of skin area in watts per square metre ($\mathrm{W.m^{-2}}$)
IEQ	Indoor Environmental Quality
ISO	International Organization for Standardization
I_{a}	Boundary air insulation
I_{cl}	Basic insulation or intrinsic insulation
I_{T}	Total clothing insulation
RANS	Reynolds Averaged Navier-Stokes
RH	Relative Humidity
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
SET	Standard Effective Temperature
SNI	Standard National Indonesia
T_a	air temperature
t_{o}	operative temperature
t_r	radiant temperature
TCV	Thermal Comfort Vote
TSV	Thermal Sensation Vote
$\bar{t}_{\mathrm{sk}}$	mean skin surface temperature

Chapter 1 Introduction

Investing in high-quality classrooms and school buildings is crucial for any country, as these spaces are fundamental to the structured educational experiences of successive generations. The primary objective of this thesis is to optimize thermal comfort for students in Indonesian classrooms. This focus is essential because previous research has indicated that Indonesian students experience thermal discomfort (Gunawan & Ananda, 2017; Hamzah et al., 2016, 2018; Razak & Wulandari, 2020; Susanti & Aulia, 2013) which potentially impacting the quality of learning performance in their classrooms (Wargocki & Wyon, 2017).

Indonesian classrooms are predominantly designed with natural ventilation, relying heavily on the outdoor climate for indoor thermal performance. The hot and humid climate of Indonesia poses significant challenges to the design of schools and classrooms. These challenges are exacerbated by the lack of comprehensive occupant-centric guidelines for school and classroom design. Furthermore, the school uniform worn by Indonesian Muslim female students, which covers most of the body except the face and palms, increases clothing insulation, thereby heightening discomfort under year-round hot and humid conditions.

Ensuring an optimal learning environment is imperative, as prior studies have demonstrated the profound impact of thermal comfort on students' health, productivity, and academic performance. Discomfort from inadequate thermal conditions can lead to reduced focus and attentiveness, ultimately hindering students' educational attainment and scholastic outcomes.

1.1 The importance of providing thermally comfortable classrooms for students

Previous research indicates that the indoor environmental quality of school classrooms, encompassing factors such as the thermal environment, indoor air quality, and lighting and acoustic conditions, significantly influences the health and performance of both students and teachers, with particular emphasis placed on the thermal environment (Mendell & Heath, 2005).

Higgins et al. (2005) note that inadequate temperature control, lighting, and poor air quality detrimentally affect students' concentration, mood, well-being, and cognitive development. Cui et al. (2013) and Wargocki & Wyon (2013) found that air temperature directly influences motivation, thereby significantly shaping students' performance in the classroom. Additionally, Primi et al. (2012) highlight that students' motivation, interest, and dedication serve as pivotal predictors of intellectual development.

Research evidence supporting the assertion that thermal comfort significantly impacts student performance has been found worldwide, including in contexts such as China (Jiang et al., 2018; Lee et al., 2012; Xiong et al., 2018), Saudi Arabia (Almaqra et al., 2019; Riham Jaber et al., 2017), Romania (Sarbu & Pacurar, 2015), Italy (Barbic et al., 2019), the Netherlands (Mishra et al., 2017), Serbia (Bajc et al., 2019), Brazil (Siqueira et al., 2017), and the United States (Hoque & Weil, 2016). These studies consistently report improved performance on various cognitive assessments—such as tests of distributive attention, memory, reasoning, knowledge, and perception—when students are exposed to temperatures within their preferred comfort range, which varies by climatic context. In contrast, thermal discomfort caused by excessively high or low temperatures adversely affects students' learning performance (Jiang et al., 2018). Furthermore, Jiang et al. (2018) found that temperature variations not only influence thermal comfort but also affect students' overall well-being. Additionally, the impact of temperature on learning performance varies significantly depending on the nature of the task (Jiang et al., 2018).

Previous studies notably demonstrated that thermal discomfort manifests in various symptoms, including headaches, dizziness, and a sense of heaviness in the head, which subsequently result in confusion, impaired thinking, difficulty concentrating, and fatigue, ultimately leading to suboptimal cognitive test outcomes (Barbic et al., 2019; Hoque & Weil, 2016; Riham Jaber et al., 2017). These investigations collectively underscore the significance of providing thermally comfortable classroom environments to enhance students' learning outcomes.

1.2 Thermal comfort and its influencing factors

According to ASHRAE, thermal comfort is defined as a state of mind indicating satisfaction with the thermal environment, subjectively assessed by individuals (ASHRAE, 2020). When individuals experience thermal comfort—feeling neither excessively hot nor cold—their bodies and minds can function optimally, resulting in increased productivity. Given its profound impact on human well-being, performance, and building energy consumption, thermal comfort has emerged as a crucial component of indoor environmental quality (Al Horr et al., 2016; De Giuli et al., 2012).

Physiologically, achieving thermal comfort involves maintaining a balance between the body's internal heat production and heat loss to the environment, ensuring that the core body temperature remains within a narrow operating range (typically around 36.5°C for humans) to sustain the normal functioning of bodily organs, particularly the brain (Choi & Loftness, 2012; Nicol et al., 2012). Consequently, thermal comfort is significantly influenced by the heat transfer processes between the human body and the environment during physical activities and metabolic processes in daily life.

During physical activities, human bodies experience heightened metabolic activity, resulting in the generation of heat. Efficient dissipation of this metabolic heat is crucial to support a stable core body temperature and subjective comfort. Various heat transfer mechanisms operate to achieve this equilibrium. Conduction involves the direct transfer of heat between the body and surrounding objects, such as furniture or the ground. Convection facilitates heat transfer through the movement of air around the body, which can be augmented by factors like airflow or wind. Radiation entails the emission or absorption of energy via electromagnetic waves, with the surface of the body gaining or losing heat based on temperature differentials with its surroundings. Evaporation emerges as a pivotal mechanism during physical exertion, as sweat evaporates from the skin surface, carrying the latent heat of vaporisation away and cooling the body. Likewise, in everyday metabolic processes like digestion, circulation, and cellular respiration, the body continually generates heat. Effective heat transfer mechanisms are indispensable for dissipating this generated heat and maintaining thermal equilibrium, thereby fostering thermal comfort.

From a general perspective, the human body operates like a heat engine, exchanging heat with the environment through convection, radiation, and evaporation, as described by the following equation:

$$M = E \pm C \pm R \pm S \qquad [1.1]$$

Where M represents heat produced by metabolism, E is heat exchanged by evaporation, C is heat exchanged by conduction, R is heat exchanged by radiation, and S is heat added to or taken.

Fanger (1970) explored the primary environmental and personal factors that impact the body's thermal comfort by influencing the equilibrium between heat production and heat loss. Environmental factors encompass air temperature, mean radiant temperature, air movement, and humidity levels. Additionally, two personal factors influencing thermal comfort are clothing insulation and physical activity levels (Fanger, 1970). These factors collectively contribute to an individual's perception of thermal comfort by modulating the interplay between heat generation and dissipation within the body.

Thermal comfort is a multifaceted construct influenced not only by meteorological conditions but also by changes in individuals' physiological and psychological characteristics over time (Naheed & Shooshtarian, 2021). Adaptation to local circumstances is influenced by individual thermal perceptions and practices, such as clothing choices and activity patterns (Middel et al., 2016; Morgan & de Dear, 2003). Moreover, the preference for thermal comfort is subjective, as it is influenced by various physiological factors, including age, gender, and body mass index, which affect metabolic rate (Indraganti & Rao, 2010; Jowkar, Rijal, et al., 2020; Karjalainen, 2007; Kwak et al., 2023; Maykot et al., 2022; Taylor et al., 1995; Y. Wu et al., 2023).

Furthermore, psychological factors, including thermal perception and past thermal experiences, also shape thermal comfort preferences (De Dear et al., 1997). Past thermal experiences, thermal history, play a crucial role in thermal comfort perception, as they inform evaluations of current indoor environments and shape comfort expectations (Brager & de Dear, 1998; De Dear et al., 1997; De Vecchi et al., n.d.; Jowkar, Rijal, et al., 2020). For instance, individuals accustomed to cold climates may have different thermal comfort preferences than those from tropical climates, reflecting acclimatization processes that confer higher tolerance for specific temperature ranges (Heng & Chow, 2019).

Moreover, cultural values, lifestyles, and adaptation to local circumstances such as clothing choices and activity patterns (Middel et al., 2016; Morgan & de Dear, 2003) are significant variables influencing thermal comfort preferences. A study by Indraganti and Rao (2010) compared the thermal comfort preferences of individuals living in the same climatic zone of Hyderabad, India, but with different lifestyles, economic conditions, and comfort expectations. It found that heavy usage of air conditioning systems influenced the chosen range of neutral comfort. Individuals with higher economic status and who were accustomed to air conditioning preferred lower neutral temperatures, whereas those with lower economic status preferred higher neutral temperatures, exceeding the comfort band specified in Indian standards (Indraganti & Rao, 2010). This research highlights how socio-economic background influences tolerance for a broader range of temperatures based on lifestyle choices and comfort experiences and expectations.

In conclusion, these research findings underscore the variability in thermal comfort preferences and acceptability across different demographic groups and geographic regions. It is evident that a single standard of thermal comfort, tailored to a specific setting within one climatic region, may not be universally applicable across diverse climates. Therefore, there arises a necessity for nuanced standards of thermal comfort catering to specific demographic groups residing in distinct climatic conditions, characterized by shared values or cultural backgrounds.

1.3 The importance of clothing insulation as a variable that influences thermal comfort

Previous studies have demonstrated a significant relationship between clothing insulation and thermal comfort (Morgan & de Dear, 2003; Ogulata, 2007; Teli et al., 2012). ASHRAE defines clothing insulation as "the resistance to sensible heat transfer provided by a clothing ensemble," encompassing heat transfer from all parts of the body, including those not covered by clothing, such as the head and hands (ASHRAE, 2020). Typically, clothing insulation is quantified in clo units, where 1 clo equals 0.155 m^2 K/W (Gagge et al., 1941).

Clothing acts as a barrier between the body and the external environment, influencing the exchange of heat (Udayraj et al., 2016; Voelker et al., 2009). Through adjustments to their clothing ensemble, individuals can maintain proper thermal balance in various environmental conditions (Ogulata, 2007). In hot environments, clothing serves as a protective layer, impeding direct heat transfer from the external environment. Conversely, in colder temperatures, clothing functions as thermal insulation, preventing a drop in body temperature that could lead to hypothermia.

The significance of clothing insulation in achieving thermal comfort is well-documented, with numerous studies confirming that adjusting clothing based on varying climatic conditions is one of the most cost-effective and efficient strategies for maintaining comfort (Bouden &

Ghrab, 2005; Parsons, 2002). Furthermore, appropriate clothing adjustments can expand the range of thermal comfort (Gagge et al., 1976) and significantly influence the thermal sensation experienced by building occupants (Bouden & Ghrab, 2005; Efeoma, 2016; Parsons, 2002).

Additionally, ASHRAE (2020) indicates that modifying clothing insulation for individuals engaged in nearly sedentary activities can adjust the optimal operative temperature by approximately 6 °C per clo unit. For instance, incorporating a thick, sleeveless vest into a clothing ensemble increases clothing insulation by approximately 0.22 clo, thereby decreasing the optimal operative temperature by approximately 1.3 °C (6 °C/clo × 0.22 clo).

Furthermore, enabling individuals to achieve thermal comfort through clothing adjustments alone can reduce the energy consumption required for temperature regulation in buildings (De Carli et al., 2007; Newsham, 1997).

Morgan and de Dear (2003) observed that clothing choices are influenced by both indoor and outdoor thermal environmental exposures, as field studies have demonstrated significant variations in the clothing ensembles chosen for different climatic conditions, ranging from hot to moderate and cold environments. Given its crucial role in thermal comfort, the opportunity for occupants to adjust clothing is an essential aspect of thermal adaptive behaviour, particularly in naturally ventilated buildings. These buildings rely heavily on outdoor weather for indoor thermal performance, whereas air-conditioned buildings allow for easier control and adjustment of indoor conditions to suit occupant preferences. Unfortunately, not all indoor settings provide occupants with the opportunity to select and change their clothing based on personal preferences, thereby limiting their ability to adapt behaviourally to achieve thermal comfort. Classrooms and offices are examples of indoor settings where occupants are required to wear specific uniforms during work hours. In such environments, it is important to carefully choose the style and insulation properties of a clothing ensemble by considering both the nature of the activities and the characteristics of the work environment.

Moreover, global variations in dress are influenced by factors beyond climate, including cultural values, religious practices, trends, and socioeconomic status (Oluseyi et al., 2020; Tajuddin, 2018). These factors can also influence the design of uniforms for office workers and students. Different countries may have varying regulations regarding school uniforms. In classroom settings, where strict uniform policies are applied during school hours, the design of these uniforms becomes crucial. They must not only reflect the values and culture of the community but also be relevant and adaptable to the climate to ensure thermal comfort for students.

Previous studies in thermal comfort have relied on standards to determine the clothing insulation values necessary for thermal comfort calculations. Standards such as the International Organization for Standardization (ISO) 9920, ISO 7730, and those set forth by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), including the ASHRAE Standard 55–2020 (ASHRAE, 2020; British Standards Institution, 2006, 2009), serve as key resources providing information on clothing insulation values for typical clothing ensembles, based on measurements performed on a standing thermal manikin under the condition of air movement below 0.2 m/s. However, it is important to note that these standards predominantly focus on clothing insulation values for Western clothing ensembles. Clothing styles are heavily influenced by cultural, religious, and societal values, leading to significant differences between Eastern and Western clothing. Currently, the study conducted by Havenith et al. (2013) is the only research that addresses Eastern-style clothing involving the measurement of clothing insulation using a thermal manikin. Therefore, more measurements of Eastern-style clothing ensembles are needed. Understanding the insulation of Eastern-style clothing is crucial, as it provides essential data for thermal comfort research.

This study was conducted within the context of Indonesia, an Eastern country where clothing styles, including school uniforms, are heavily influenced by Islamic culture. One of the focuses of this research is the clothing insulation properties of typical Indonesian school uniforms. This variable was selected due to the significant impact that Indonesia's distinctive school uniform styles are expected to have on students' thermal comfort, particularly in the country's hot and humid tropical climate. Moreover, measuring the clothing insulation of Indonesian school uniforms will contribute to the existing body of knowledge on Eastern-style clothing insulation. By examining this specific aspect within the Indonesian cultural context, this research aims to enhance understanding and inform strategies for improving thermal comfort in Indonesian educational settings.

1.4 Indonesian context

In thermal comfort studies, climate variables such as air temperature, humidity, and air velocity are widely recognized as key determinants of human comfort. Additionally, cultural factors and individual values play a significant role in shaping activities and clothing behaviours, both of which are integral components of thermal comfort. Therefore, before investigating thermal comfort within a specific context, it is essential to develop a comprehensive understanding of the prevailing climatic conditions and cultural nuances of the region.

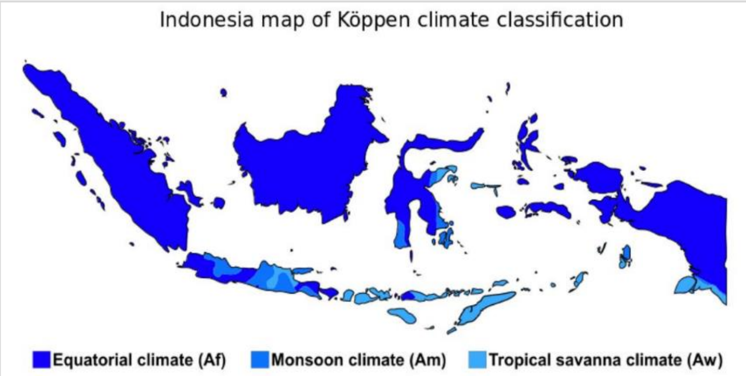
This section provides an overview of Indonesia, chosen as the focus country for this study. The discussion begins by examining Indonesia's climate, followed by an exploration of how cultural beliefs influence the clothing preferences of its inhabitants, including the design of school uniforms. Furthermore, a detailed discussion on Indonesian classroom environments and previous research on thermal comfort within such settings will offer valuable context for this study.

1.4.1 Indonesian climate

This research was conducted in the context of Indonesia's hot and humid tropical climate. Positioned between latitudes 11°S and 6°N and longitudes 95°E and 141°E, Indonesia is a tropical archipelago straddling the equator. This geographical location subjects the country to the influences of monsoon winds, perpetuating hot and humid conditions throughout the year.

As one of the largest archipelagic nations, comprising over 17,000 islands, Indonesia displays significant variations in ambient temperatures across its numerous towns and cities.

The Köppen climate classification system has been widely adopted in Indonesia to clarify these climatic variations. According to this system, the Indonesian climate is divided into three zones: tropical rainforest, tropical monsoon, and tropical savanna. These zones are primarily differentiated by their precipitation levels. The tropical rainforest zone receives more than 60 mm of precipitation annually, typical of an equatorial climate. The tropical monsoon zone experiences precipitation levels ranging from 60 mm to 100 mm per year. In contrast, the tropical savanna zone receives less than 60 mm of precipitation annually (Arnfield, 2023).



Climatic type	Precipitation Level (average in a month)
Equatorial	> 60 mm
Monsoon	60 mm < Am < 100 mm
Tropical Savanna	< 60 mm

Figure 1.1 Indonesian map of Köppen climate classification (edited from Fong et al., 2019)

One limitation of the Köppen climate classification system is that it classifies climate zones based on precipitation levels and temperature, factors that primarily influence vegetation patterns in Indonesia. However, thermal comfort studies require consideration of multiple climatic variables, including temperature, wind velocity, and humidity. Consequently, the use of the Köppen classification to detail variations in Indonesia's climate characteristics is deemed unreliable and unsuitable for studies focused on thermal comfort.

Given its status as the largest archipelagic nation with predominantly coastal and numerous mountainous regions, Indonesia exhibits varied topographical characteristics that significantly affect its climate. An analysis of hourly climate data from 2007-2018, collected from 114 meteorological stations across Indonesia (Climate. OneBuilding, 2023), highlights the temperature differences across cities based on elevation. Cities and towns in lowland and coastal areas situated less than 500 meters above sea level report average daily temperatures ranging from 26.6°C to 29.4°C. In contrast, highland cities, located at elevations between 539 and 1770 meters, experience cooler temperatures, with average daily temperatures ranging from 20.4°C to 24.3°C. These variations also impact relative humidity levels, with lowland cities exhibiting average daily relative humidity between 83.3% and 83.4%, whereas highland cities see slightly higher humidity levels, averaging 87.5%. Regarding wind speed, meteorological data indicate that wind speeds across Indonesia are generally low. Cities in lowland areas have average wind speeds ranging from 0.5 to 3.9 m/s, while highland cities experience slightly lower wind speeds, ranging from 0.7 to 2.2 m/s (Climate. OneBuilding, 2023).

The majority of Indonesian cities, including prominent urban hubs like Jakarta, Surabaya, Medan, and Banjarmasin, are situated in lowland coastal areas (see map in Figure 1.2). Conversely, highland regions in Indonesia encompass areas such as the Jayawijaya mountain range, Citeko Bogor, the Dieng highlands, and Ruteng in West Nusa Tenggara (see map in Figure 1.2). Notably, previous thermal comfort studies in Indonesia have largely focused on lowland regions, with limited research conducted in highland areas (Karyono, 2015).

To capture the diverse climatic variations within Indonesia's hot and humid tropical climate, Surabaya and Ruteng were selected as case study cities. Surabaya represents a lowland coastal area characterized by higher daily temperatures, while Ruteng exemplifies a highland city with lower temperatures. This selection was informed by recognition of the influence of thermal history on individual thermal comfort preferences (Brager & de Dear, 1998; Jowkar, Rijal, et al., 2020). As previously noted, the thermal environment in which individuals reside significantly shapes their thermal preferences and comfort thresholds (Corgnati et al., 2009; Jowkar, Rijal, et al., 2020). Consequently, the thermal preferences and expectations of students who have previously resided in lowland cities, characterized by relatively high temperatures, may differ from those hailing from highland cities with lower temperatures.

Figure 1.2 The location of several lowland coastal and highland regions in Indonesia (edited from https://365psd.com/vector/free-vector-map-of-indonesia-30727)

1.4.2 Indonesian clothing style and school uniforms design

Clothing styles and preferences are profoundly influenced by cultural and religious beliefs and values (Tajuddin, 2018). This subsection will delve into how Indonesian culture and religion shape clothing styles and preferences, including those related to school uniforms.

Indonesia is globally recognized for hosting one of the world's largest Muslim populations, comprising approximately 85% of its 276 million inhabitants. Islamic culture exerts a significant influence on the daily habits and behaviours of Indonesians, including their attire choices (Kusumawati et al., 2020). Islamic teachings, as outlined in the Holy Quran, designate certain parts of a woman's body, excluding the face and palms, as "aurat," to be covered and concealed from any man who is not her husband or family. Abiding by these values, Muslim women in Indonesia adhere to wearing loose garments that envelop their entire body, accompanied by a headscarf or veil to cover their head and hair (Arifah et al., 2018).

The popularity of Muslim attire, particularly among Indonesian Muslims, has surged in recent times. Historically, during the 1970s and 1980s, Indonesia enforced a ban on the use of headscarves, deeming them inappropriate, especially within educational settings. During this period, headscarves or veils were primarily worn by Muslims exhibiting strong religious devotion, particularly within Islamic boarding schools (Kusumawati et al., 2020). However, this trend has undergone a significant shift. Today, the practice of wearing headscarves or veils to cover the head and hair has expanded beyond older women and those associated with Islamic boarding schools to include younger women (Arifah et al., 2018). A growing number of Muslims perceive wearing Muslim attire as a divine mandate from Allah, as documented in the Al-Qur'an, rendering it a form of religious observance. Consequently, Muslim women who choose to wear the hijab are often regarded as demonstrating a deeper commitment to their religious beliefs (Arifah et al., 2018). For many Muslim women, this mode of dress is considered vastly superior to not wearing a headscarf at all (Agustina, 2015). Consequently, this phenomenon is steadily gaining traction and aligning with prevailing fashion trends in Indonesia, exerting influence over women's fashion choices, including the design of Indonesian school uniforms for women.

The Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia governs the style and design of Indonesian school uniforms through Regulation Number 50 of 2022 (Kemdikbudristek Republik Indonesia, 2022). This regulation specifically outlines the prescribed style and colour scheme of the national school uniform, which is mandatory attire for all elementary, junior high, and senior high school students throughout the country during school hours.

According to Regulation Number 50 of 2022, Indonesian students are obligated to adhere to three distinct types of school uniforms: the national uniform (illustrated in Figure 1.3), the scouts' uniform (illustrated in Figure 1.4), and specific school uniforms reflecting regional characteristics. Both the national and scouts' uniforms maintain standardized styles across all schools in Indonesia. The regulation emphasizes that uniformity in attire among students serves to promote nationalism and foster a sense of unity nationwide (Kemdikbudristek Republik Indonesia, 2022). However, the design of specific uniforms may vary among schools based on policies established by local government authorities.

The national uniforms for senior high school students, typically worn from Monday to Wednesday, are illustrated in Figure 1.3.

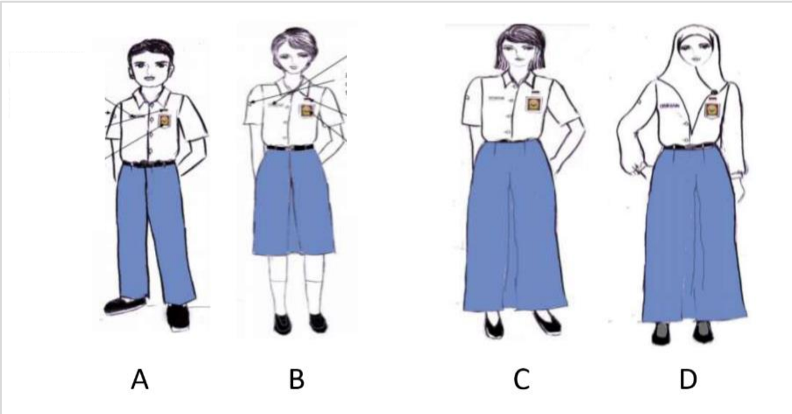


Figure 1.3 Indonesian national school uniforms Source: Kemdikbudristek Republik Indonesia, 2022

The uniform options for senior high school students in Indonesia comprise Type A for male students and Types B, C, and D for female students. The regulation stipulates that female students have the autonomy to select a uniform type based on their beliefs and religion. Given Indonesia's predominantly Muslim population, many female students opt for Type D, which includes a long shirt, long skirt, and a headscarf for modesty. Both genders are required to incorporate a tie, white socks, and black shoes into their national school uniforms. Additionally, wearing a cap during the flag ceremony, typically held on Monday mornings, is mandatory.

The scout's clothing uniform illustrated in Figure 1.4 is typically worn on Fridays and Saturdays. The guidelines for the scout's uniform are delineated in Decision Number 174 of 2012 by the National Quartier of the Scouts, which establishes the standards for scout uniform attire (Kwartir Nasional Gerakan Pramuka, 2012). Like the national uniform standards, the scout's clothing uniform provides options for long attire and a headscarf or veil for female

Muslim students. For a comprehensive depiction of the complete scout's uniform attire, please refer to the Figure 1.4.

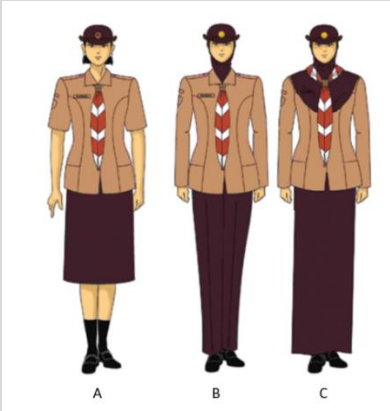


Figure 1.4 Indonesian national scout uniforms Source: Kwartir Nasional Gerakan Pramuka, 2012

Figure 1.4 depicts the alternative scout uniform options available for senior high school female students in Indonesia. Type A is designated for non-Muslim female students, while Types B and C are specifically designed for Muslim students. Type B comprises a combination of a long-sleeve shirt and long trousers, whereas Type C combines a long-sleeve shirt with a long skirt. Among the two alternatives provided for Muslim female students, it is common for Indonesian senior high school students to wear Type C.

The clothing insulation of Indonesian Muslim uniforms was identified as a crucial variable for investigation in this research. These uniforms are typically specified and designed by adults who do not wear them and often lack a thorough understanding of activity-related metabolic rates and experiences (Barrett et al., 2013; Choi et al., 2013; Katafygiotou & Serghides, 2014). Notably, there appears to be a dearth of scientific deliberation in the process of uniform selection (De Dear et al., 2015; De Giuli et al., 2012; Nam et al., 2015), indicating a perceptible gap between the needs, preferences, and expectations of students and the policy decisions regarding the dress codes and environments they encounter at school. This situation highlights the necessity of measuring clothing insulation in Indonesian Muslim school uniforms to inform the design of uniforms tailored to students' thermal comfort preferences.

Furthermore, the assessment of specific clothing insulation across various contextual scenarios in thermal comfort investigations presents challenges, primarily due to the costly research equipment involved. Historically, thermal comfort research has often relied upon the standardized clothing insulation values provided by authoritative bodies such as ASHRAE Standard 55, ISO-7730, and ISO-9920. However, it is pertinent to note that the prescribed clothing insulation values in ASHRAE Standard 55 and ISO-9920 largely reflect Western-style attire, which possesses different characteristics compared to non-Western clothing typologies such as Indonesian Muslim women's attire.

In a study conducted by Havenith et al., (2013), a range of non-Western clothing ensembles were measured, including a traditional national uniform worn by senior high school students in Indonesia. Nevertheless, the ensemble configurations assessed by Havenith et al., (2013) notably excluded leggings, a common undergarment worn by Muslim women in Indonesia beneath their skirts. The omission of leggings from these ensembles undeniably impacts the overall estimation of clothing insulation. Hence, a primary objective of the present study is to evaluate the clothing insulation of various Muslim school uniform combinations in Indonesia, with and without leggings, with the aim of augmenting the dataset concerning the clothing insulation properties of Indonesian Muslim attire.

Assessing the clothing insulation of various Indonesian Muslim school uniform ensembles will enable the identification of combinations that offer optimal thermal comfort for students in classroom settings. This data can inform the selection and design of school uniforms aimed at enhancing comfort and thermal regulation, thereby improving the learning environment for students in Indonesia.

1.4.3 Indonesian school and classroom

The responsibility for providing school facilities, including classrooms, in public schools throughout Indonesia falls under the purview of the Ministry of Education and Culture. The primary regulatory framework governing the standards for educational infrastructure in elementary, junior high, and senior high schools is outlined in Regulation Number 24 of 2007 issued by the Minister of Education of Indonesia (Kemdiknas Republik Indonesia, 2007). However, it is noteworthy that this regulation lacks detailed specifications concerning design aspects. Appendix 4 of Regulation Number 8 of 2018 of the Operational Guidelines for the Procurement of Buildings and Educational Facilities in Indonesia, issued by Indonesia's Ministry of Education and Culture includes an example of a drawing of a standard classroom floor plan; however, it does not provide a scientific rationale for the underlying design principles (Kementrian Pendidikan dan Kebudayaan Republik Indonesia, 2018). Figure 1.5 depicts the typical floor plan and view of Indonesian classrooms as outlined in Appendix 4 of Regulation Number 8 of 2018, with the window details illustrated in Figure 1.6. Additionally, Figure 1.7 presents the standard classroom layout in Indonesian schools.

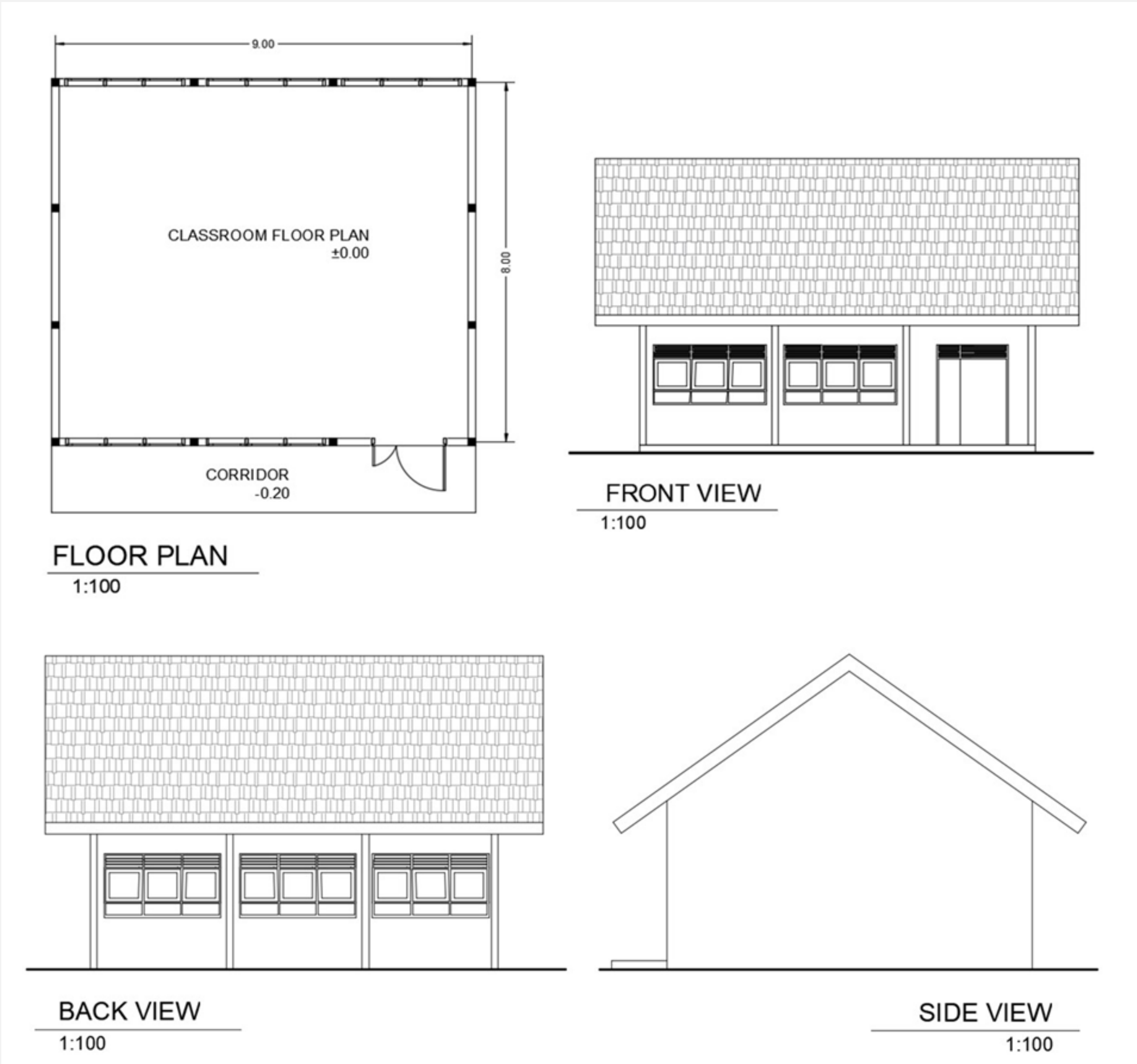


Figure 1.5 Standard of Indonesian classrooms floor plan and view, redrawn from Kementrian Pendidikan dan Kebudayaan Republik Indonesia (2018)

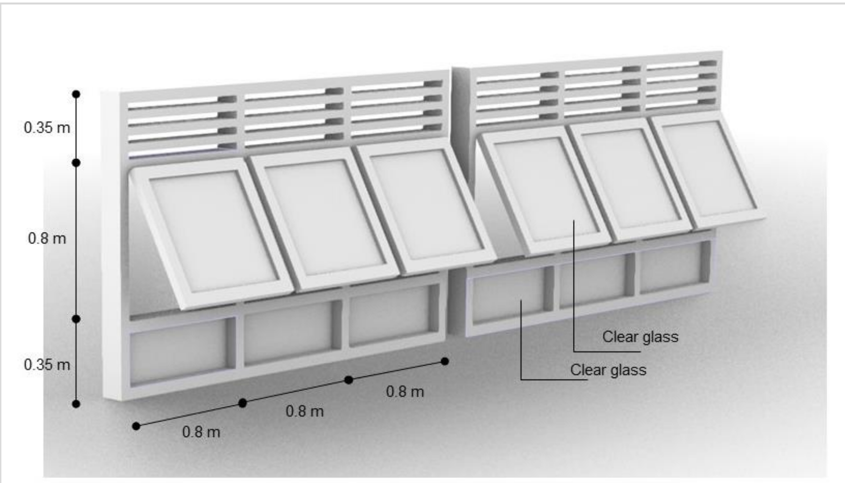


Figure 1.6 Windows detail, redrawn from Kementrian Pendidikan dan Kebudayaan Republik Indonesia (2018)

Figure 1.7 Situation in Indonesian classrooms (Sources: Adminweb, 2021; Humas, 2013)

Indonesia lacks a specific thermal comfort standard tailored exclusively to classrooms. Instead, the country adheres to a unified thermal comfort standard, SNI 6390:2011, applicable to all buildings nationwide (Badan Standardisasi Nasional Indonesia, 2011). This standard prescribes a singular comfort temperature of 25.5°C T_a, with a permissible range of +1.5°C T_a, and relative humidity of 60% ± 5% for a workplace, including schools and classrooms. However, extensive research conducted in various Indonesian cities, including Yogyakarta and Surabaya, has demonstrated that individuals can still experience thermal comfort even at temperatures exceeding 27°C, clearly surpassing the boundaries set by the current Indonesian thermal comfort standard (Alfata et al., 2012; Feriadi & Wong, 2004).

Furthermore, Regulation Number 24 of 2007 recommends the implementation of double-sided ventilation, utilizing top-hung windows, in the design of Indonesian classrooms (Kemdiknas Republik Indonesia, 2007). However, due to site constraints and various other factors, many schools may opt for single-sided ventilation arrangements in specific classrooms.

In urban areas, many Indonesian schools rely on ceiling fans to enhance ventilation within the classrooms. However, it is important to acknowledge that numerous classrooms across Indonesia still solely rely on natural ventilation. There is no precise data available regarding the percentage of Indonesian classrooms without fans. Nonetheless, Badan Pusat Statistik Indonesia (2023) reports that over 45% of classrooms across the country are in damaged or severely damaged condition. While specific details on the condition of these classrooms are not provided, it is likely that they are not equipped with ceiling fans. Given Indonesia's location in the hot and humid tropical region, characterized by relatively low wind speed (Putra et al., 2022), the presence of fans plays a crucial role in enhancing natural ventilation and ensuring students achieve thermal comfort. It is noteworthy that existing regulations do not explicitly mandate mechanical ventilation, such as fans or air conditioning systems, to supplement natural ventilation.

Regarding building materials, Indonesian regulations governing the design of schools and classrooms do not stipulate specific requirements. Nonetheless, architectural drawings provided in the regulation's appendix depict permanent building structures with plastered brick walls and concrete tile roofs (Kemdiknas Republik Indonesia, 2007). In Indonesia, a typical classroom design is uniformly applied nationwide, regardless of the diverse local climates. Furthermore, this uniform design is implemented across all educational levels, from elementary to senior high school, irrespective of the varying age groups of students. This approach is suboptimal as it overlooks the importance of adapting buildings to local climate conditions to create comfortable learning environments. Additionally, it fails to address the differing thermal comfort needs and preferences among students of different ages (Hamzah et al., 2016, 2018, 2020). It is widely recognized that each educational stage requires unique learning approaches and levels of concentration, emphasizing the necessity of considering age-specific requirements (National Research Council, 2000).

The absence of standardized guidelines or reference documents for designing classrooms based on educational stages exacerbates this situation. Studies by Kim and De Dear (2018) and Teli et al. (2012) highlight the significance of considering both climate and age range when designing classrooms.

Accounting for local climate conditions and students' age ranges during the design and implementation of classroom standards can significantly enhance the learning environment. Customizing classroom designs to suit specific age groups and local climate variations can improve comfort levels, positively impacting students' focus, well-being, and overall learning experiences.

This study explores the impact of building systems and clothing insulation on students' thermal comfort in classroom settings within Indonesia's hot and humid tropical climate. Given the lack of specific design guidelines for schools and classrooms in Indonesia, the findings of this research will serve as valuable guidance in developing standards for thermally comfortable schools and classrooms tailored to the unique Indonesian context.

1.5 Previous studies related to thermal comfort in classroom setting

This section examines prior research on thermal comfort in classrooms, with a focus on elementary, junior high, and senior high schools. It begins with a concise overview of global studies on thermal comfort before proceeding to a specific review of research conducted in Indonesian classroom settings. This discussion offers insights into the methodologies employed in previous studies, the typical thermal conditions within classrooms, and the thermal comfort experienced by students in various locations across Indonesia.

Romero et al. (2023), Singh et al. (2018), and Singh et al. (2019) have conducted extensive reviews of literature concerning thermal comfort in classroom settings worldwide. Their investigations revealed a trend of significant dissatisfaction among students regarding indoor thermal conditions across diverse educational levels, regardless of the ventilation system employed—be it air-conditioned or naturally ventilated (Singh et al., 2018, 2019). Remarkably, this dissatisfaction trend spans across both developing and developed countries (Auliciems, 1972, 1973; Humphreys, 1977; Kwok, 1998; Liang et al., 2012; Singh et al., 2019; Wong & Khoo, 2003; Yun et al., 2014).

A primary factor contributing to this dissatisfaction appears to stem from the absence of tailored standards addressing the thermal comfort requirements specific to educational buildings and classrooms (Singh et al., 2019). Such standards are essential for accommodating the specific thermal comfort needs of students at different educational stages. The lack of these standards results in educational facilities being designed without distinctive consideration for the unique thermal comfort demands of educational settings (Djongyang et al., 2010; Martinez-Molina et al., 2017; Stazi et al., 2017). This issue is particularly pronounced in Indonesia, where there is a notable absence of appropriate design guidelines for schools and classrooms, as well as a lack of a reliable thermal comfort standard grounded in local scientific research. Consequently, there exists a pressing need for research aimed at providing insights into designing thermally comfortable classroom environments tailored to the Indonesian context.

Given the widespread dissatisfaction with indoor thermal conditions in classrooms, it is evident that further research is required to identify effective strategies for improving thermal comfort. Such research not only holds significance for enhancing student satisfaction and learning outcomes, but also plays a crucial role in informing the development of pertinent standards and design practices tailored to educational environments.

Investigations into thermal comfort within Indonesian school classrooms are limited. Among the small volume literature available, only eleven relevant studies were identified. These studies were distributed across different educational levels: four in elementary schools (Amin, 2017; Delyuzir & Murni, 2019; Hamzah et al., 2016; Tayeb et al., 2016), four in junior high schools (Hamzah et al., 2018; Razak et al., 2015; Razak & Wulandari, 2020; Yunita et al., 2018), and three in senior high schools (Aienna et al., 2016; Gunawan & Ananda, 2017; Susanti & Aulia, 2013).

The research was predominantly conducted in urban areas located in lowland regions of Indonesia, characterized by temperatures ranging from 28.8°C to 34°C, with an average daily temperature of about 31.9°C and relative humidity ranging from 66% to 80%. Most of the classrooms under examination were naturally ventilated (Amin, 2017; Gunawan & Ananda, 2017; Hamzah et al., 2016, 2018; Razak et al., 2015; Tayeb et al., 2016). Aienna et al. (2016)

and Delyuzir and Murni (2019) conducted studies in classrooms equipped with fans in Banjarmasin and Jakarta, respectively. Furthermore, Susanti and Aulia (2013) conducted research in a classroom equipped with an air conditioning system.

Out of the eleven previous Indonesian classroom studies, not all were focused on assessing students' responses to the thermal environment of these classrooms. Studies by Gunawan and Ananda (2017), Razak et al. (2015), and Tayeb et al. (2016) relied solely on surveys to evaluate the thermal performance of classrooms. Their aim was to determine whether the thermal conditions in Indonesian classrooms complied with the criteria outlined by the Indonesian National Standard for thermal comfort.

Several previous studies on thermal comfort in Indonesian classrooms adopted different approaches, combining surveys, measurements, and observations to gather primary data aimed at understanding students' thermal comfort experiences and preferences in classroom environments. Personal data were acquired through observations of respondents' attire and activities. Measurements of air temperature, relative humidity, and air velocity were conducted to evaluate the indoor microclimate of the classrooms. Questionnaires were employed in certain studies to survey respondents and assess their level of thermal comfort. These questionnaires typically comprised several questions, covering aspects such as thermal sensation vote (TSV), thermal comfort vote (TCV), thermal preference, and thermal acceptance (Aienna et al., 2016; Razak & Wulandari, 2020). The TSV responses were assessed using the seven-point scale outlined in the ASHRAE standard 55, which evaluates the thermal sensation experienced by respondents (Aienna et al., 2016; Hamzah et al., 2018; Razak & Wulandari, 2020; Susanti & Aulia, 2013). In addition to capturing students' preferences regarding air temperature, Hamzah et al. (2018) included questions to gauge respondents' preferences for air velocity and humidity levels in the classrooms.

Amin (2017), Hamzah et al. (2020), and Susanti and Aulia (2013) utilized the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) index to evaluate students' thermal comfort. The PMV results were then compared with thermal sensation votes obtained from questionnaires. PMV model is considered the earliest classical thermal comfort model that was developed based on Franger's principle of human thermal heat balance (Van Hoof, 2008). Initially, this model was formulated and validated through experimental research on college-age subjects in controlled climate chambers, aiming to predict thermal comfort and optimum temperature in air-conditioned environments rather than naturally ventilated ones (Fanger, 1970; Van Hoof, 2008). Previous studies have indicated that the PMV model tends to either overestimate or underestimate thermal comfort, especially in naturally ventilated buildings (Abiodun, 2014; Hamzah et al., 2018, 2020; Jia et al., 2020; Van Hoof, 2008; Wong & Khoo, 2003). Given that most classrooms in Indonesia are designed as naturally ventilated buildings, the use of the PMV as a thermal comfort index for assessing students' thermal comfort may not be appropriate.

None of the prior studies conducted in Indonesia have utilized the Standard Effective Temperature (SET) as a metric for evaluating students' thermal comfort. According to ASHRAE Standard 55. Unlike the Predicted Mean Vote (PMV) model, where skin temperature and sweat rate are solely functions of metabolic activities, the SET index considers the effect of air velocity on both convective heat exchange and sweat evaporation (Gao et al., 2015). In comparison to the adaptive comfort model, which primarily considers the relationship between neutral temperature and outdoor temperature (De Dear et al., 1997), the Standard Effective Temperature (SET) may offer advantages due to its comprehensive consideration of multiple parameters (Ji et al., 2022). The SET index is deemed here to be more suitable for naturally ventilated buildings, particularly in hot and humid climates, as it incorporates the impact of air velocity on both convective heat exchange and sweat evaporation (Karyono, 2015; Zhang et al., 2010). Prior research suggests that SET can predict thermal sensation more accurately than PMV, especially in the context of naturally ventilated buildings (Zhang et al., 2010).

Out of the eleven previous studies conducted in Indonesia, only three offered thorough details concerning the clothing insulation of students' school uniforms worn during the survey. Hamzah et al. (2018) and Susanti and Aulia (2013) reported that male students typically wear short-sleeved shirts with trousers as their school uniform, while female students predominantly wear Muslim school uniforms that include a veil. Both studies concurred in assigning a clothing insulation value of 0.57 clo to male uniforms (Hamzah et al., 2018; Susanti & Aulia, 2013). As for the clothing insulation of female Muslim uniforms with a veil, Susanti and Aulia (2013) designated a value of 0.9 clo, while Hamzah et al. (2018) indicated a value of 0.8 clo. The discrepancy in the assigned clothing insulation values for Muslim school uniform ensembles may have arisen because ASHRAE did not provide information on clothing insulation for Muslim clothing ensembles with veils, necessitating guesstimates.

Furthermore, the study by Hamzah et al. (2016), which concentrated on elementary school classrooms in Makassar, reported that 89.3% of the students wore vests on top of their uniforms, while 99% of female students wore veils. These observational data indicate that male students' uniforms have lower clothing insulation than those of females. Given that clothing insulation is one of the variables influencing thermal comfort, the differences between male and female students' clothing insulation may further affect their thermal acceptability. However, none of the previous studies compared the thermal comfort response between male and female students to determine whether gender and uniform style have an influence on students' thermal comfort.

Previous Indonesian studies have documented that classroom environments consistently exhibit elevated thermal conditions, exceeding the thermal comfort boundaries outlined in both the ASHRAE 55 standard and the Indonesian National Standard (Aienna et al., 2016; Delyuzir & Murni, 2019; Gunawan & Ananda, 2017; Hamzah et al., 2016, 2018; Razak et al., 2015; Razak & Wulandari, 2020; Susanti & Aulia, 2013). Specifically, Hamzah et al. (2018) reported indoor air temperatures ranging from 28.2°C to 33.6°C, with an average of 30.8°C, in surveyed secondary classrooms in lowland Makassar. The radiant temperatures in these classrooms mirrored the air temperature, indicating minimal airflow (Hamzah et al., 2018). Similarly, Susanti and Aulia (2013) observed temperatures during school hours ranging from 27°C to 30°C, with relative humidity ranging from 68% to 80% in classrooms in lowland Padang. In lowland Mandau, Gunawan and Ananda (2017) found temperatures ranging from 27.7°C to 36.6°C during school hours. Previous studies confirmed extremely low air velocities in surveyed classrooms, varying from 0 m/s for naturally ventilated classrooms to 0.5 m/s for those equipped with ceiling fans (Susanti & Aulia, 2013).

Despite the prevalent hot thermal environments with elevated temperatures and low air velocities in most surveyed classrooms, research indicates variations in students' responses to their classroom thermal conditions. In lowland Banjarmasin, Aienna et al. (2016) noted that senior high school students began feeling discomfort due to heat around 10:00 am. Similarly, in surveyed classrooms in Makassar, Hamzah et al. (2016) found that 67.9% of the total 11,111 elementary school students experienced discomfort due to thermal conditions and desired increased indoor air velocity. However, in secondary schools in Makassar surveyed by Hamzah et al. (2018), 80% of the 1,594 respondents found the elevated temperature acceptable, although 87% would prefer a temperature decrease. Despite this tolerance, 70% of students in surveyed secondary classrooms in Makassar expressed a preference for increased indoor air velocity. These findings underscore the significance of air movement in enhancing thermal comfort without necessarily requiring reduced temperature, as suggested by Mochida et al. (2005). Moreover, they align with arguments by Zamri et al. (2019), emphasizing the critical role of ventilation in influencing indoor environments and subsequent thermal comfort in naturally ventilated buildings.

Hamzah et al. (2018) calculated the neutral temperature for students in surveyed secondary school classrooms in lowland Makassar. Using a simple linear regression between thermal sensation vote (TSV) and operative temperature (To), they determined a neutral temperature of 29°C for students (Hamzah et al., 2018). This finding explains secondary students' inclination to request a temperature decrease when it exceeds 30°C, despite their assertion of being able to tolerate it (Hamzah et al., 2018).

Analysis of prior research on thermal comfort in classrooms within Indonesia's hot and humid tropical climate has identified several research gaps that need to be addressed. Previous studies indicate that Indonesian students express a preference for cooler temperatures and enhanced air circulation in classrooms. This underscores the need for additional research aimed at devising strategies to enhance students' thermal comfort within classroom environments.

1.6 Research Significance

The overarching aim of this thesis is to propose strategies to optimize the thermal comfort of students in Indonesian classrooms. It is crucial to ensure a comfortable learning environment, as previous research has argued the significant influence of students' thermal comfort on their health, productivity, and academic performance. Thermal discomfort in the classroom leads to decreased attention and concentration, ultimately hindering students' learning outcomes and achievements (Brink et al., 2021; Wargocki & Wyon, 2017).

This research is focused on Indonesia, where there are currently no specific occupant-centric design guidelines for school buildings and classrooms. Previous studies have indicated that Indonesian students are dissatisfied with the thermal conditions in classrooms, expressing a preference for cooler temperatures. Given Indonesia's status as a developing country with a hot and humid tropical climate, designing thermally comfortable learning environments poses a significant challenge, especially without established design guidelines. To address existing research gaps, the study will focus on regions in both lowland coastal areas and highland areas, representing the diverse hot and humid tropical climate of Indonesia. This approach will fill the gap left by the absence of previous studies conducted in the highland regions of Indonesia.

This study incorporates the Standard Effective Temperature (SET) index as a tool to assess students' thermal comfort in Indonesian classrooms. The SET index is considered to be a suitable comfort index for the context of naturally ventilated buildings, particularly in hot and humid climates (Karyono, 2015; Zhang et al., 2010), as it incorporates the impact of air velocity on both convective heat exchange and sweat evaporation. The absence of previous studies using the SET index in Indonesia's hot and humid climate highlights a significant gap in the literature. Therefore, this research provides valuable insights into the thermal comfort levels in naturally ventilated buildings in the context of the hot and humid climate of Indonesia.

Furthermore, this research is important as it examines the clothing insulation of Indonesian Muslim school uniforms, a key focus of the study. Clothing insulation plays a crucial role in determining thermal comfort, and proper clothing adjustments can greatly expand the comfort range. Indonesia, with one of the world's largest Muslim populations, incorporates Islamic cultural influences in the design of school uniforms. Female students typically wear veils and long garments covering much of their bodies, which necessitates an investigation into how these uniforms affect students' thermal comfort in classrooms. Additionally, measuring the thermal insulation of Indonesian school uniforms contributes valuable insights to our understanding of clothing insulation in various Eastern-style attire ensembles. The results of this study are also expected to provide insight into strategies for designing school uniforms which are not only thermally comfortable, but also aligned with the Islamic values held by Indonesian Muslim women.

1.7 Research objectives

The overarching objective of this research is to improve students' thermal comfort in Indonesian classrooms. This will be achieved through four research objectives, as follows:

1. To examine the impact of Indonesian Muslim school uniforms on students' thermal comfort in the classroom
2. To assess the thermal performance of Indonesian classrooms
3. To assess the comfort responses in Indonesian classrooms
4. To propose a strategy to optimise thermal comfort in Indonesian classrooms

1.8 Research scope

This study aims to offer insights into strategies for optimizing students' thermal comfort in Indonesian classrooms. Nonetheless, it is essential to acknowledge the scope of the research pertaining to the instruments and research methodology. Acknowledging the research scope is crucial for comprehending the extent and relevance of the findings presented in this study. In this section, the primary constraints and challenges encountered during the research process are delineated.

1.8.1 Study case

This study involves the evaluation of the simulated indoor microclimate of Indonesian classrooms. However, the simulation was limited to two cities chosen to represent the variation of local climate and geographical conditions of Indonesia. The first city selected was Surabaya, representing a lowland coastal region characterized by higher daily temperatures. The second city chosen for the case study was Ruteng, representing a highland mountainous area with lower daily temperatures.

1.8.2 Data collection and instruments

This research involves laboratory measurements using a thermal manikin to measure the clothing insulation of various Indonesian Muslim school uniform ensembles, as well as computer simulations to estimate indoor air velocity and thermal performance within Indonesian classrooms.

The thermal manikin used in this research is a dry heat (convection plus radiation) model, available at the University of Sydney's Indoor Environmental Quality Laboratory. This type of manikin simulates dry-heat loss from the body and comes with standard components and measurements (Tanabe et al., 1994). However, considering the focus on a hot and humid tropical region, utilizing a sweating thermal manikin may have offered advantages over the dry version (Ooka et al., 2010; F. Wang, 2017).

In the subsequent research phase, data on classroom thermal performance was gathered through computer simulations, using annual weather data as input. While computer simulations offer numerous benefits, such as cost-effectiveness, control, accessibility, flexibility, and predictive capabilities, they also pose certain challenges. One significant hurdle is creating accurate models that faithfully represent real-world phenomena. Moreover, simulations often rely on simplifications that may not fully capture the complexity of real-world conditions, potentially leading to inaccuracies or biases in the results.

1.8.3 Method of validating for simulation

Due to the inaccessibility of field work in Indonesia during the pandemic, it was not possible to validate the simulation models on-site in Indonesia. Obtaining actual data for Indonesian classrooms was challenging, so validation was conducted in Sydney using classrooms that resembled those in Indonesia. While this method may not replicate real-world conditions entirely, it was the most feasible option available.

1.8.4 Analysis method

One of the analyses conducted in this study aims to evaluate the thermal comfort response of Indonesian students in classrooms. A crucial preliminary step in this process involves determining the neutral temperature for the two selected cities, Surabaya and Ruteng, which serve as lowland coastal and highland exemplars. Given the absence of reliable thermal comfort standards in Indonesia, the research relies on Karyono's empirical Indonesian equation (Karyono, 2015) to establish the neutral temperature for both cities.

Karyono's study, entitled "Predicting Comfort Temperature in Indonesia, an Initial Step to Reduce Cooling Energy Consumption" (Karyono, 2015), introduced a pioneering thermal comfort predictor for Indonesia. This simple equation was designed to accurately forecast comfort temperatures nationwide. It was derived from a comprehensive reanalysis of 2,939 thermal comfort votes gathered across twelve prior studies conducted in six major Indonesian cities: Jakarta, Surabaya, Makassar, Medan, Bandung, and Yogyakarta (see Figure 1.2). Given its broad dataset, this equation serves as a solid foundation for determining the neutral temperatures in the cities selected for this study.

Nonetheless, Karyono's predictor has its constraints. It was formulated using data from cities where average daily temperatures range between 24°C and 29°C, making it most applicable to areas within this thermal bracket. Ruteng, one of the case study locations situated in the highlands, exhibits an average daily temperature of 22.1°C—slightly below the range Karyono's model was designed to address. This study will still utilize Karyono's equation to estimate the neutral temperature in Ruteng due to the absence of more applicable models.

1.9 Thesis structure and content

This thesis is structured into five chapters: Chapter 1 provides an introduction, Chapter 2 details the study’s methodology, Chapter 3 presents the results, Chapter 4 discusses these results, and Chapter 5 offers a conclusion. This thesis does not include a standalone literature review chapter. Instead, the literature review is integrated into the introduction and methodology sections to enhance cohesion and minimise redundancy. Foundational and recent literature that frames the research problem and situates the study within existing knowledge is presented in the introduction, while literature supporting the research methods, data collection, and analysis techniques is discussed in the methodology section.

Chapter 1 (Introduction)

The introduction chapter serves as the foundation for the entire research endeavour, providing an overview of the study's background, purpose, and importance. It commences by contextualizing the research, delving into the broader problem area, and pinpointing specific gaps in the existing literature that the study aims to fill. Following this, it presents clear research questions and objectives, articulating precisely what the study seeks to accomplish. Furthermore, the chapter delineates the research's scope, as well as defining any boundaries or limitations. It underscores the significance of the research, elucidating how the findings could contribute to both theoretical understanding and practical applications. Lastly, the introduction provides a brief overview of the thesis structure, summarizing the content of subsequent chapters to guide the reader through the document.

Chapter 2 (Methodology)

The methodology chapter delineates the procedures and techniques employed for data collection, analysis, and interpretation, each aligned with specific research objectives. It commences by exploring the research design and expanding on the rationale behind its selection. Detailed descriptions of sampling methods are provided in this chapter, including the selection process for school uniform ensembles and case study cities, along with the design of the simulation model. This chapter also offers an extensive account of data collection methods, detailing environmental conditions and procedures for measuring clothing insulation, simulation details, and chosen parameters. Additionally, it covers the validation procedures for the simulations and presents the outcomes of these validations.

Furthermore, the methodology chapter elaborates on the data analysis methods used, including the specific thermal comfort index employed to evaluate students' thermal comfort. It describes the calculation processes for determining the neutral temperature and the range of comfort temperatures for each case study city, as well as the method for calculating the percentage of yearly comfortable hours, which serves as a primary tool for assessing student comfort in Indonesian classrooms.

The structure of the methodology chapter is influenced by the "third skin" analogy from architectural discourse, particularly in the context of thermal comfort (Drake, 2007). This analogy likens the built environment to a protective layer, similar to human skin, where the first skin corresponds to the body's physiological response to temperature changes, the second skin to clothing for thermal adaptation, and the third skin to the architectural elements that modulate the indoor climate.

The methodology chapter is divided into three sub-chapters, each focusing on distinct aspects of the study's procedures and techniques. Sub-chapter 2.1 explores the "second skin," focusing on the impact of clothing insulation from Indonesian Muslim school uniforms on indoor environmental comfort, aiming to fulfill the first research objective. Sub-chapter 2.2 investigates the "third skin," examining the building systems as barriers between the indoor classroom environment and the exterior, aiming to address the second research objective through CFD and thermal simulations. Lastly, Sub-chapter 2.3 examines the "first skin," studying students' physiological responses to thermal comfort, with methodologies designed to meet the third research objective.

Chapter 3 (Results)

The results chapter presents the findings from data analysis, excluding any interpretation. It commences with a succinct overview of the analysis objectives and the chosen research variables to provide context. Subsequently, the chapter delves into the outcomes of data collection using visual aids like tables, graphs, and charts for clarity. Trends are described without interpreting the results.

In alignment with the preceding chapter, this results chapter follows the concept of the "three skins" in architectural discourse and thermal comfort (Drake, 2007). It is divided into three distinct sub-chapters, each focusing on different aspects related to the analogy of the third, second, and first skin, respectively.

Sub-chapter 3.1 presents results derived from measurements and calculations of the thermal insulation properties of various Indonesian Muslim school uniforms, alongside an analysis of the factors influencing them. Sub-chapter 3.2 provides insights garnered from simulating microclimates of Indonesian classrooms in Surabaya and Ruteng, reflecting the diverse climatic conditions in Indonesia. Lastly, sub-chapter 3.3 illustrates the findings obtained from calculating students' thermal comfort responses in Indonesian classrooms in the selected cities, utilizing the Standard Effective Temperature (SET) index for a standardized and comprehensive assessment.

Chapter 4 (Discussion)

The discussion chapter focuses on interpreting and contextualizing the research findings in relation to the existing body of knowledge. This chapter begins by succinctly summarizing the main results, emphasizing how they address the initial research objectives outlined in the introduction. It then delves into a deeper analysis of these findings, discussing their implications and how they compare with or diverge from the results of previous studies. This includes a thoughtful examination of any surprising or significant trends observed in the data, backed by theoretical or empirical justifications.

Like the preceding chapters, Chapter 4 is divided into three sub-chapters, employing the "third skin" analogy to structure the discussion. Sub-chapter 4.1 focuses on the "second skin," specifically investigating the impact of clothing insulation from Indonesian Muslim school uniforms on students' thermal comfort. Sub-chapter 4.2 explores the thermal performance of classrooms in Surabaya and Ruteng through simulation, analysing the influence of various architectural elements on classroom temperature. Finally, sub-chapter 4.3 examines students' thermal comfort responses, utilizing the Standard Effective Temperature (SET) index. It identifies trends in thermal comfort across different classroom settings and proposes strategies to improve thermal comfort for Indonesian students in diverse educational environments.

Chapter 5 (Conclusion)

The conclusion chapter serves as a synthesis of the main findings of the study and highlights their significance within the academic field. It begins by restating the research objectives or questions and offers a concise summary of the key findings, underlining the study's contribution to existing knowledge. This chapter goes beyond mere summary, critically reflecting on the implications of the findings, including their practical, theoretical, and policy implications. It addresses the strengths and limitations of the study, highlighting how these aspects influence the validity and applicability of the results. Additionally, the conclusion offers recommendations for future research, suggesting specific areas where further inquiry could provide additional insights or address unresolved issues.

Chapter 2 Methodology

2.1 Overall methodology

As described in the preceding chapter, the primary aim of this study is to enhance thermal comfort within Indonesian classrooms. This overarching objective is achieved through four research objectives, as follows:

1. To examine the impact of Indonesian Muslim school uniforms on students' thermal comfort in the classroom
2. To assess the thermal performance of Indonesian classrooms
3. To assess the comfort responses of students within Indonesian classrooms
4. To propose strategies to optimise thermal comfort in Indonesian classrooms

To comprehensively investigate the research inquiries, this study uses laboratory-based measurements and computational simulations. Data acquisition proceeded through three phases: laboratory-based measurements utilizing thermal manikins, computational simulations, and assessment of thermal comfort responses.

The initial phase of data collection aimed to measure the thermal insulation properties of various Indonesian Muslim school uniforms. This study utilized a thermal manikin positioned within the Indoor Environmental Quality (IEQ) Laboratory at the University of Sydney, as described by de Dear et al. (2013), to conduct this examination.

The second phase of the research aimed to simulate the microclimatic conditions prevalent within Indonesian classrooms. This encompassed the simulation of indoor parameters such as air velocity, air temperature, mean radiant temperature, operative temperature, and relative humidity. The computational simulation encompassed the application of Computational Fluid Dynamics through the utilization of OpenFOAM (The OpenFOAM Foundation, 2011), using

Butterfly plugins of Grasshopper (Ladybugs Tool LLC, 2017) to model indoor air velocity. Additionally, the Honeybee and Ladybug plugins (Roudsari & Pak, 2013)—in conjunction with Grasshopper, Open Studio (National Renewable Energy Laboratory & US Department of Energy, n.d.), and EnergyPlus—were employed to simulate the thermal conditions within Indonesian classrooms.

In the subsequent phase, the thermal comfort response of students in Indonesian classrooms was assessed using the Standard Effective Temperature (SET) comfort model proposed by Gagge (1971). Analysis was conducted to determine the percent of yearly comfortable occupied hours, facilitating the selection of optimal variable combinations to achieve maximum comfort in the classroom setting. Ultimately, the outcomes of this analysis informed the formulation of strategies to optimize thermal comfort in Indonesian classrooms. Figure 2.1 below presents a schematic representation of the research process for reference.

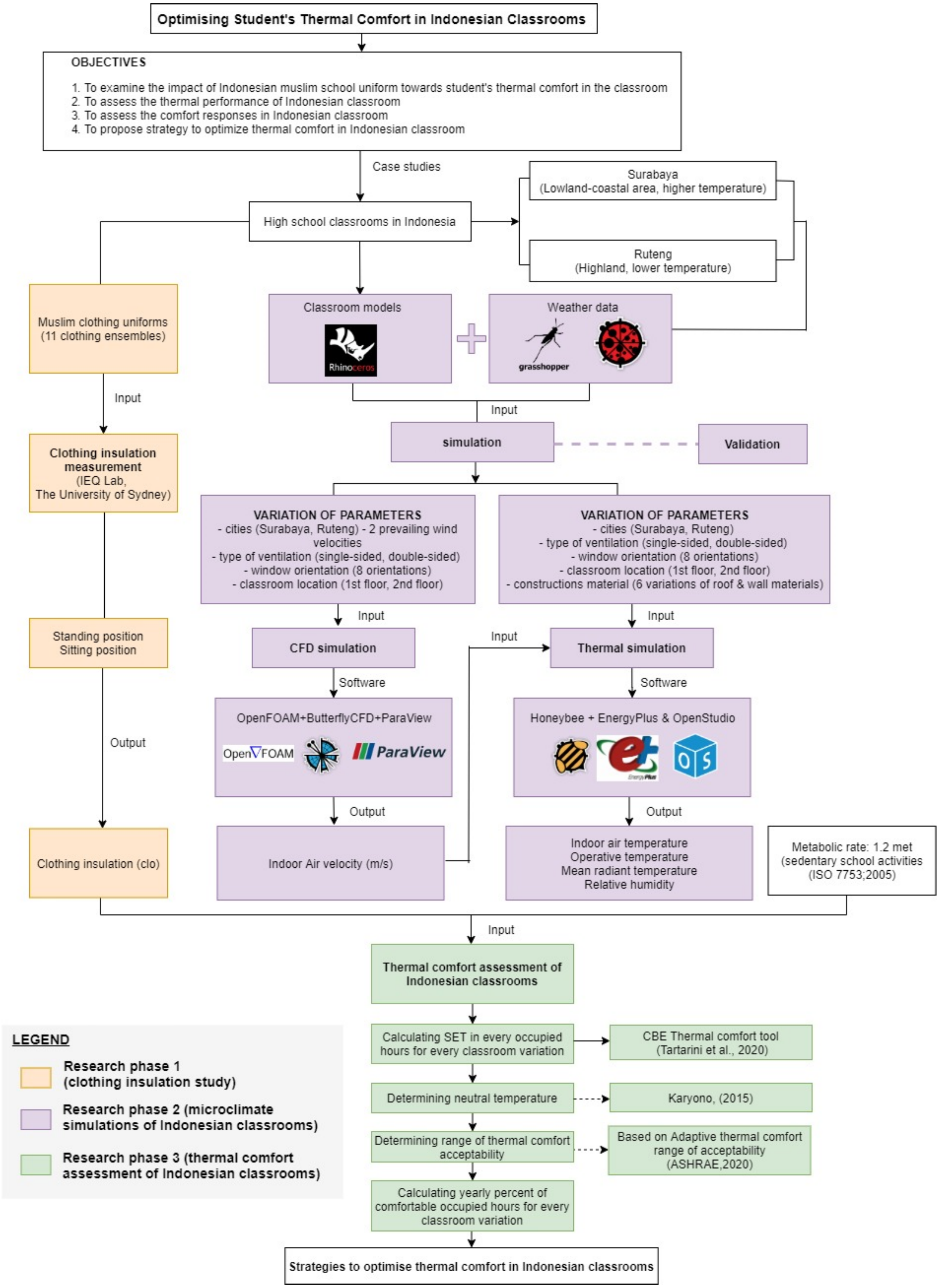


Figure 2.1 Schematic diagram of research process

The methodology chapter is structured around the concept of the "third skin" analogy, drawn from architectural discourse and particularly relevant to discussions of thermal comfort (Drake, 2007). The "third skin" metaphor conceptualizes the built environment as a protective layer akin to the first and second skins of the human body. While the first skin represents the physiological responses of the human body to temperature variations, and the second skin refers to the clothing worn for thermal adaptation, the third skin denotes the built environment itself, including architectural elements, materials, and systems that collectively influence the indoor climate.

In alignment with this analogy, Sub-chapter 2.2 of this chapter aims to delve into the concept of the second skin. It outlines the methodology utilized in the initial phase of the research, focusing on the measurement of thermal insulation in various Indonesian Muslim school uniforms. In Sub-chapter 2.3, the focus shifts to comprehending the role of the third skin. This section outlines the methodology employed in the second phase of the research, which involves simulating the microclimates of Indonesian classrooms. Lastly, Sub-chapter 2.4 aims to understand the response of the first skin. This section outlines the methodology employed in the third phase of the research, which pertains to assessing students' thermal comfort responses in Indonesian classrooms.

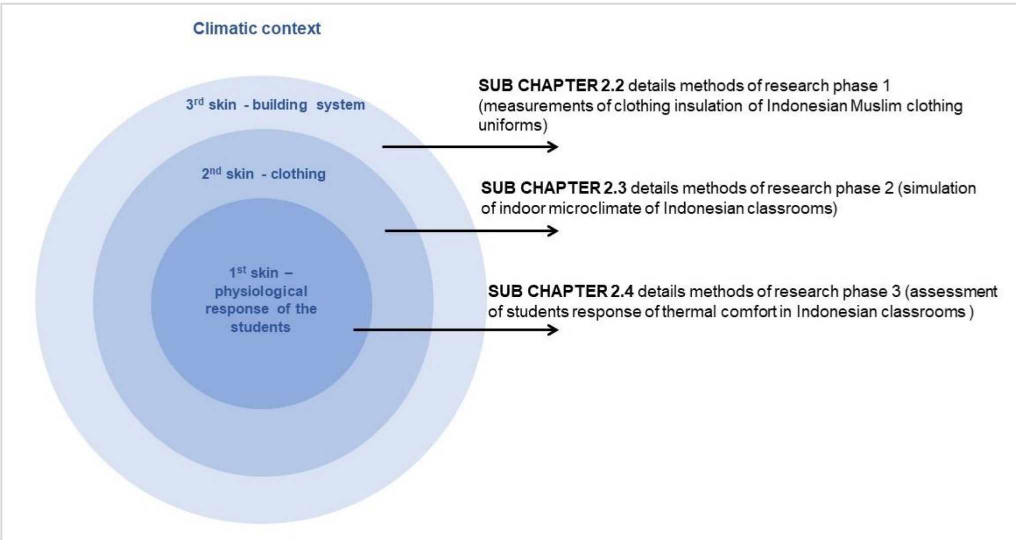


Figure 2.2 The “third skin” analogy used to structure the methodology chapter

2.2 Clothing insulation measurement with a thermal manikin

This section delineates the method employed for measuring clothing insulation using a thermal manikin. It commences with a literature review concerning clothing insulation and its influencing factors, offering a foundational understanding of the concept and considerations for ensemble selection in research. Subsequently, it provides detailed descriptions of the chosen ensembles. Lastly, the section elucidates the procedures for measuring clothing insulation with a thermal manikin, including the environmental conditions during thermal manikin measurements.

2.2.1 Thermal insulation of clothing ensemble

Clothing insulation stands as a pivotal parameter in the evaluation of thermal comfort (ASHRAE, 2020; Fanger, 1970; Havenith, 2002). Proper adjustment of clothing has the potential to significantly expand the range of comfort; therefore, it is crucial to carefully examine clothing insulation in order to optimize thermal comfort (Wang et al., 2019). The concept of the 'clo' unit, introduced by Gagge et al. (1941), quantifies the thermal resistance of clothing, referred to as 'clothing insulation’. It is important to note that clothing insulation not only characterizes the heat transfer attributes of fabrics but also accounts for air movement within clothing caused by bodily motions or wind.

The measurement of the thermal resistance of clothing materials is typically conducted either using human subjects or thermal manikins. A thermal manikin, a full-sized human model equipped with standard measurements and components designed to simulate dry-heat loss from a human body, has been adopted extensively by researchers (Tanabe et al., 1994). It serves to augment the database of clothing insulation (Al-ajmi et al., 2008; Bouskill et al., 2002; Gao et al., 2023; Havenith et al., 1990, 2013, 2015; Lei, 2019; Tang et al., 2022) as it faithfully replicates the manner in which clothing is worn. Quantifying the thermal behaviour of clothing on an individual is inherently complex due to its dynamic nature, which is influenced by various factors (Parsons, 2014). Consequently, owing to its simplicity, repeatability of experimental procedures, and precision of results, thermal manikins represent the prevalent tool for measuring clothing thermal insulation (British Standards Institution, 2009; Lei, 2019).

In elucidating the sensible heat loss from the skin to the environment through clothing and the computation of ensemble thermal resistance, various terminologies are employed in the literature (British Standards Institution, 2009). These terminologies encompass total clothing insulation (I_{T}), boundary air insulation (I_{a}), intrinsic insulation (I_{cl}), and clothing area factor (f_{cl}). Total clothing insulation, denoted as (m² °C W⁻¹), encapsulates thermal insulation from the skin surface to the surrounding environment, encompassing enclosed air, clothing layers, and surface air layers. Intrinsic clothing insulation (I_{cl}) encompasses thermal insulation from the skin surface to the outermost clothing layer, accounting for enclosed air and clothing layers. Boundary air insulation (I_{a}) represents thermal insulation of the boundary air layer surrounding the outer clothing or, in the absence of clothing (nude condition), around the skin. The clothing area factor (f_{cl}) is defined as the ratio of the outer surface area of a clothed human body to that of an unclothed human body. This study particularly focuses on intrinsic clothing insulation (I_{cl}), a key parameter employed in various thermal comfort indices and thermoregulation models (Fiala et al., 2001; S. Gao et al., 2023; Huizenga et al., 2001). A schematic representation illustrating total, intrinsic, and air insulation is provided in Figure 2.3.

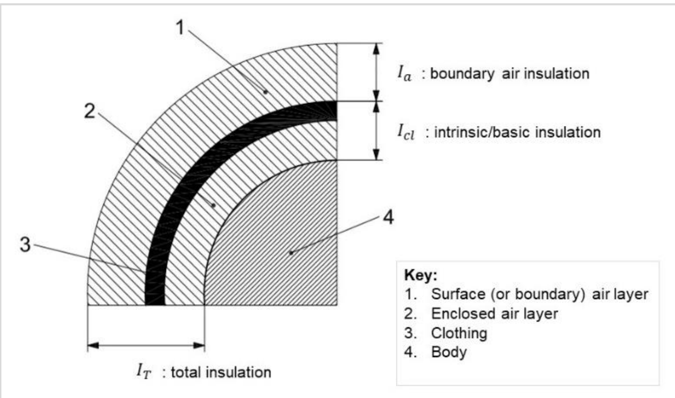


Figure 2.3 Schematic representation of clothing system; total, intrinsic, and air insulations. Source: ISO 9920:2009

2.2.2 Factors influencing clothing insulation

Previous studies have revealed that the thermal insulation of clothing is significantly influenced by a multitude of factors. These factors encompass various fabric structural and physical properties, including thickness and fabric weave (Atasagun et al., 2019), fabric permeability (Bouskill et al., 2002; Havenith et al., 1990). Design elements of apparel, such as clothing fit (Atasagun et al., 2019; Bouskill et al., 2002; Chen et al., 2004; Ke & Wang, 2020; Mert et al., 2016), clothing ventilation (Bouskill et al., 2002), and wearing style (Li et al., 2012), also exert a substantial impact. Furthermore, environmental conditions, such as wind velocities and wind direction (Bouskill et al., 2002; Havenith et al., 1990; Havenith & Nilsson, 2004; Młynarczyk, 2019; Vogt et al., 1983), have been demonstrated to be influential factors affecting clothing insulation. Human body movement (Havenith et al., 1990; Lu et al., 2015) and body posture (Gao et al., 2023; Havenith et al., 1990) likewise play a crucial role in determining clothing thermal insulation.

Chen et al. (2004), Havenith et al. (1990), and Ke and Wang (2020) conducted empirical research to gauge the effect of clothing fit on clothing insulation across varying wind speeds, including low, moderate, and high wind speeds. The consensus in prior research is that loosely fitting attire generally affords greater thermal insulation than tight-fitting garments, particularly in conditions of low wind speed. For instance, Chen et al. (2004) and Havenith et al.(1990) found that tight-fitting ensembles exhibited 6-31% less insulation than their loose-fitting counterparts.

Moreover, Chen et al. (2004) and Ke and Wang (2020) observed that, in calm or nearly windless conditions, thermal insulation progressively increases with the enlargement of the air gap, peaking at approximately 1 cm thickness—an approximate 7.5 cm difference in girth between the garment and the body (Chen et al., 2004). A parallel trend was discerned in windy conditions, albeit with slightly lower thermal insulation values compared to no-wind conditions. This phenomenon can be elucidated by the principle that thermal insulation occurs when air trapped beneath clothing is warmed by the body, thereby minimizing heat loss. Loose-fitting clothing permits a greater volume of air to become trapped under the attire, resulting in heightened clothing insulation. However, excessive looseness in attire allows for the release and circulation of trapped air with the surrounding environment, resulting in a decline in insulation beyond the maximum threshold. This phenomenon primarily arises due to the presence of natural or forced convection within the clothing microclimate (Młynarczyk, 2019).

Chen et al. (2004) found that the existence of wind has the potential to disrupt the air that becomes trapped within clothing. The presence of wind in the surrounding environment has the effect of augmenting the convective heat transfer coefficient. Additionally, it can exert pressure on clothing or infiltrate via gaps in clothing, leading to a hastened reduction in overall thermal insulation (Młynarczyk, 2019). Existing literature supports the notion that the acceleration of wind velocity and the augmentation of clothing apertures can potentially lead to a reduction in clothing insulation. According to Młynarczyk (2019), theoretical analysis indicates that alterations in air velocity beyond the threshold of 0.3-0.5 m/s exert a substantial influence on the overall thermal insulation. Młynarczyk (2019) investigated the impact of wind on the insulating properties of three distinct clothing ensembles, with thermal resistance values ranging from 0.7 to 1.6 clo. The experiment involved the application of three varying air velocities, specifically 0.4 m/s, 0.8 m/s, and 1.2 m/s. It was observed that irrespective of the number of layers present in the ensembles, an increase in air velocity from 0.4 to 0.8 m/s resulted in a reduction in thermal insulation by around 13-14% when employing the serial technique computation, and by approximately 14-17% when utilising the parallel methods. Additionally, Młynarczyk (2019) stated that an increase in air velocity (Va) from 0.4 to 1.2 m/s resulted in a threefold increment. The number of material layers was also found to have an impact on the reduction of insulating value. The reduction in garment insulation value is directly proportional to the decrease in the number of material layers. According to Chen et al. (2004), loose-fitting ensembles saw a more significant decrease in thermal insulation due to the presence of wind, accounting for 25% of the drop, while tight-fitting ensembles accounted for 24% of the reduction in thermal insulation.

Another significant determinant of clothing insulation is the posture and movements of individuals wearing such clothing ensembles. Gao et al. (2021) and Havenith et al. (1990) investigated the influence of air velocity and body posture on clothing insulation. Their research revealed that the intrinsic clothing insulation for a standing posture exceeded that of a sitting posture. While the previous studies concur that clothing insulation in a sitting position is lower, they report varying magnitudes of difference. Havenith et al. (1990) noted a 6-31% reduction, while Nishimura et al. (1994) observed a 14% decrease, and Gao et al. (2021) reported a 15% difference. The variations in reported differences in clothing insulation between standing and sitting positions may be due to differences in the types of chairs used in prior studies (Havenith et al., 1990).

Gao et al. (2023) stated that the reduction in clothing insulation in the sitting posture may be attributed to the compression of clothing in the back and thigh areas, resulting in a thinner air layer compared to that in a standing posture, as suggested by ISO 9920:2009 (British Standards Institution, 2009). Furthermore, Gao et al. (2023) corroborated this finding, noting that while intrinsic clothing insulation for the standing posture was greater in most body segments compared to the sitting posture, statistically significant differences were only observed at the pelvis and thigh regions due to the compression of the enclosed air layer in the sitting posture.

Concerning movement, Havenith et al. (1990) and Nielsen et al. (1985) concurred that activities such as walking and bicycling diminish clothing insulation. Physical movements during these activities induce the circulation of air trapped within clothing, leading to increased convective heat transfer and reduced thermal insulation. Moreover, during movement, the pumping effect, contingent on air temperature, may either augment or diminish the total resultant thermal insulation (Vogt et al., 1983). Human movements generate variations in the enclosed air volume, inducing airflow (pumping effect) and heightening forced convective heat transfer within enclosed air layers and around the human body. Consequently, human movement diminishes effective total thermal insulation due to increased convective heat transfer and ventilation through fabric and openings (Berger, 1988; Joshi et al., 2021).

The insights garnered from research into the factors influencing clothing insulation are invaluable for designing thermally comfortable attire suitable for diverse activities within varying thermal environments. This study's specific context pertains to naturally ventilated classrooms situated in the hot and humid tropical climate of Indonesia. In such naturally ventilated classrooms, indoor air velocity predominantly relies on external wind conditions. Given the typically low wind speeds in many Indonesian cities, indoor air movement within classrooms tends to be minimal. This condition is unfavourable as the presence of air movement is critical for achieving thermal comfort, particularly in hot and humid climates, as it facilitates the evaporation of sweat, thus preventing discomfort. Additionally, indoor air movement helps reduce clothing insulation, aiding heat dissipation from the body.

In terms of clothing insulation, prior research consistently indicates that the presence of wind contributes to reduced clothing insulation values. Low-insulation clothing ensembles offer increased breathability and heat dissipation, essential attributes for ensuring comfort in the hot and humid tropical climate. Given the low wind speeds within these naturally ventilated classrooms, relying on wind to lower clothing insulation becomes impractical. Consequently, clothing ensembles must be meticulously designed to adapt to climate conditions, thereby facilitating thermal comfort for occupants. Within the scope of this research, factors associated with clothing insulation, as gleaned from previous research, will serve as crucial determinants in the selection of ensembles earmarked for testing.

2.2.3 Ensembles selection

Figure 2.4 depicts the four primary clothing ensembles selected for measurement in this study. Two of these ensembles conform to the national Indonesian high school uniform standards, as outlined in Regulation Number 50 of 2022 by the Ministry of Education, Culture, Research, and Technology (Kemdikbudristek Republik Indonesia, 2022) see Figure 2.4 (a) and (b)). Additionally, scout uniforms, as specified by the Indonesian National Quartier of The Scouts (Kwartir Nasional Gerakan Pramuka, 2012), were included for measurement (see Figure 2.4 (c)). Another ensemble consists of long-sleeve shirts and trousers, including a hijab (see Figure 2.4 (d)). While Indonesian school uniform regulations traditionally designate trousers for boys and skirts for girls, the inclusion of long-sleeve shirts and trousers (with hijab) reflects the anticipation of lower clothing insulation compared to ensembles featuring long skirts, particularly those paired with leggings.

Figure 2.4 Four primary clothing ensembles selected for measurements

Figure 2.4 (a) displays an ensemble with a long-pleated skirt, whereas both Figures 2.4 (b) and (c) show ensembles with a long-span skirt. A pleated skirt is characterized by folds or pleats in the fabric, created by folding the material back and forth in a specific pattern, resulting in a structured and often voluminous appearance. In contrast, a span skirt is typically a form-fitting garment that conforms to the body's curves and often features a narrow, straight cut.

According to Chen et al. (2004); Havenith et al. (1990), and Ke and Wang (2020), garment fit can influence clothing insulation. Therefore, the differing characteristics and fits of pleated skirts and span skirts might offer variations in the insulation of the ensembles chosen for measurement in this research.

Beyond these four primary ensembles, several additional ensembles were curated for testing. These supplementary ensembles were derived from the primary set but incorporated modifications in terms of the manner of clothing worn (tucked-in versus untucked shirt), and the inclusion of an extra layer of lower underwear (legging) being a customary choice among Indonesian women when wearing a skirt. The modification of clothing style, specifically the tucked-in versus untucked shirt, was chosen for this research because different styles of wearing might have influenced the formation of clothing apertures within the ensembles. As noted by Młynarczyk (2019), clothing apertures could reduce clothing insulation. Conversely, the inclusion of leggings as an additional layer beneath the skirt might increase clothing insulation in conditions of still air velocity. Therefore, these factors were selected as determinants in the selection of ensembles to be measured in this study. By comparing the clothing insulation of several ensembles with different combinations of factors, we aimed to gain insights into the design of school uniforms that are thermally comfortable for naturally ventilated classrooms in Indonesia and meet the requirements of Islamic culture.

All selected ensembles were measured in two different body postures: standing and seated. This decision acknowledges the fact that the primary classroom engagements of students generally occur while they are seated. In conclusion, a total of 22 measures were obtained by assessing 11 different ensembles in both standing and sitting postures. Table 2.1 contains comprehensive information regarding the selected ensembles.

Table 2.1 Detail of selected ensembles for measurement

Ensemble Category	Code	Notes	Garments		Material	Weight (kg)
Long-sleeve shirt with span skirt (B)	B1.1	long span skirt + long-sleeve loose-fitting shirt not tucked in	Head cover	Inside hijab	spandex+polyester	0.045
				Hijab/head scarf	cotton+polyester	0.125
			Upper body clothing	Bra	cotton+polyester	0.1
				Undershirt, sleeveless	cotton	0.08
				Long-sleeve shirt medium fitting	cotton+polyester	0.22
			Lower body clothing	Panties	cotton	0.04
				Span skirt	cotton+polyester	0.31
				Socks	cotton+spandex	0.03
				Shoes	cotton canvas + rubber	0.725
	B1.2	long span skirt + long-sleeve loose-fitting shirt not tucked in + legging	Head cover	Inside hijab	spandex+polyester	0.045
				Hijab/head scarf	cotton+polyester	0.125
			Upper body clothing	Bra	cotton+polyester	0.1
				Undershirt, sleeveless	cotton	0.08
				Long-sleeve shirt	cotton+polyester	0.22
			Lower body clothing	Panties	cotton	0.04
				Legging	spandex+polyester	0.18
				Span skirt	cotton+polyester	0.31
				Socks	cotton+spandex	0.03
				Shoes	cotton canvas + rubber	0.725
	B2.1	long span skirt + long-sleeve medium-fitting shirt tucked in	Head cover	Inside hijab	spandex+polyester	0.045
				Hijab/head scarf	cotton+polyester	0.125
			Upper body clothing	Bra	cotton+polyester	0.1
				Undershirt, sleeveless	cotton	0.08
				Long-sleeve shirt medium fitting	cotton+polyester	0.22
			Lower body clothing	Panties	cotton	0.04
				Span skirt	cotton+polyester	0.31
				Socks	cotton+spandex	0.03
				Shoes	cotton canvas + rubber	0.725
	B2.2	long span skirt + long-sleeve medium-fitting shirt tucked in + legging	Head cover	Inside hijab	spandex+polyester	0.045
				Hijab/head scarf	cotton+polyester	0.125
			Upper body clothing	Bra	cotton+polyester	0.1
				Undershirt, sleeveless	cotton	0.08
				Long-sleeve shirt medium fitting	cotton+polyester	0.22
			Lower body clothing	Panties	cotton	0.04
				Span skirt	spandex + polyester	0.31
				Legging	spandex+polyester	0.18
				Socks	cotton+spandex	0.03
				Shoes	cotton canvas + rubber	0.725

B1.1 & B1.2 standing position	**B1.1 & B1.2 sitting position**	**B2.1 & B2.2 standing position**	**B2.1 & B2.2 sitting position**
			

Ensemble Category	Code	Notes	Garments		Material	Weight (kg)
Long-sleeve shirt with trousers (C)	C1	medium fitting long-sleeves not tucked into the trousers	Head cover	Inside hijab	spandex+polyester	0.045
				Hijab/head scarf	cotton+polyester	0.125
			Upper body clothing	Bra	cotton+polyester	0.1
				Undershirt, sleeveless	cotton	0.08
				Long-sleeve shirt medium fitting	cotton+polyester	0.22
			Lower body clothing	Panties	cotton	0.04
				trousers	cotton+polyester	0.385
				Socks	cotton+spandex	0.3
				Shoes	cotton canvas+rubber	0.725
			C1 standing position		**C1 sitting position**	
						
	C2	A1 tucked into the trousers	Head cover	Inside hijab	spandex+polyester	0.045
				Hijab/head scarf	cotton+polyester	0.125
			Upper body clothing	Bra	cotton+polyester	0.1
				Undershirt, sleeveless	cotton	0.08
				Long-sleeve shirt medium fitting	cotton+polyester	0.22
			Lower body clothing	Panties	cotton	0.04
				trousers	cotton+polyester	0.385
				Socks	cotton+spandex	0.03
				Shoes	cotton canvas+rubber	0.725
			C2 standing position		**C2 sitting position**	
						

Ensemble Category	Code	Notes	Garments		Material	Weight (kg)
Long-sleeve shirt with trousers (C)	C3	trousers + long-sleeve shirt (loose-fitting) not tucked in	Head cover	Inside hijab	spandex+polyester	0.045
				Hijab/head scarf	cotton+polyester	0.125
			Upper body clothing	Bra	cotton+polyester	0.1
				Undershirt, sleeveless	cotton	0.08
				Long-sleeve shirt	cotton+polyester	0.22
			Lower body clothing	Panties	cotton	0.04
				trousers	cotton+polyester	0.385
				Socks	cotton+spandex	0.03
				Shoes	cotton canvas+rubber	0.725
			C3 standing position		**C3 sitting position**	
						

As previously described, many Indonesian women commonly wear leggings as an undergarment beneath their skirts. This observation gives rise to the classification of two distinct variations within the category of ensembles featuring skirts, namely those which incorporate leggings (designated as ensembles A1.1, A2.1, B1.1, and B2.1) and those that do not include leggings (specifically ensembles A1.1, A2.2, B1.2, and B2.1).

It is imperative to note that the cultural and religious considerations prevalent in this context render tight-fitting attire unsuitable for Muslim women. Consequently, the selection of clothing ensembles for the purpose of measurements in this research exclusively encompasses medium- and loose-fitting garments. Furthermore, all the chosen women's uniform ensembles uniformly incorporate the hijab and inner hijab as integral components, the donning of which is essential to ensure the secure and proper positioning of the hijab. To facilitate comprehension, Figure 2.5 provides a visual representation of the sequential order in which these ensembles are worn, commencing from the innermost layer, denoting underwear, and extending outwardFigure 2.5.

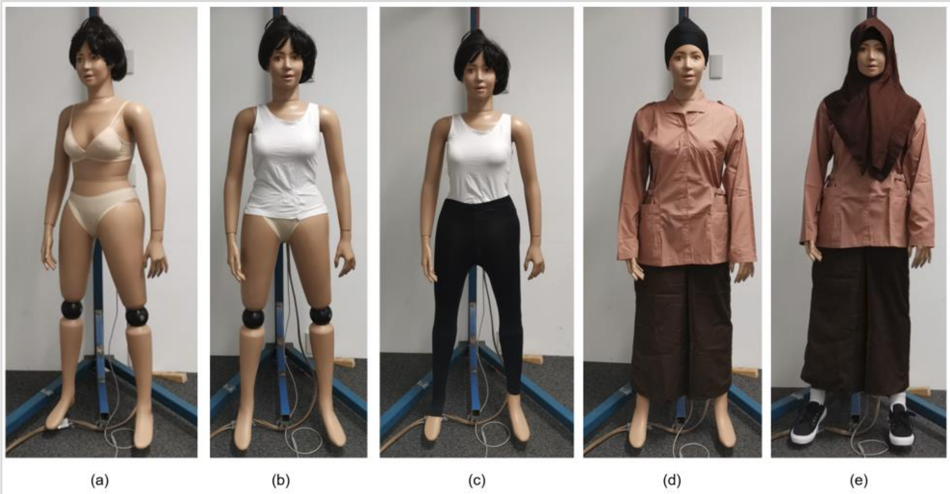


Figure 2.5 The sequential order in which the ensembles are worn. a) bra and panties; b) undershirt; c) legging; d) inner-hijab and the uniform; e) Complete ensemble worn

2.2.4 Procedures of measurement

The thermal manikin measurements for this research were carried out in the IEQ Laboratory situated at the University of Sydney, Australia (De Dear et al., 2013). The assessment of clothing insulation properties was conducted within Climate Chamber 1, which forms part of the Indoor Environmental (IEQ) Laboratory at the University of Sydney. The dimensions of this chamber encompass a length of 4.2 meters, a width of 5.63 meters, and a height of 2.6 meters, with a raised floor accessible at a height of 0.25 meters.

A full-sized female thermal manikin by the name of Laura Palmer was employed for the measurements in this study. Laura Palmer has a total skin surface area of 1.561 m^2 and anatomy comprising 22 distinct body segments. Notably, each of these body segments is equipped with precise control mechanisms for skin temperature regulation, each integrated with its own precision power supply. The manikin's "comfort" control mode was applied throughout the measurement process to sustain skin temperatures at various anatomical segments at levels that align with the thermal comfort expectations for a typical adult (Tanabe et al., 1994).

Figure 2.6 Laura Palmer, female thermal manikin at IEQ Lab, The University of Sydney

Strict adherence to environmental conditions, including parameters such as operative temperature, air temperature, humidity, and air velocity, was maintained within the chamber throughout the measurement process. These conditions were meticulously set according to the specifications outlined in ISO 9920:2009 (British Standards Institution, 2009). The mean skin temperature of the manikin in this study was regulated within the range of 33-34°C. Following ISO 9920:2009 guidelines, it was imperative to keep the air temperature at least 12°C below the mean skin temperature (British Standards Institution, 2009). Consequently, during the measurement phase, the air temperature within the chamber was tightly controlled, maintaining it within a narrow tolerance range of ± 0.1°C, specifically set at 21.6°C. Additionally, the operative temperature was aligned with the air temperature. Details of the environmental conditions for clothing insulation measurement can be found in Table 2.2.

Table 2.2 Environmental conditions for clothing insulation measurement

Parameter	Specification
Air velocity	0.1 m/s
Difference between air and mean radiant temperature	< 1°C
Relative humidity (steady state)	30% - 70%, preferably 50%
Mean skin temperature of thermal manikin	33°C -34°C
Room operative temperature	21.6°C (typically > 12°C below mean skin temperature
Test period	Stability for > 20 minutes

During the measurement process, comprehensive data pertaining to the environmental conditions within the occupied zone, situated near the thermal manikin, were collected. These measurements included parameters such as air temperature, mean radiant temperature, relative humidity, and air velocity. These data were captured using TSI Velocicalc 9545 sensors, as depicted in Figure 2.7, with detailed specifications of these sensors provided in Table 2.3.

Figure 2.7 TSI Velocicalc 9545

Table 2.3 Specification of TSI Velocicalc 9545 sensor

Measurement	Specification
Indoor air temperature	Accuracy : ± 0.3°C Range: -50°C to +50°C
Indoor relative humidity	Accuracy : ±3% Range: 5% to 95% RH
Indoor air velocity	Accuracy: ±3% of reading or ±3 ft/min (±0.015 m/s) whichever is greater. Range: -50°C to +50°C

2.2.4.1 Measurements of clothing surface area factor

In this study, a crucial parameter required for the calculation of clothing insulation is the clothing area factor (f_{cl}). The clothing area factor (f_{cl}) represents the ratio of the outer surface area of a clothed manikin to that of a nude manikin. To determine the clothing area factors for the selected ensembles, a photographic method was employed. This involved capturing frontal and side-view images of both the nude manikin and the clothed manikin. Subsequently, Adobe Photoshop software was utilized to process these images, following the established procedures detailed in prior studies (Havenith et al., 2013; McCullough et al., 2005).

To obtain accurate measurements of the clothing surface area factors, photographs of both the nude and clothed manikins were taken from both the frontal (0° angle) and side (180° angle) perspectives, with the camera positioned at the height of the manikin's centre. A laser measuring tool was employed to ensure the camera's alignment was perpendicular to the centre of the manikin. In the subsequent image processing stage, Adobe Photoshop was utilized to refine the images, isolating the manikin from its background and rendering the manikin in black while ensuring a white background. Image adjustment tools within Photoshop were applied to fine-tune parameters such as brightness, contrast, and image curves to achieve the desired visual effect.

The calculation of clothing surface area factors was performed by evaluating the ratio of pixels encompassing the clothed manikin to the pixels representing the nude manikin, as determined by the following equation:

$$f_{cl} = \frac{[(zero\ degree\ picture\ clothed - residualblack) + (90\ degree\ picture\ clothed - residualblack)]}{[(zero\ degree\ picture\ nude - residualblack) + (90\ degree\ picture\ nude - residualblack)]}$$

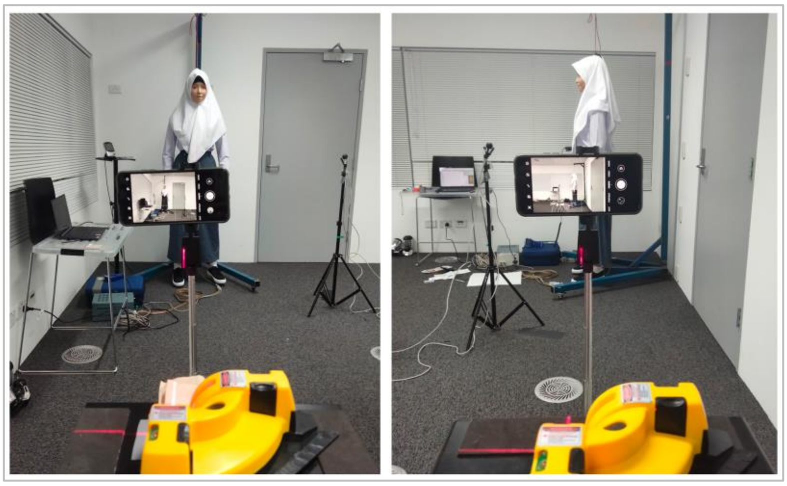


Figure 2.8 Set up for 0º and 90º angle pictures with the help of laser measurement

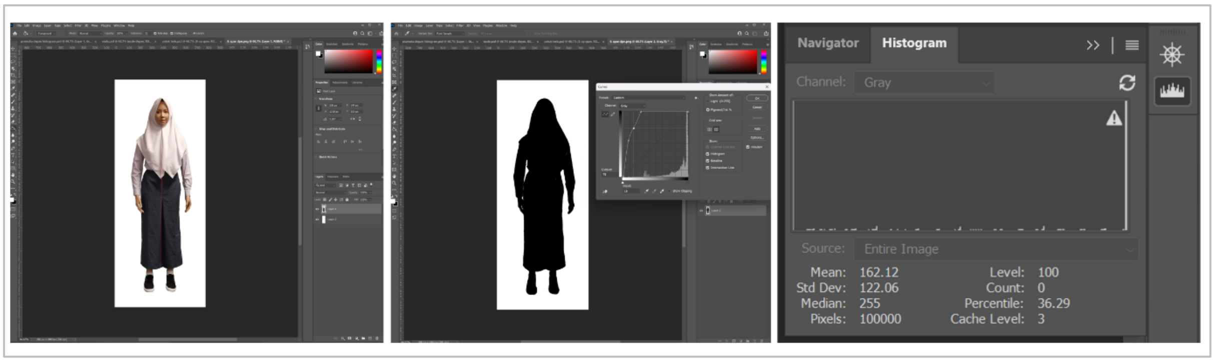


Figure 2.9 Process of image editing in Adobe Photoshop to obtain pixel information

While McCullough et al. (2005) demonstrated that, for protective clothing, a single frontal photograph yielded equivalent information compared to a more comprehensive measurement approach involving six pictures from varying angles (with a high degree of correlation indicated by $r^2 = 0.99$ and minimal mean square error of 0.015), it was decided in the context of this study to utilize both frontal and side-view photographs. This decision was influenced by the distinctive and possibly unconventional styles of the clothing under examination, which may benefit from a more comprehensive visual assessment provided by both perspectives (Havenith et al., 2013).

2.2.4.2 Measurement process

The experiments were conducted in two distinct stages. During the initial stage, the total thermal insulation for a nude manikin was assessed to derive the boundary air insulation (I_{a}). This measurement was performed using the following equation:

$$I_{\mathrm{T}} = \frac{\bar{t}_{\mathrm{sk}} - t_{\mathrm{o}}}{H}$$

Where $\bar{t}_{\mathrm{sk}}$ is the mean skin surface temperature in ºC, t_{o} is the operative temperature in ºC (usually equal to the air temperature, t_{a}), and H is the dry heat loss per square metre of skin area in watts per square metre ($W.m^{-2}$).

In the second stage of the experiments, the total insulation (I_{T}) for various combinations of clothing ensembles was evaluated, with measurements conducted in both standing and sitting positions. To simulate the sitting position typical in Indonesian high schools, a wooden chair was employed, replicating the seating arrangement commonly found in Indonesian classrooms. This approach enabled a comprehensive assessment of the clothing ensembles' insulation properties in real-world scenarios, considering the sitting posture commonly adopted by students during classroom activities.

$$I_{\mathrm{T}} = \frac{\bar{t}_{\mathrm{sk}} - t_{\mathrm{o}}}{H}$$

Where $\bar{t}_{sk}$ is the mean skin surface temperature in ºC, t_o is the operative temperature in ºC (usually equal to the air temperature, t_a), and H is the dry heat loss per square metre of skin area in watts per square metre ($W.m^{-2}$)

Given that the boundary air insulation (I_a) remains constant, the intrinsic insulation (I_{cl}), measured in units of square meters per kilowatt (m^2KW^{-1}), can be calculated using the following equation:

$$I_{cl} = I_T - \frac{I_a}{f_{cl}} = \frac{\bar{t}_{sk} - t_o}{H} - \frac{I_a}{f_{cl}}$$

Where f_{cl} is the clothing area factor.

Following ISO 9920:2009, to ensure the reliability and consistency of the measurements, each clothing ensemble underwent a total of three separate measurement runs. This approach was adopted to verify that there were no significant differences in the results obtained from each measurement session (British Standards Institution, 2009). Conducting multiple measurements enhances the robustness of the data and helps validate the accuracy and repeatability of the experimental procedures, thereby ensuring the reliability of the study's findings.

2.3 Simulation of indoor microclimate of Indonesian classroom

2.3.1 Introduction

This phase of the research was subdivided into two distinct processes, which were the Computational Fluid Dynamics (CFD) and thermal simulation. CFD simulations were conducted to acquire data on indoor air velocity within Indonesian classrooms, while thermal simulations were aimed at obtaining various thermal parameters, including indoor air temperature, mean radiant temperature, operative temperature, and relative humidity within these classroom settings. Subsequently, these collected variables were employed to compute the Standard Effective Temperature (SET; Gagge, 1971) for Indonesian classrooms. This multifaceted approach provided a comprehensive understanding of the thermal and airflow conditions within these educational spaces, ultimately contributing to the evaluation of thermal comfort in Indonesian classrooms

2.3.1.1 Chosen cities as the case study

Despite Indonesia's predominantly tropical climate, the world's largest archipelagic nation encompasses diverse temperature profiles across its towns and cities. Based on an analysis of 2007-2021 hourly climate data taken from 114 weather stations across various Indonesian cities and towns taken from onebuilding.com (Climate. OneBuilding, 2023), Indonesian lowland coastal areas typically experience relatively higher average daily temperatures, falling within the range of 26.6°C to 29.4°C. Conversely, locations at higher altitudes (exceeding 500 meters above sea level) tend to exhibit lower daily temperatures, spanning from 20.4°C to 24.3°C. This variation in temperature across different regions underscores the need to account for local climate nuances and conditions when addressing thermal comfort considerations in Indonesia (Karyono, 2015).

Thermal history plays a pivotal role in influencing an individual's thermal comfort preferences (Brager & de Dear, 1998; Jowkar, de Dear, et al., 2020). The thermal environment in which someone resides can significantly shape their thermal preferences and comfort thresholds (Corgnati et al., 2009; Jowkar, de Dear, et al., 2020). Consequently, students who have previously lived in lowland cities characterized by relatively high temperatures may exhibit different thermal preferences compared to students hailing from highland cities with lower temperatures. To investigate this phenomenon, Surabaya, a lowland coastal city, and Ruteng, a highland city, were chosen as study locations. These cities represent the contrasting thermal conditions typical of lowland coastal and highland regions in Indonesia. Figure 2.10 illustrates the geographical locations of lowland Surabaya and highland Ruteng on the Indonesian map.

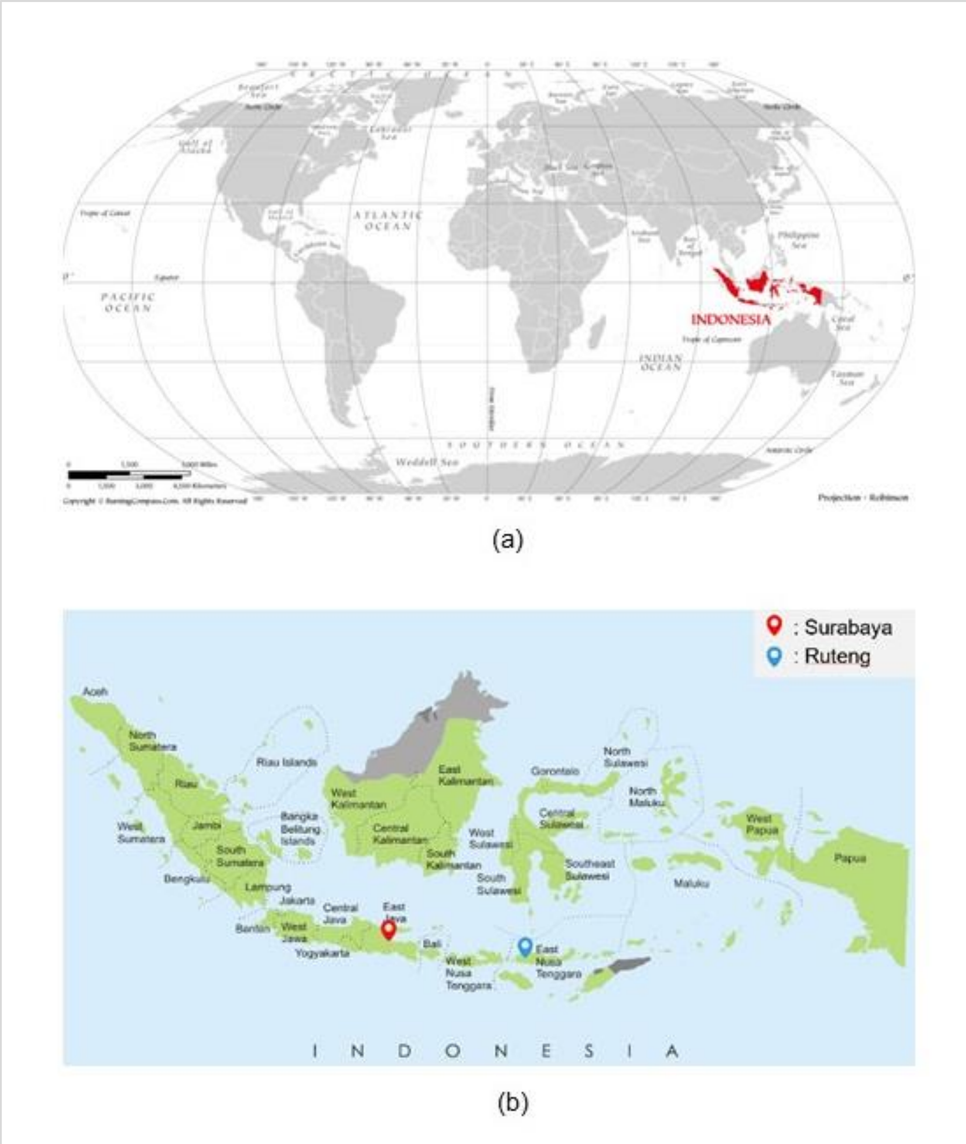


Figure 2.10 a) Location of Indonesia in the world map; b) Locations of Surabaya and Ruteng within Indonesia, modified after https://www.burningcompass.com/on-world-map/indonesia-on-world-map.html

Surabaya, the capital city of the province of East Java, stands as the second-largest city in Indonesia, following Jakarta. As the province's capital, this city is characterized by a high population density, with approximately 7,134 people per square kilometre, based on 2022 census data from BPS, the Central Statistics Agency of Indonesia (Badan Pusat Statistik, 2023). Positioned on the northeastern coast of the island of Java, along the Madura Strait, Surabaya is situated at an elevation of 2 meters above sea level. Historically, Surabaya holds the distinction of being one of the earliest port cities in Southeast Asia.

Figure 2.11 (a) Location of Surabaya in Indonesia; (b) Location of Surabaya on the island of Java; (c) map of Surabaya; modified after https://en.wikipedia.org/wiki/Surabaya

Under the Köppen climate classification system, Surabaya falls within the tropical wet and dry climate category (Aw). This classification entails the presence of distinct wet and dry seasons. Based on 2007-2021 yearly weather data within Surabaya (Climate. OneBuilding, 2023), its daily temperatures exhibit a range of 20°C to 35.5°C, with an average daily temperature of 29°C. Relative humidity levels fluctuate between 60% and 94%, with an average daily relative humidity of approximately 75%. Air velocity within the city varies from 0 to 5 m/s, with an average air velocity of 2.1 m/s.

Ruteng is a small town nestled in the highlands towards the western end of Flores Island, Indonesia. It serves as the administrative capital of the Manggarai Regency and is accessible through the Frans Sales Lega Airport, also known as Ruteng Airport. Ruteng is situated on the island of Nusa Tenggara and is positioned at an elevation of 1,170 m above sea level. According to 2020 census data, Ruteng is inhabited by a population of 41,533 residents, yielding a population density of approximately 300 individuals per square kilometre.

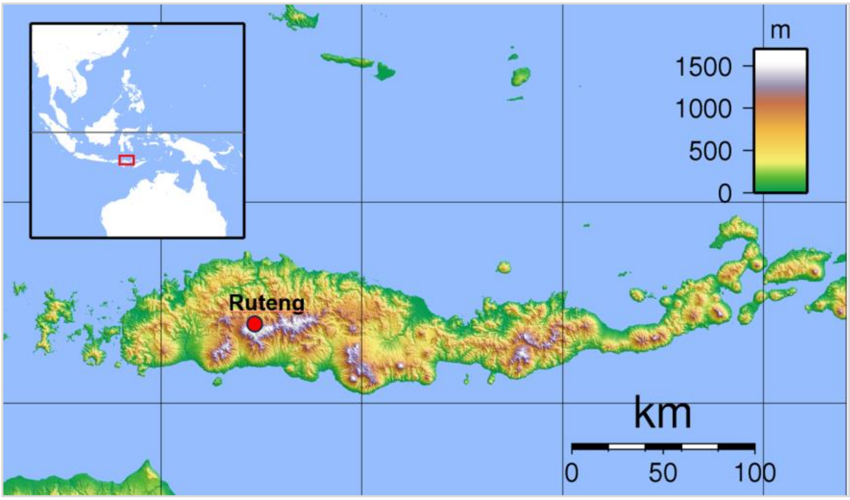


Figure 2.12 Location of Ruteng within Indonesia and location of Ruteng on the island of Nusa Tenggara; sourceshttps://upload.wikimedia.org/wikipedia/commons/c/c6/Flores_Locator_Topography.png

The town of Ruteng experiences a tropical monsoon (Am) climate according to the Köppen-Geiger classification (Arnfield, 2023). Analysis of the 2007-2021 yearly weather data of Ruteng (Climate. OneBuilding, 2023) found that temperatures in Ruteng exhibit a range of 13.8°C to 26.2°C, with an average daily temperature of 22°C. Relative humidity levels in Ruteng fluctuate between 67% and 96%, with an average relative humidity of approximately 82.7%. Wind velocities in the area vary from 0.35 m/s to 4.8 m/s, with average daily wind velocities measuring at 1.69 m/s.

In order to replicate the climate conditions in this research, meteorological data was obtained from onebuilding.com, a platform that provides accessible information on standard Indonesian meteorological data obtained from hourly weather data spanning from 2007 to 2021 (Climate. OneBuilding, 2023). The study utilised data that was generated from the Integrated Surface Database (ISD) of the United States National Oceanic and Atmospheric Administration (NOAA). The data was created utilising the procedures outlined in the TMY/ISO 15927-4:2005 standards (Climate. OneBuilding, 2023).

Surabaya, which is one of the cities included in this study, is served by three separate meteorological stations, namely Surabaya Juanda, Surabaya Perak, and Surabaya Gedangan. Among the three weather stations considered, Surabaya Gedangan was chosen as the focus of this study due to its proximity to schools and residential areas. This decision was guided by its perceived superiority over the alternative stations, thus rendering it a more suitable subject for the current research endeavour.

2.3.1.2 Design of classrooms for simulation

Regulation Number 24 of 2007, issued by the Minister of Education of Indonesia (Kemdiknas Republik Indonesia, 2007), provides guidelines for the facilities that should be available in Indonesian schools. However, this regulation lacks detailed specifications regarding design aspects. In Indonesia, a typical classroom design is applied nationwide, irrespective of the diverse local climates. Moreover, this standard design is implemented across all educational levels, from elementary to senior high school, without consideration for the varying age groups of students. Additionally, Indonesia lacks a specific thermal comfort standard tailored exclusively for classrooms.

The classroom models employed for simulation within this study were designed based on the floor plan and elevation drawings outlined in Appendix 4 of regulation number 8, Operational Guidelines for the Procurement of Buildings and Educational Facilities in Indonesia, issued in 2018 by the Ministry of Education and Culture (Kementrian Pendidikan dan Kebudayaan Republik Indonesia, 2018). This design template serves as a general standard for the construction of Indonesian classrooms. However, the regulation does not provide a scientific rationale for the underlying design principles.

The window design adheres to the recommendation provided in the regulation, featuring a top-hung window. However, it should be noted that the regulation does not specify a minimum or maximum angle for window openings. Classrooms in Indonesia typically utilize window opening angles of 15°, 20°, and 30° as the maximum allowable angles. Consequently, for this study, a window opening angle of 30° was selected. This choice was made to facilitate maximum airflow into the classroom, considering that Indonesia experiences very low wind speeds. The use of larger window openings, permitting a greater influx of air, is anticipated to extend the duration of comfortable thermal conditions within the classrooms.

Appendix 4 of regulation number 8 (Kementrian Pendidikan dan Kebudayaan Republik Indonesia, 2018) recommends the use of cross-ventilation in Indonesian classrooms. However, there are many Indonesian classrooms that are found to utilize single-sided ventilation due to site limitations. Consequently, both single-sided ventilation and double-sided ventilation designs were employed for simulation within this study. This approach enables a comparative analysis of the thermal performance of classrooms with varying ventilation configurations.

Moreover, both the single-sided and cross-ventilation classrooms were modelled as two-story buildings. This design choice allows the research to assess and compare thermal comfort within classrooms located on both the first and second floors, accounting for potential variations in thermal conditions between these two levels.

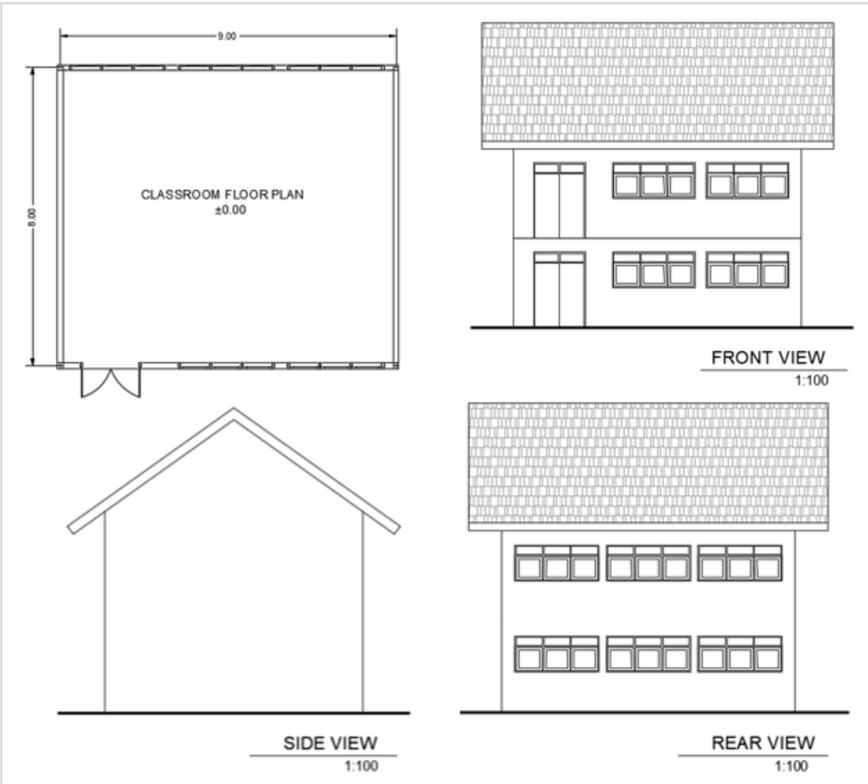


Figure 2.13 Classroom design for simulation (with cross-ventilation type)

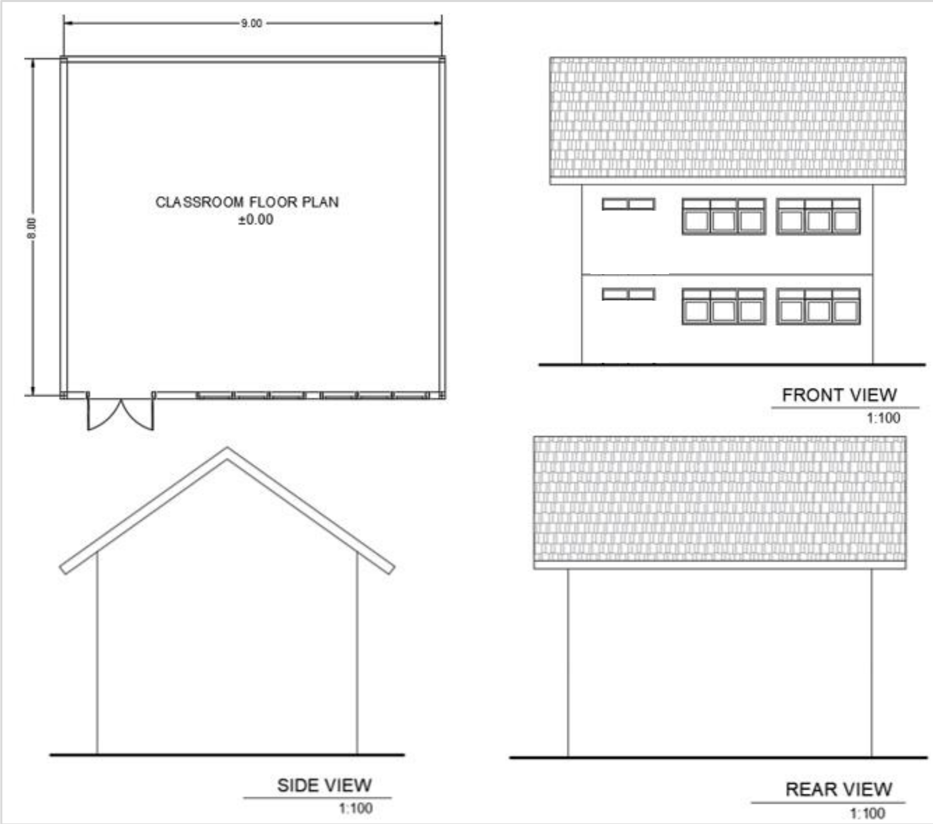


Figure 2.14 Classroom design for simulation (with single-sided ventilation type)

The classroom models were created using Rhinoceros 7.0 (Mc Neel & Associates, 1993), a software selected for its compatibility with Grasshopper (Davidson, n.d.). Grasshopper served as the interface for both Computational Fluid Dynamics (CFD) and thermal simulations, facilitating the integration of these essential components in the study's analysis. Both CFD and thermal simulations in this study were conducted with the assumption that classroom doors were closed and all windows were open.

2.3.2 Computational Fluid Dynamics Simulation

Given that Indonesian classrooms predominantly rely on natural ventilation strategies, Computational Fluid Dynamics (CFD) simulations were employed in this research to model indoor air velocity within typical Indonesian classrooms in both selected cities. The indoor air velocity data obtained from the CFD simulations served as a critical input for both the thermal simulation phase and the subsequent thermal comfort calculations.

The selection of CFD for this research was grounded in its capability to effectively address the complexities inherent in natural ventilation phenomena, including the natural variability of wind characteristics over time. CFD software was well-established and validated through its alignment with experimental data, making it a cost-effective choice compared to generating high-resolution data through other means. (Blocken, 2015; Ferrucci & Brocato, 2019; Hawendi & Gao, 2017; Yang et al., 2006).

2.3.2.1 Chosen simulation softwares

A selection of software and plugins were carefully chosen to facilitate the Computational Fluid Dynamics (CFD) simulations in this study. These tools included OpenFOAM (The OpenFOAM Foundation, 2011) as the CFD solver, Grasshopper (Davidson, n.d.) and its plugin Butterfly (Ladybugs Tool LLC, 2017) as the CFD interface, and ParaView (Kitware Inc, 2023) as the post-processing program that provided interactive visualization.

OpenFOAM (Jasak et al., 2007; The OpenFOAM Foundation, 2011; Weller et al., 1998), the chosen CFD solver, is an open-source (The Open Source Initiative, 2006) CFD solver that has gained considerable popularity in both academic research and industrial use. It offers extensive capabilities, including a wide range of physical modelling options, robust discretization methods, and the ability to handle complex geometries, similar to commercial CFD software like ANSYS Fluent. This software has undergone rigorous validation, incorporating both on-site measurements and data from wind-tunnel experiments (Gartmann et al., 2011; Kubilay et al., 2014). However, it is worth noting that OpenFOAM is programmed in C++ (Jasak et al., 2007), requiring expertise not only in fluid dynamics but also in programming skills.

Butterfly (Ladybugs Tool LLC, 2017), a CFD plug-in integrated within the Grasshopper interface, was selected to conduct the Computational Fluid Dynamics (CFD) simulations in this research. Butterfly conducts simulations by harnessing the capabilities of the validated external CFD solver, OpenFOAM, ensuring computational precision and efficiency (Brooke-Lawson & Holz, 2020; Chronis et al., 2017; Hu et al., 2023). Among the available CFD plug-ins compatible with Grasshopper, Butterfly stands out as a well-established tool widely utilized for predicting airflow conditions in urban blocks (Brooke-Lawson & Holz, 2020; Chronis et al., 2017; B. Jia et al., 2021; Loh & Bhiwapurkar, 2022; Sakiyama et al., 2021; Xu et al., 2019). Notably, Butterfly's selection is underpinned by its capacity for coupling simulations with a range of Grasshopper plug-ins, including Ladybug Tools (Roudsari & Pak, 2013), which employs EnergyPlus/OpenStudio for thermal comfort simulations (Ellis et al., 2008).

ParaView (Kitware Inc, 2023), a freely available and open-source data analysis and visualization software, was chosen for the CFD data post-processing phase in this study. The selection of ParaView was based on several key factors. Firstly, it aligns with the research's commitment to open-source tools, ensuring transparency and accessibility. Additionally, ParaView's compatibility with OpenFOAM, the chosen CFD solver, enhances its suitability for this research. Furthermore, ParaView is recognized for its robust capabilities in visualizing large datasets, making it an ideal choice for effectively analysing and interpreting the extensive CFD simulation results generated in this study.

The utilization of a Computational Fluid Dynamics (CFD) plug-in, enabling the seamless integration of CFD software within architectural design platforms, has significantly contributed to rendering CFD more accessible and comprehensible (Hu et al., 2022, 2023). These plug-ins facilitate the simplification of various aspects of CFD models, encompassing numerical schemes (Sousa et al., 2015), turbulence models (Natanian et al., 2020; Si et al., 2016), grid schemes, and mesh generation methods (Löhner, 1997; Nakahashi et al., 2003), thereby enhancing the ease with which CFD simulations can be comprehended and executed.

Regarding their proficiency and precision, a substantial body of research demonstrates that the majority of CFD plug-ins exhibit the capability to forecast airflow patterns and the dispersion of pollutants (Chronis et al., 2017; Elwy et al., 2018; Roudsari & Pak, 2013).

Furthermore, when integrated with other performance simulation tools on design platforms, CFD plug-ins facilitate comprehensive assessments of design performance.

2.3.2.2 Procedure of simulations

The simulation activities were categorized into three distinct phases: pre-processing, calculation, and post-processing. Pre-processing entailed the initial stages of the simulation, involving tasks such as defining the geometric parameters and spatial context for the study. This phase was pivotal for determining the wind speed and wind direction, which were selected based on pertinent weather data to be employed throughout the simulation. The calculation phase encompassed various settings utilized for mesh generation and the selection of an appropriate airflow model employed in the simulation. This step necessitated iterations across different wind speed and wind direction scenarios. The post-processing phase involved the transformation of the CFD simulation outcomes into indoor air velocity data. Each of these phases relied on multiple software tools for their execution: Rhinoceros 7 for the creation of the model, Grasshopper and Butterfly plug-ins for the CFD simulation interface, OpenFOAM as the CFD solver, and ParaView for data post-processing. A schematic depiction of the simulation procedure is provided in Figure 2.15.

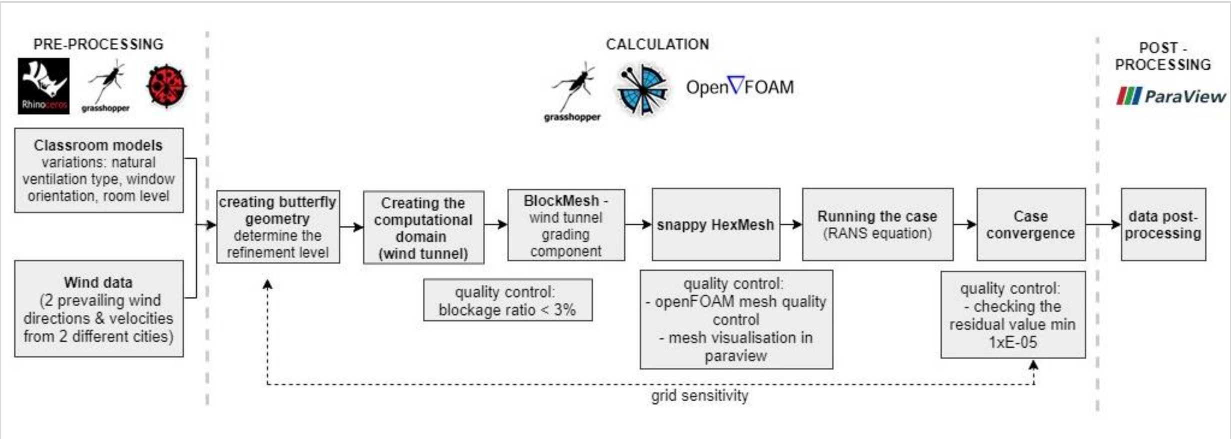


Figure 2.15 Schematic diagram of CFD simulation process

a. *Pre-processing*

The pre-processing phase entailed the definition of the geometry and spatial parameters. Two distinct geometric models of standard Indonesian classrooms were created, each representing different modes of natural ventilation: single-sided ventilation and cross-ventilation. Each of these models comprised two-story classrooms, including a first-floor classroom and a second-floor classroom. For the duration of the simulation, it was assumed that all windows were open while doors remained closed. Figure 2.16 depicts geometric models created for the simulation, while Tables 2.4 and 2.5 contain details of the room size and opening area overview for geometric model number 1 (single-sided ventilation type) and geometric model number 2 (cross-ventilation type), respectively.

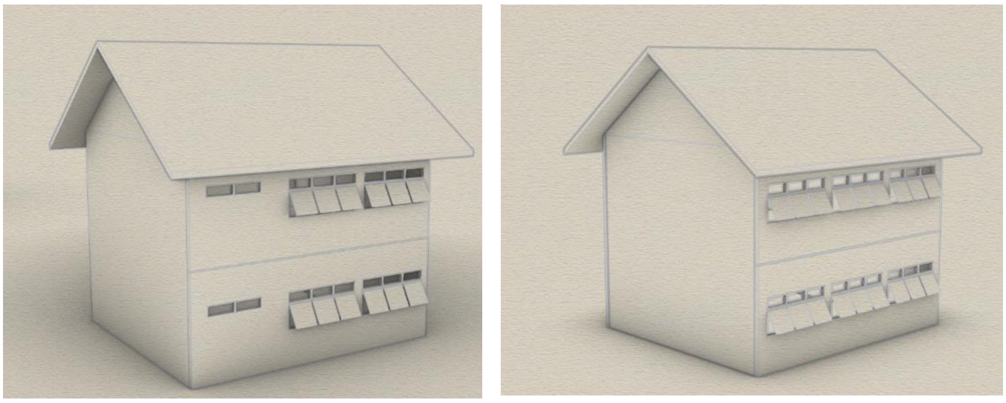


Figure 2.16 Geometric model number 1 (single-sided ventilation type) and geometric model number 2 (cross-ventilation type)

Table 2.4 Room and opening area overview for Geometric model 1 (single-sided ventilation)

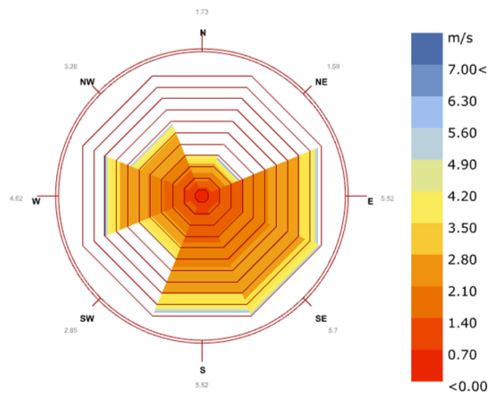
Room	**Room size**	**Room area (m2)**	**Opening type**	**Openable area (m2)**	**% Openable area**
1st floor classroom	8 x 9 x 3.5 m^3	72	top hung window	2.62	6.30%
			clerestory window	1.96	
2nd floor classroom	8 x 9 x 3.5 m^3	72	top hung window	2.62	6.30%
			clerestory window	1.96	

Table 2.5 Room and opening area overview for Geometric model 2 (cross- ventilation)

Room	Room size	Room area (m2)	Opening type	Openable area (m2)	% Openable area
1st floor classroom	8 x 9 x 3.5 m^3	72	top hung window	6.55	14.8%
			clerestory window	4.12	
2nd floor classroom	8 x 9 x 3.5 m^3	72	top hung window	6.55	14.8%
			clerestory window	4.12	

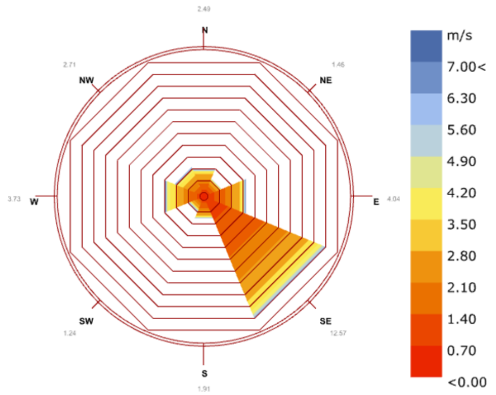
Given the temporal variability of wind conditions, a critical aspect of the simulation process involved the analysis of available wind data to ascertain the specific wind speed and wind directions to be employed. To facilitate this, wind rose analysis was carried out utilizing Ladybug (Ladybug Tools LLC, 2017b; Roudsari & Pak, 2013), an extension within the Grasshopper environment, which utilized wind data sourced from the EnergyPlus Weather File (.epw) as its input

The wind rose analysis was conducted for the annual hourly weather data of both Surabaya Gedangan and Ruteng for the typical meteorological year of 2007-2021 (Climate. OneBuilding, 2023). Importantly, this analysis was restricted to school-occupied hours, spanning from 7.00 am – 14.00 pm. In this analysis, wind direction was categorized into eight distinct orientations. The outcomes of the wind rose analysis for Surabaya and Ruteng are visually presented in the Figures 2.17 and 2.18, respectively.



Wind direction (°)	Wind velocities (m/s)	Frequencies (%)
9.5	2.64	1.73
45	2.79	1.59
90	2.97	5.52
135	1.99	5.7
180	1.24	5.52
225	1.09	2.85
270	1.88	4.62
315	2.39	3.28

Figure 2.17 Yearly wind rose data of Surabaya-Gedangan during school occupied hours (7am - 2pm)



Wind direction (°)	Wind velocities (m/s)	Frequencies (%)
0	1.85	2.49
45	1.78	1.46
90	1.45	4.04
135	1.79	12.57
180	2.07	1.91
225	1.67	1.24
270	2.75	3.73
315	2.6	2.71

Figure 2.18 Yearly wind rose data of Ruteng, during school-occupied hours (7am - 2pm)

Figures 2.17 and 2.18 illustrate the corresponding wind velocity and frequency distributions for the various wind directions during school-occupied hours in the lowland coastal area of Surabaya Gedangan and highland Ruteng, respectively. The percentages presented in these figures represent the proportion of specific average wind velocities originating from distinct wind directions. To streamline the simulation process and reduce both time and cost, this study focused solely on the two most prevalent wind velocities for each city. Specifically, for Surabaya-Gedangan, the chosen prevailing wind velocities and associated wind directions were 1.99 m/s from the southeast (135°) and 2.97 m/s from the east (90°). Although both 90° and 180° directions occurred with the same frequency, a wind direction of 90° was selected over 180° due to its higher wind velocity, allowing for the assessment of indoor air velocity under the highest outdoor wind potential. Whereas for Ruteng, the selected wind velocities for the CFD simulation were 1.79 m/s from the southeast (135°) and 1.45 m/s from the east (90°).

In summary, the CFD simulation conducted in this study encompassed several distinct variations. These variations included two geometric models, each representing a different ventilation configuration: cross-ventilation and single-sided ventilation. Additionally, the study considered two different urban locations, lowland Surabaya and highland Ruteng, requiring two different wind directions for each city. Furthermore, the analysis incorporated eight different building orientations (north 0°, northeast 45°, east 90°, southeast 135°, south 180°, southwest 225°, west 270°, northwest 315°). In succinct terms, the CFD simulation entails a total of 64 CFD scenarios, comprising 32 for cross-ventilation and 32 for single-sided ventilation, and encompassing variations in wind speeds and building orientations. Given that each CFD model comprises two distinct classroom levels (first-floor classroom and second-floor classroom), the study will generate indoor air velocity data for a total of 128 classrooms, each featuring diverse parameter combinations for subsequent analysis. The details of the variation in parameters for the CFD simulations can be seen in Table 2.6.

Table 2.6 Variation of parameters for the CFD simulations

Parameter	Variation	
Cities, wind velocities & wind direction	Surabaya	1.99 m/s, wind direction 135°
		2.97 m/s, wind direction 90°
	Ruteng	1.79 m/s, wind direction 135°
		1.45 m/s, wind direction 90°
Modes of natural ventilation	Single-sided	
	Cross-ventilation	
Floor level	First-floor	
	Second-floor	
Windows orientation	0°	
	45°	
	90°	
	135°	
	180°	
	225°	
	270°	
	315°	
Total of scenarios	**64**	

b. Calculation phase

The CFD simulations in this study were conducted using the open-source CFD software OpenFOAM (The OpenFOAM Foundation, 2011). The simulations involved the steady flow of air within a three-dimensional model. Notably, the study exclusively focused on wind-driven ventilation, omitting considerations for thermal-driven ventilation (buoyancy). Consequently, the simulations were executed under isothermal conditions. The thermal driven or bouyancy driven ventilation was not considered in the simulation because in the hot tropical climate, the difference between indoor and outdoor temperature is relatively small (Moosavi et al., 2014). Furthermore, the high humidity levels in the hot and humid region mean less significant density differences between warm and cooler air, further limiting buoyancy-driven airflow.

The simulation model involved an integrated indoor-outdoor CFD simulation approach. In this configuration, the geometry was situated within a computational domain that accounted for the dynamic interaction between the external and internal environments surrounding the openings (Ramponi & Blocken, 2012; Tan & Glicksman, 2005; Tong et al., 2016).

The dimensions of the computational domain were determined in adherence to best practices, particularly with consideration of the blockage ratio (Tominaga et al., 2008). To mitigate the effects of compressed flow, prior research has advised maintaining a blockage ratio of less than 3% (Muhsin et al., 2017; Tominaga et al., 2008). In the present study, the computational domain, depicted in Figure 2.19, was sized as follows: 5L for the windward side, 6H for the height, 5L for the lateral sides, and 15L for the leeward side to facilitate flow redevelopment. Here, L represents the length of the geometry (9 m) and H represents its height (10 m), resulting in blockage ratios of 1.71% and 1.4% for the double-sided ventilation and single-sided ventilation geometries, respectively. These blockage ratios conform to the recommended values established in prior studies, maintaining a blockage ratio of less than 3%.

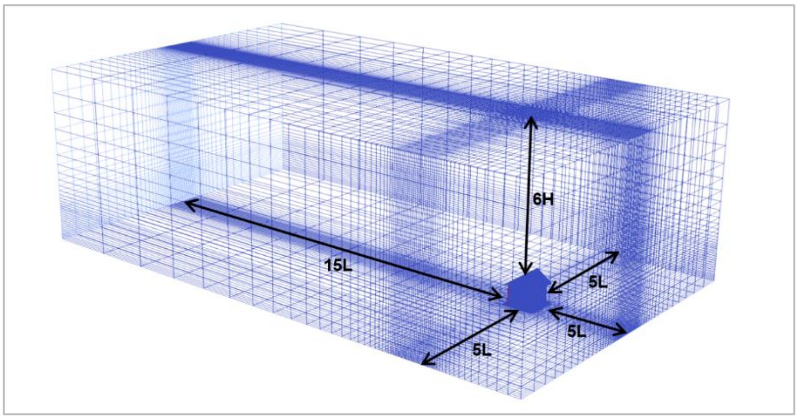


Figure 2.19 Computational domain

The precision of the CFD results was directly contingent upon the quality of the mesh, which was generated using the blockMesh and snappyHexMesh utilities in OpenFOAM. Initially, blockMesh was responsible for crafting a foundational mesh that outlined the domain extensions and established a base-level mesh. Subsequently, snappyHexMesh was employed to fashion a three-dimensional polyhedral mesh encompassing the geometry under investigation, defined by a tri-surface mesh composed of hexahedral cells.

Within the blockMesh utility, the computational grid was meticulously structured, with greater refinement evident in the immediate vicinity of the geometric model. In this region of interest, the cell size was set at 0.5, coupled with an expansion ratio of 1.15, ensuring a seamless transition from a fine mesh near the wall surfaces while avoiding substantial aspect ratios that might compromise convergence. The outcome of the blockMesh process in the computational domain is visually represented in Figure 2.20.

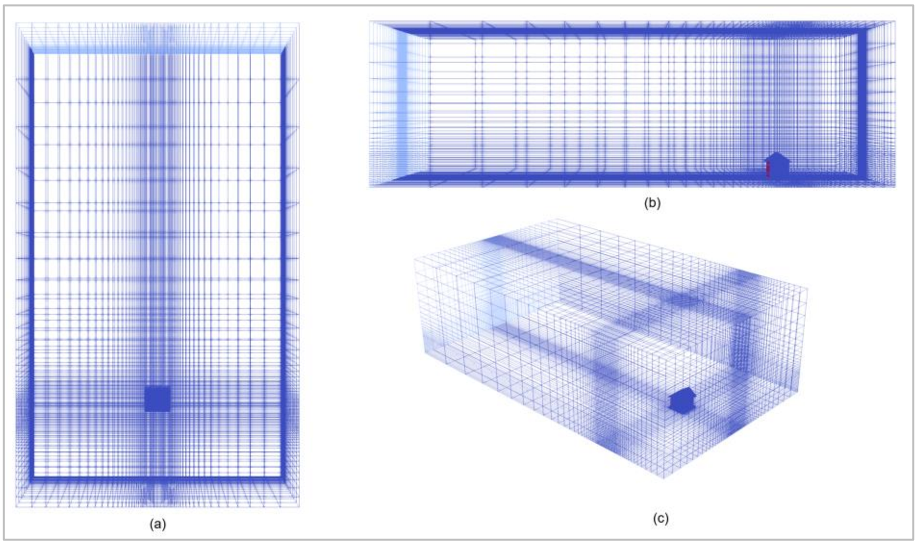


Figure 2.20 BlockMesh of the computational domain. a) top view; b) side view; c) perspective

SnappyHexMesh constructed a three-dimensional polyhedral mesh encompassing the examined geometry, initially represented by a tri-surface mesh composed of hexahedral cells. To optimize the meshing process, the geometry was subdivided into three distinct regions, each tailored to specific refinement levels according to the desired levels of detail. Notably, regions containing windows and other openings, as well as the immediate vicinity of these openings, were allocated a higher refinement level to enhance simulation accuracy.

The outcomes of the meshing process for both the single-sided and cross-ventilation geometries are visually depicted in Figure 2.21. The mesh quality satisfactorily adhered to the criteria established by OpenFOAM's mesh quality control protocols, which include factors such as boundary openness, maximum cell openness, maximum aspect ratio, face area magnitudes, cell volumes, maximum mesh non-orthogonality, face pyramids, and maximum skewness. Furthermore, the mesh quality underwent visual verification using ParaView to ensure its integrity and suitability for the subsequent simulations.

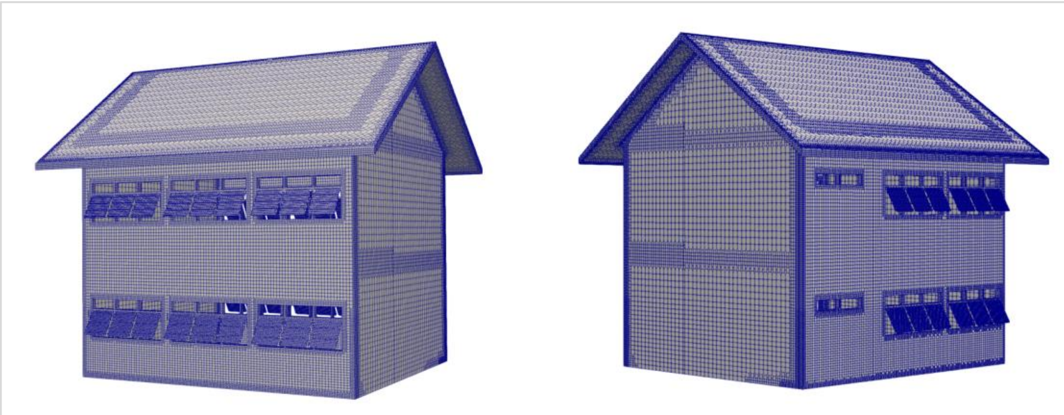


Figure 2.21 Geometry meshing

In this study, the airflow is characterized as turbulent, necessitating the application of a turbulence model. The Reynolds-Averaged Navier-Stokes (RANS) equations (Cebeci et al., 2005) were employed in the calculations for determine wind pressure and velocity.

In the context of examining air distribution within an enclosed space, mean air parameters hold greater utility than instantaneous turbulent-flow parameters. Therefore, employing the RANS (Reynolds Averaged Navier-Stokes) equations presents an efficient method to predict air patterns swiftly, as described by Zhai et al. (2007). The RANS approach is widely used within the realm of indoor air distribution due to its relatively modest computational resource requirements and a lower threshold for user expertise (Zhai et al., 2007).

To ensure the convergence of the simulations, both residual values and the monitoring of specific locations (probes) were established as convergence criteria. For the latter, monitoring points were strategically placed on the window surface areas, where velocity and pressure outputs were continuously monitored. The solutions exhibited convergence at a maximum residual level of 1E-5, with solution imbalances maintained at less than 0.5% (Sakiyama et al., 2021).

Grid sensitivity studies were carried out to verify that the chosen grid did not exhibit significant variations with finer grid resolutions. Consequently, mesh configurations of different coarseness levels, namely coarse, medium, and fine, were generated for both the single-sided and cross-ventilation geometries by adjusting the number of refinement levels. It is worth noting that the ratio between the smallest and largest meshes falls outside the conventional range, albeit the discrepancies in results among them are discernible only to the third decimal place. Table 2.7 and 2.8 provide information on the total number of cells, model residuals, and the calculated mean scalar velocity values for the first-floor classroom of the single-sided and cross-ventilation geometries, respectively. Given that the difference between the coarse and fine grid is approximately 1.5%, and the difference between the medium and fine mesh is below 1%, all simulations were conducted employing medium mesh configurations.

Table 2.7 Grid sensitivity for the single-sided geometry (Geometric model 1)

Mesh type	Regions	Refinement level	Count cell	Blockage ratio	Mean air velocity (1st floor)	Residual			
						Ux	Uy	Uz	p
Coarse	Window + opening	3,3	573102	1.41%	0.01025847	2.30E-05	9.60E-07	2.70E-05	7.30E-06
	Wall around opening + roof	2,2							
	Wall	1,2							
Medium	Window + opening	4,4	771880		0.010798389	1.30E-05	9.28E-07	1.46E-05	7.01E-06
	Wall around opening + roof	3,3							
	Wall	2,2							
Fine	Window + opening	5,5	1.319.023		0.011554277	1.11E-05	9.03E-07	1.23E-05	6.97E-06
	Wall around opening + roof	4,4							
	Wall	3,3							

Table 2.8 Grid sensitivity for the cross-ventilation geometry (Geometric model 2)

Mesh type	Regions	Refinement level	Count cell	Blockage ratio	Mean air velocity (1st floor)	Residual			
						Ux	Uy	Uz	p
Coarse	Window + opening	3,3	822.477	1.70%	0.1290212	3.50E-05	7.20E-07	3.10E-05	9.50E-06
	Wall around opening + roof	2,2							
	Wall	1,2							
Medium	Window + opening	4,4	955.356		0.122877333	2.12E-05	6.15E-07	2.29E-05	9.37E-06
	Wall around opening + roof	3,3							
	Wall	2,2							
Fine	Window + opening	5,5	1.974.076		0.119191013	2.04E-05	6.00E-07	2.12E-06	9.21E-06
	Wall around opening + roof	4,4							
	Wall	3,3							

c. *Post-processing*

Subsequent to the successful convergence of all CFD simulations, data post-processing was performed using ParaView (Kitware Inc, 2023). This post-processing computed mean indoor air velocity within the classroom, considering different building orientations and floor levels. The calculations of indoor air velocities were performed at three distinct heights: 0.1 m, 0.6 m, and 1.1 m above the floor, aligning with the reccommendations specified in the ISO 7726:2001 (British Standard Institution, 2002).

2.3.2.3 Model validation

To validate the accuracy of the numerical simulations, the velocity components predicted by the RANS CFD model were compared to field measurement results. The field measurements were carried out in room 481 on the fourth level of the Wilkinson Building at the University of Sydney in Australia. Room 481 was chosen due to its similarity in characteristics to the classroom models, which feature single-sided top-hung windows.

It is worth noting that the measurements were conducted in Sydney, Australia, rather than in actual Indonesian classrooms. This decision was influenced by constraints related to time and the unavailability of the necessary tools and equipment required for measurements in the Indonesian classroom settings.

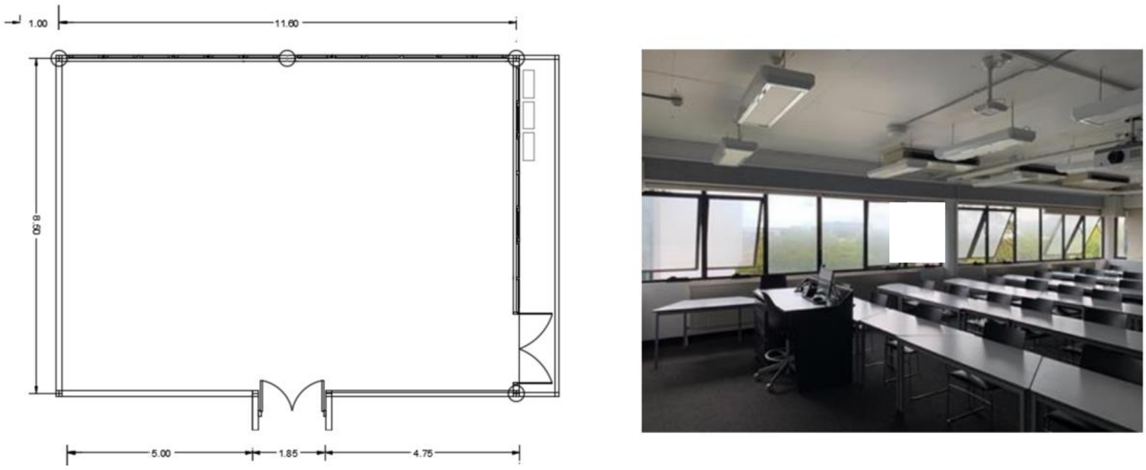
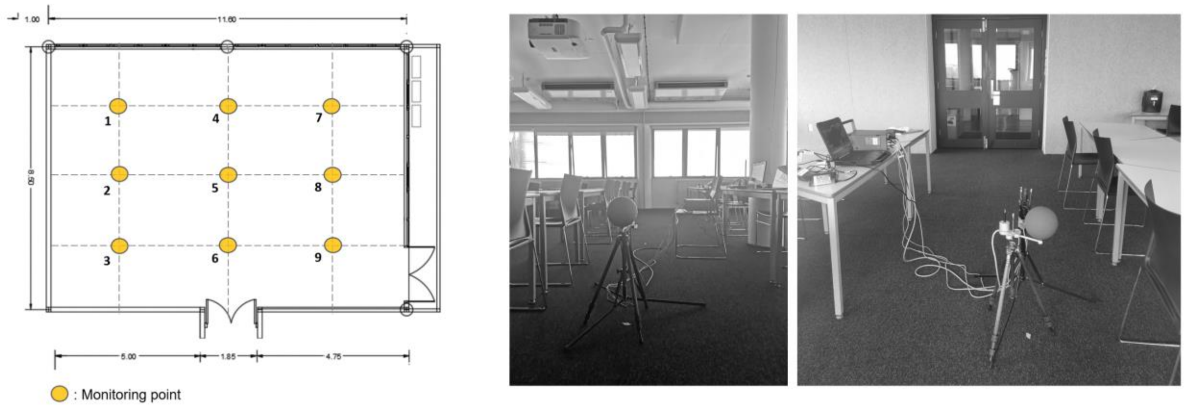


Figure 2.22 Floor plan and situation of room 481 of Wilkinson Building at the University of Sydney

As previously stated, validation was conducted by comparing the result of the average indoor air velocity of room 481 obtained from the field measurements to the result of the average indoor air velocity obtained from the simulation.



a) b)

Figure 2.23 a) Monitoring points in room 481; b) indoor measurement in room 481 of the Wilkinson Building

Figure 2.23 depicts the plan of measurements and the indoor measurements in room 481 of the Wilkinson Building at the University of Sydney. Measurement of indoor air velocity and air temperature was conducted on 16 February 2023 at nine different points of the room at a height of 0.6 m above the floor, following ISO 7726:2001 (British Standard Institution, 2002). The nine points represent locations that are far from the windows, locations in the centre of the room, and locations close to the windows. The air temperature and indoor air velocity were measured and recorded using the INNOVA thermal comfort data logger 1221. Since only one sensor was available to measure the indoor air velocity and temperature while nine different points were selected to be measured, the measurement was conducted sequentially, progressing from one monitoring point to the next. Each point was measured every 10 seconds for six minutes before the sensors were moved to the next point. The average indoor air velocity and average air temperature were then calculated for every point measurement and were also used to obtain the average indoor air velocity and average air temperature of the room.

Table 2.9 Specification of sensors used in INNOVA thermal comfort data logger 1221

Sensor	Accuracy	Range	Response time
Air Velocity Transducer MM0038	va<1m/s: ±(0.05va + 0.05)m/s for any flow direction greater than 15˚ from rear of transducer axis 1<va<10m/s: typically better than ±0.1va m/s perpendicular to transducer axis and typically better than ±0.25va m/s for flow directions more than 15˚ from rear of transducer axis	0 to 10m/s (0 to 2000ft/minute)	<0.2s to 90% of step change
Air Temperature Transducer MM0034	5 to 40˚C range: ±0.2˚C	–20 to 50˚C	20s to 50% of step change, 50s to 90% in still air
	–20 to 50˚C range: ±0.5˚C		

The weather data used for the CFD simulation was sourced from a Davis Vantage Pro2 weather station situated atop the fifth level of the Wilkinson building. The weather station's location in relation to room 481 is visually depicted in Figure 2.24. Detailed weather data captured by the weather station at the time of the field measurement is provided in Table 2.9. Additionally, specifications of the Davis Vantage Pro2 Weather station are provided in Table 2.10.

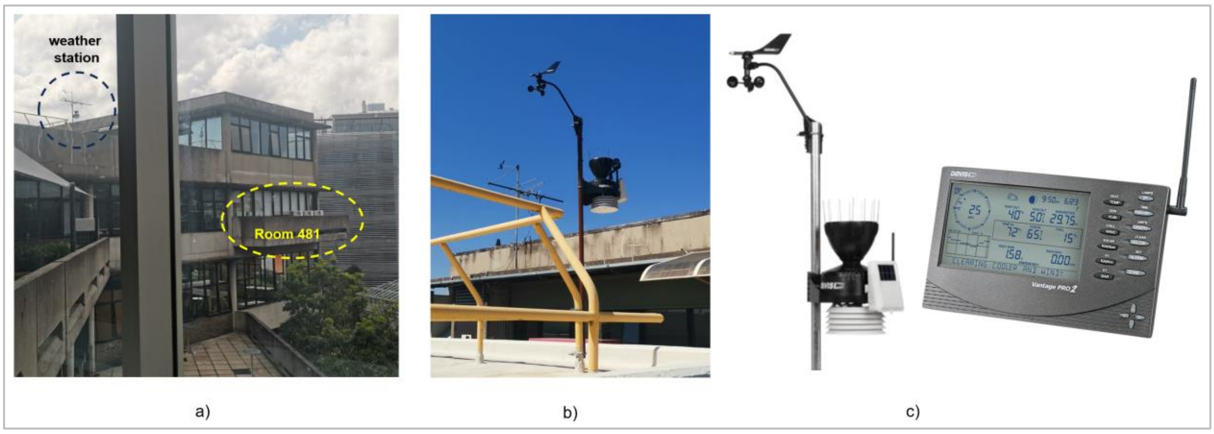


Figure 2.24 a) Weather station location in relation to room 481; b) Davis Vantage Pro 2 weather station at Wilkinson building; c) Davis Vantage Pro2 Weather Station

Table 2.10 Data taken from Davis Vantage Pro2 Weather station during field measurement

Date	Outdoor Relative humidity (%)	Outdoor Temperature (°C)	Outdoor Wind speed	Outdoor predominant wind direction
16.02.2023	85	22.3	2.7 m/s	E

Table 2.11 Specification of Davis Vantage Pro2 Weather station

Sensor	Accuracy	Range
Temperature sensor	± 0.3°C	-40°C - 65°C
Relative humidity sensor	±3%	0% -100%
Barometric pressure sensor	± 0.01 inHg (0.3 hPa)	26 – 32 inHg (880 -1080 hPa)
Wind speed sensor	±1-2 miles per hour (mph) or ±1-2 meters per second (m/s)	0 to 200 miles per hour (0 to 322 km/h) or 0 to 176 knots
Wind direction sensor	± 3°	Full 360° range
Rain gauge	0.01 inches (0.25 mm) per tip of tipping bucket	

The CFD simulation was conducted within the geometric model of Room 481 of the Wilkinson building for the single-sided ventilation scenario. Mesh settings were established in accordance with the CFD configurations for Indonesian classrooms, as previously outlined. This configuration resulted in a blockage ratio of 2.7%, which aligns with the recommended value of less than 3% according to best practice guidelines, as indicated by Tominaga et al. (2008).

To maintain consistency in comparisons, the results of the CFD simulation were extracted at precisely the same coordinates as the monitoring points, positioned at a height of 0.6 meters above the floor, thus mirroring the measurements taken during the field study. Figure 2.25 illustrates the comparison between the average indoor air velocity results at each monitoring point obtained from the CFD simulation and those obtained from the field measurements. The average indoor air velocity was used instead of the maximum or minimum values, as the simulation results only provide average values.

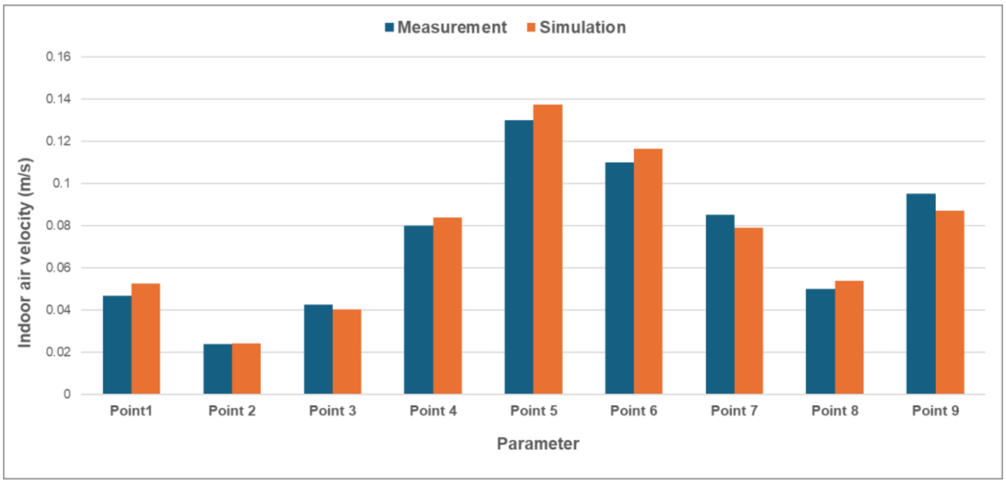


Figure 2.25 Comparison of average indoor air velocity between the room measurements and simulation

Figure 2.25 illustrates some disparities between the results of the CFD simulation and the measurements, notably at monitoring points 1, 4, 5, 6, and 8. However, it is important to note that these discrepancies remain within an acceptable range, with the differences between CFD simulations and measurements being less than 10% (Norton et al., 2010). Overall, the air velocity values at the monitoring points obtained from the CFD simulation are well-aligned with the measurement results.

It is essential to acknowledge that various uncontrollable factors can influence these disparities, such as fluctuations in wind speed and direction over time, as well as the impacts of neighbouring buildings on ventilation rates through the building openings. Furthermore, variations between results could also stem from potential errors in measurement tools and unmeasured parameters (Baharvand et al., 2013). As such, despite the observed differences, considering the good overall agreement between the CFD results and measurements and the fact that these differences remain within acceptable limits (no more than 10% difference), the results can be reasonably regarded as valid (Norton et al., 2010).

2.3.3 Thermal simulation

After acquiring indoor air velocity data through the CFD simulation, the next step in this analysis involved conducting a thermal simulation. This phase of the simulation aimed to collect data pertaining to the indoor thermal performance of Indonesian classrooms. The parameters of interest encompassed indoor air temperature, indoor operative temperature, indoor mean radiant temperature, and indoor relative humidity. These parameters, in conjunction with clothing insulation and indoor air velocity data obtained from the previous stage, were integrated to calculate the Standard Effective Temperature. This standardized metric was then employed to evaluate the thermal comfort response of Indonesian students within these classroom settings.

The geometries of Indonesian classrooms were designed using Rhinoceros (Mc Neel & Associates, 1993), a renowned and robust 3D Computer-Aided Design (CAD) software. As previously explained, this software was selected for its user-friendly interface and compatibility with a range of open-source environmental simulation plugins. Notably, it facilitated the integration of plugins like Ladybug Tool (Roudsari & Pak, 2013), which comprises Ladybug (Ladybug Tools LLC, 2017b; Roudsari & Pak, 2013) and Honeybee (Ladybug Tools LLC, 2017a) for thermal simulation in this study, as well as CFD Butterfly (Ladybugs Tool LLC, 2017), which was employed in the earlier Computational Fluid Dynamics (CFD) simulation.

Grasshopper (Davidson, n.d.), a graphical algorithm editor seamlessly integrated with Rhino's 3-D modelling tools, served as the graphical interface for conducting the simulation. As previously mentioned, Ladybug and Honeybee—open-source plugins integrated with

Grasshopper—were selected to carry out the thermal simulation in this study. The Ladybug plugin (Ladybug Tools LLC, 2017b; Roudsari & Pak, 2013) facilitated the importation of standard EnergyPlus Weather files for use in the simulation. In addition, Honeybee plugin (Ladybug Tools LLC, 2017a) collaborated with several simulation engines, including Radiance and Daysim for daylight and radiation simulations, and EnergyPlus/OpenStudio (National Renewable Energy Laboratory & US Department of Energy, n.d.) for energy and thermal simulations. The Ladybug and Honeybee plugins have gained widespread adoption in the field of parametric modelling in architecture (Bahdad et al., 2021; Soflaei et al., 2020), daylight simulation (Bahdad et al., 2021; Khani et al., 2022), thermal comfort simulation (Khani et al., 2022; Soflaei et al., 2020), and building energy consumption analysis (Bahdad et al., 2021; Khani et al., 2022; Lobaccaro et al., 2018; Tabadkani et al., 2019).

2.3.3.1 Variations of Parameters

Previous research has firmly established that the thermal performance of a building is significantly influenced by various factors, including climate and architectural features (Givoni, 1998; Hien & Liping, 2006; Wong & Khoo, 2003). To comprehensively evaluate the impact of these variables on students' thermal comfort in Indonesian classrooms, this study encompassed two distinct cities: the highland city of Ruteng and the lowland coastal area of Surabaya, selected to represent the climatic variation in Indonesia. Additionally, the study considered several variations in building features, including two modes of natural ventilation (single-sided and cross-ventilation), two floor levels (first and second), eight building orientations ranging from north (0°) to northwest (315°), and six combinations of wall and roof materials. This comprehensive approach resulted in a total of 348 scenarios for thermal simulations. For further details regarding the variations in design parameters incorporated into the simulation, please refer to Table 2.11.

Table 2.12 Variation of parameters for the thermal simulations

Parameter	Variation	Number of variation
Cities	Surabaya	2
	Ruteng	
Modes of natural ventilation	Single-sided	2
	Cross-ventilation	
Floor level	First-floor	2
	Second-floor	
Windows orientation	0°	8
	45°	
	90°	
	135°	
	180°	
	225°	
	270°	
	315°	
Construction material	AAC wall + clay tile roof	6
	AAC wall + concrete tile roof	
	AAC wall + corrugated aluminium roof	
	Bricks wall + clay tile roof	
	Bricks wall + concrete tile roof	
	Bricks wall + corrugated aluminium roof	
Total of scenarios		**348**

Indoor air velocity data obtained from the CFD simulation serves as an essential input for the subsequent thermal simulation stage. To streamline the analysis and limit the number of scenarios, only the indoor air velocities corresponding to the most prevailing wind velocities in each city were considered for the simulation.

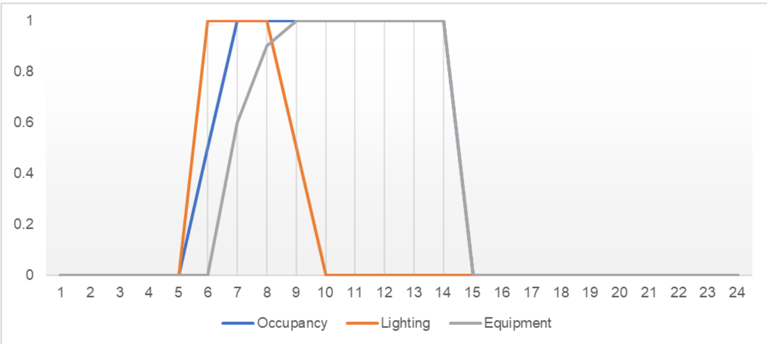
Furthermore, the simulation settings encompassed a range of factors, including physical zone programs, loads, and schedules, all of which were configured to align with the conditions specific to Indonesia. A comprehensive overview of the parameter settings and their corresponding values for thermal simulation in this study is presented in Table 2.12 for reference.

In Indonesian classrooms, student activities typically commence at 7:00 a.m. and conclude at 2:00 p.m. Theefore, the activity schedule, lighting, and equipment settings for this simulation were centred around these occupied hours. Various parameters, including lighting density, were established in accordance with Indonesian regulations pertaining to lighting standards for classrooms. Moreover, the number of occupants per unit area adhered to the guidelines outlined in the Indonesian Ministry of Education's regulation number 24 of 2007 (Kemdiknas Republik Indonesia, 2007).

Nevertheless, it is important to acknowledge that there are currently no established regulations requiring the inclusion of certain electrical equipment within classrooms in Indonesia. For the sake of this simulation, it was assumed that classrooms would be furnished with an LCD projector, a computer, and a limited number of laptops during the designated hours of occupancy.

Infiltration rates were computed distinctively for different classrooms, varying based on the type of ventilation and building orientations. These calculations were determined according to the indoor air velocities obtained from the prior CFD simulation, ensuring a tailored approach for each scenario.

Table 2.13 Values assumed during thermal simulations

Parameters	**Assigned value**
Physical program	Secondary school
Internal loads	Equipment per load area: 7.92 W/m2
	Lighting density: 12.5 W/m2; lighting level: 300 lux
	Number of people: 33 ppl/72 m2
	Infiltration rate per area facade: calculated based on the indoor air velocity obtained from CFD simulation (m3/s)
Modes of natural ventilation	Window natural ventilation (single-sided & cross-ventilation)
Heating set point	Not assigned
Cooling set point	Not assigned
Daily (weekday) operational profile	

Indonesian schools lack specific regulations regarding the materials used in construction. Therefore, the materials assigned for the classroom model in this simulation were selected based on common practices in Indonesian schools. Typically, these classrooms featured reinforced concrete construction with brick walls. Additionally, Autoclaved Aerated Concrete (AAC) was included as a variation in wall material, as its use had gained popularity in Indonesia.

Furthermore, the study considered various roofing materials, including clay tiles, concrete tiles, and corrugated aluminium. Concrete and clay tiles are widely used in most Indonesian cities, such as Surabaya in the lowland coastal region. Conversely, corrugated aluminium is preferred in specific cities, with the highland city of Ruteng serving as a notable example. Table 2.13 provides the thermal properties of the variations in wall and roof materials that were integrated into this study.

Table 2.14 Thermal properties of the wall and roof construction materials used in the simulation

Construction type	Material name	Layer	Name	Roughness	Thickness (m)	Conductivity (W/m·K)	Density (kg/m3)	Specific heat (J/kg·K)
Wall material type 1	Brick wall	1	Cement plaster	Medium smooth	0.02	0.72	1860	800
		2	Cement plaster with sand	Medium rough	0.03	0.721	1858	837
		3	Brick	Rough	0.12	0.807	1760	800
		4	Cement plaster with sand	Medium rough	0.03	0.721	1858	837
		5	Cement plaster	Medium smooth	0.02	0.72	1860	800
Wall material type 2	AAC wall	1	Cement plaster	Medium smooth	0.02	0.72	1860	800
		2	AAC	Medium rough	0.1	0.303	750	1000
		3	Cement plaster	Medium smooth	0.02	0.72	1860	800
Roof material type 1	Clay tile roof	1	Clay tile	Medium rough	0.06	0.84	1900	800
Roof material type 2	Concrete tile roof	1	Concrete tile	Medium rough	0.08	1.1	2100	837
Roof material type 3	Corrugated Alumumium	1	Corrugated Alumunium	Medium smooth	0.0015	45.006	7680	418.4

2.3.3.2 Model validation

The model validation for thermal simulation involved comparing the simulated thermal data of Indonesian classroom microclimates with measurement data gathered from classrooms surveyed by Hamzah et al. (2018). The measurements took place at SMAN 21 Makassar, a public high school in Makassar, a lowland city in Indonesia. According to Hamzah et al. (2018), the measurements occurred on August 3, 2017, during school hours from 8:10 am to 1:45 pm. The classrooms chosen were standard Indonesian classrooms, each measuring 8m x 9m (72 m²), using cross-ventilation for natural ventilation. These buildings were permanent structures with plastered brick walls and concrete tile roofs.

Figure 2.26 Situation in the surveyed classrooms. Source: Hamzah et al. (2018)

As detailed by Hamzah et al. (2018), the measurement employed various instruments. The LSI-Lastem Thermal Comfort Multi Logger, which comprises multiple sensors and data loggers, was utilized for the measurements. Additionally, it was noted that six HOBO loggers were used to monitor the thermal environments at six points within each classroom. Two types of loggers were employed: the HOBO temp/Relative Humidity (RH) logger (Hobo-1) and the HOBO temp/RH/Light/External logger (Hobo-2). Four HOBO temperature/RH loggers measured air temperature and relative humidity, and two HOBO temp/RH/Light/External loggers measured air temperature, relative humidity, and airflow velocity. The arrangement of these instruments in the surveyed classrooms is depicted in Figure 2.27, while their detailed specifications are provided in Table 2.14.

Furthermore, Hamzah et al. (2018) mentioned that sensors for environmental data measurement were positioned 100 cm above the floor. Due to the limited number of instruments, the Mean Radiant Temperature (MRT) was recorded at only one central point in the room, and air temperatures were recorded at two points (A and B). Instruments at points C, D, E, and F measured only air temperature and relative humidity (refer to Figure 2.27). The measurement results were then calculated to determine the average air temperature (Hamzah et al., 2018).

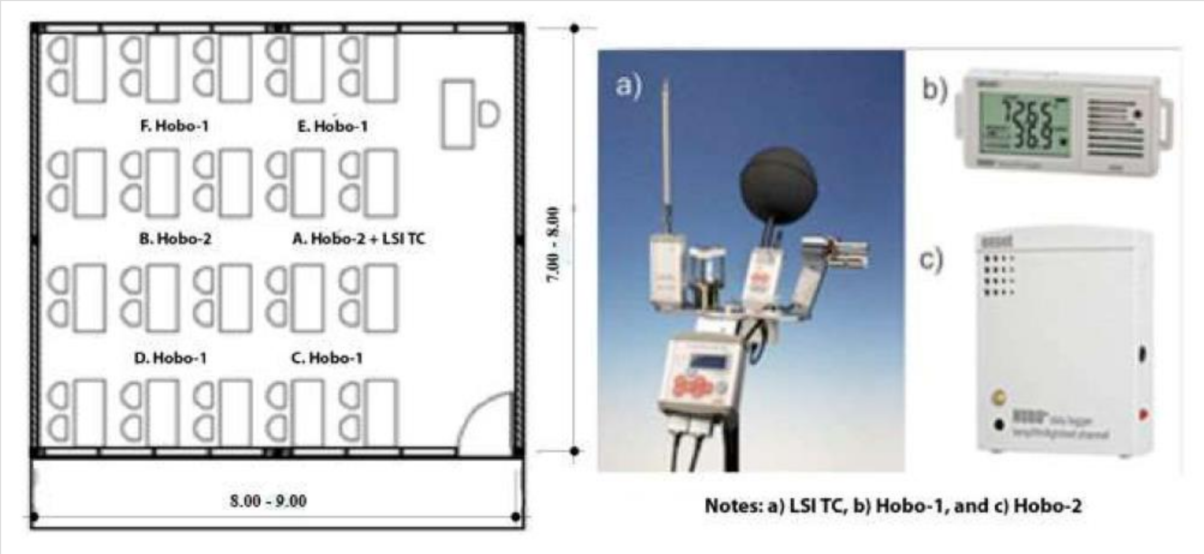


Figure 2.27 The arrangement of instruments in the typical classrooms (left) and the instruments (right): (a) LSI-Lastem; (b) Hobo-1, Hobo temp/Relative Humidity (RH); and (c) Hobo-2, Hobo temp/RH/Light/External logger (airflow velocity). Source: Hamzah et al. (2018)

Table 2.15 The specifications of the instruments used in the survey

No	Instrument Name	Range	Accuracy	Resolution
1	Black Globe Radiant temperature (EST131)			
	Radiant temperature	-40 to +80°C	NA	0.01°C
2	Psychrometer Sensor (ESU102)			
	Air temperature	-5 to +60°C	NA	0.01°C
	Relative humidity	0 to 100%	NA	1%
3	Hot wire anemometer (ESV106)			
	Air velocity	0.01 to 20 m/s	NA	0.01 m/s
4	HOBO Temp/RH logger (UX100-011)			
	Air temperature	-20 to +70°C	±0.21°C	0.024°C
	Relative humidity	5 to 95%	±2.5%	0.05%
5	HOBO Temp/RH/Light/External (U12-012)			
	Air temperature	-20 to +70°C	±0.21°C	0.024°C
	Relative humidity	5 to 95%	±2.5%	0.05%
	Air velocity	0.15 to 10 m/s	±0.05 m/s	NA

Source: Hamzah et al. (2018)

The thermal simulation was performed using a geometric model of an Indonesian classroom, focusing on a first-floor, cross-ventilated classroom with windows oriented west at 270°. The model included bricks and concrete tiles for the walls and roof, reflecting the conditions of the classrooms where the measurements were taken. Weather data for the simulation came from Sultan Hasanuddin International Airport's typical meteorological data for 2007-2021 (Climate.

OneBuilding, 2023). Climate data from Sultan Hasanuddin International Airport was selected because it is the nearest weather station, approximately 20 km from the city centre (Hamzah et al., 2018).

The simulation was conducted using the Ladybug (Ladybug Tools LLC, 2017b; Roudsari & Pak, 2013) and Honeybee (Ladybug Tools LLC, 2017a) plugins for Grasshopper (Davidson, n.d.), with OpenStudio (National Renewable Energy Laboratory & US Department of Energy, n.d.) as the simulation engine. The settings and values assumed during the simulation matched those used in the thermal simulation for this study, as detailed in Table 2.12.

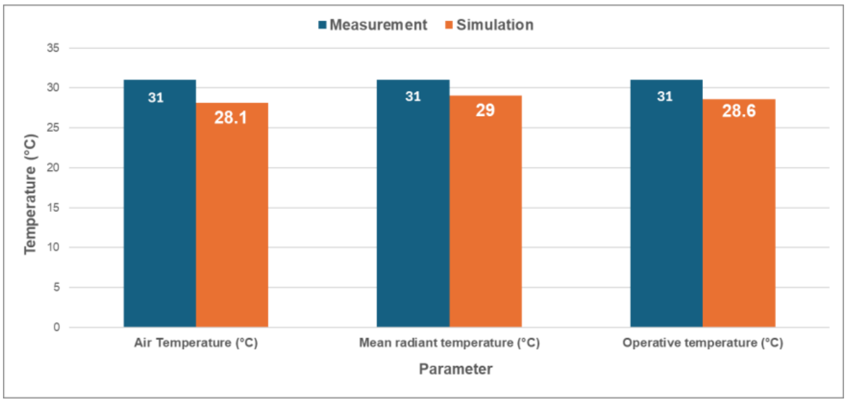


Figure 2.28 Comparison of air temperature, mean radiant temperature, and operative temperature between the room measurements and simulation

Figure 2.28 presents a comparison of air temperature, mean radiant temperature, and operative temperature parameters from both the measurement in the surveyed classroom and the simulation. It is crucial to note that only these three parameters were compared, as Hamzah et al. (2018) did not provide detailed results for indoor air velocity and relative humidity for this specific classroom. Figure 2.28 reveals discrepancies between the thermal simulation results and the measurements. However, these discrepancies are within an acceptable range with the differences between simulations and measurements being less than 10%. Overall, the air temperature, mean radiant temperature, and operative temperature values from the thermal simulation are well-aligned with the measurement results.

One possible cause of the disparities between the surveyed and simulation data in this study is the use of climate data from a weather station distant from the site, which could lead to a loss of accuracy since the weather data may not perfectly reflect the microclimate conditions at the site. Despite these differences, the overall agreement between the thermal simulation results and measurements is good, and the differences remain within acceptable limits. Therefore, the results can be reasonably regarded as valid (Norton et al., 2010).

2.4 Assessment of the thermal comfort response of Indonesian students in the classrooms

The final phase of this research assessed students' thermal comfort responses in Indonesian classrooms, incorporating various parameters obtained from the first and second phases. This analysis aims to provide a deeper understanding of the impact of clothing insulation and building feature variables, specifically ventilation type, floor level, and window orientation, on students' thermal comfort. Evaluating thermal comfort responses in Indonesian cities is crucial for gaining insights to enhance thermal comfort in classrooms. The assessment of students' thermal comfort in Indonesian classrooms consists of four distinct stages:

1. Calculation of Standard Effective Temperature (SET) for every classroom, considering the various combinations of clothing insulation and building feature parameters involved in this study.
2. Determination of the neutral temperature for both cities in the case study.
3. Establishment of the range of comfort acceptability for students in the classrooms of both cities within the case study.
4. Calculation of the percentage of yearly comfortable occupied hours for each classroom with different parameter variations, aiming to identify the combinations of parameter variations resulting in a higher percentage of comfortable hours.

The Standard Effective Temperature (SET) was chosen as the thermal comfort model to assess thermal comfort responses in this study. SET is defined as the temperature of an imaginary environment with 50% relative humidity and an average air speed of less than 0.1 m/s, where the total heat loss from the skin of an imaginary occupant, with an activity level of 1.0 metabolic equivalent of task (met) and a clothing level of 0.6 clo, is equivalent to that of a person in the actual environment (ASHRAE, 2020). SET is derived from the two-node model proposed by Gagge (1971). This model enables researchers to predict values of thermal quantities related to the human body, such as skin temperature, skin wettedness, or heat loss from the skin (Ji et al., 2022). Unlike the Predicted Mean Vote (PMV) model, where skin temperature and sweat rate are solely functions of metabolic activities, the SET index takes into account the effect of air velocity on both convective heat exchange and the evaporation of sweat (Gao et al., 2015; Ji et al., 2022).

The SET index is considered more suitable in the context of naturally ventilated buildings, particularly in hot and humid climates, as it incorporates the impact of air velocity on both convective heat exchange and sweat evaporation (Karyono, 2015; Zhang et al., 2010). Previous research has indicated that SET can predict thermal sensation more accurately than PMV, especially in the case of naturally ventilated buildings (Zhang et al., 2010).

2.4.1 Calculation of Standard Effective Temperature (SET) in every classroom with different combinations of parameters involved

The initial step in assessing the thermal comfort responses in Indonesian cities involved the calculation the Standard Effective Temperature (SET) for every hour of occupancy across 768 simulated classroom configurations situated in the lowland coastal area of Surabaya and the highland region of Ruteng, as detailed in Table 2.14. These configurations encompass diverse building feature parameters, including two types of natural ventilation (single-sided and cross-ventilation), two different floor levels (first and second floor), eight window orientations spanning from north (0°) to northwest (315°), and six combinations of wall and roof materials.

The SET calculation involved hourly data of simulated indoor air velocity, air temperature, mean radiant temperature, and relative humidity for each classroom with different combinations of building features. Additionally, the SET calculation incorporated variables such as metabolic rate and clothing insulation. The metabolic rate estimated for this study was 1.2 metabolic equivalents of task (MET), representing seated sedentary school activities, including reading, writing, typing, and filing, as specified by ISO 7730:2005 (British Standards Institution, 2006). Clothing insulation values used in the SET calculation were the highest and lowest values measured in Indonesian Muslim uniform ensembles taken from the first research phase of this study (thermal manikin measurement). This approach ensured that the thermal comfort analysis accounted for the range of clothing insulation values associated with various configurations of Indonesian Muslim attire worn by students in classrooms.

The SET calculations were conducted using the Center for the Built Environment (CBE)'s thermal comfort tools developed by Tartarini et al. (2020). The selection of the CBE thermal comfort tool for calculating the Standard Effective Temperature (SET) was based on its reputation as a reliable tool for thermal comfort calculations and visualizations. This tool adheres to the standards set by ASHRAE 55–2017, ISO 7730:2005, and EN 16798–1:2019 (Tartarini et al., 2020). Furthermore, the CBE tool incorporates major thermal comfort models, including the SET model, which was used to assess students' thermal comfort responses in this study (Tartarini et al., 2020).

These SET calculations for each classroom were performed during the occupied hours spanning from 7:00 a.m. to 2:00 p.m. throughout the year. Table 2.15 provides variations of parameters included in the SET thermal comfort calculations.

Table 2.16 Variation of parameters in the SET thermal comfort calculations

Parameter	Variation	Number of variation
Cities	Surabaya	2
	Ruteng	
Modes of natural ventilation	Single-sided	2
	Cross-ventilation	
Floor level	First-floor	2
	Second-floor	
Window orientation	0°	8
	45°	
	90°	
	135°	
	180°	
	225°	
	270°	
	315°	
Construction material	AAC wall + clay tile roof	6
	AAC wall + concrete tile roof	
	AAC wall + corrugated aluminium roof	
	Bricks wall + clay tile roof	
	Bricks wall + concrete tile roof	
	Bricks wall + corrugated aluminium roof	
Clothing insulation	Lowest clothing insulation	2
	Highest clothing insulation	
Metabolic rate	1.2 met	1
Total of variations		**786 variations**

2.4.2 Determining the neutral temperature of Indonesian cities and range of comfort acceptability

Identifying the neutral temperature and the acceptable range of comfort temperatures is essential before evaluating thermal comfort responses. Neutral temperature refers to the specific temperature at which individuals do not feel either warm or cool, thus representing the optimal condition for thermal comfort (Fanger, 1970). The acceptable comfort range encompasses the temperatures within which individuals feel neither too hot nor too cold, deeming it suitable for thermal comfort. Establishing these parameters was critical as they provided baseline measures for assessing how individuals perceived and reacted to their thermal surroundings.

The preferences for neutral temperature can vary among individuals and is influenced by various factors, including thermal past experiences, clothing levels, activity levels, and other variables (Brager & de Dear, 1998; Jowkar, de Dear, et al., 2020). In previous thermal comfort studies utilizing field surveys, the thermal neutral temperature was determined by performing a simple regression analysis between thermal sensation votes and indoor air temperature (Alfata et al., 2012; Cen et al., 2024; Wu & Wagner, 2024). However, this study relied on laboratory measurements and computer simulations, with no available data on thermal sensation votes. Consequently, the neutral temperature for this study was established based on neutral temperatures obtained from prior research on thermal comfort conducted in Indonesia.

For the determination of the neutral temperature in this study, prior research conducted by Karyono (2015) served as a foundational reference. Karyono's study, titled "Predicting Comfort Temperature in Indonesia, an Initial Step to Reduce Cooling Energy Consumption" (Karyono, 2015), aimed to propose an initial Indonesian thermal predictor in the form of a simple equation, capable of accurately predicting comfort temperatures across the country.

Karyono's equation was chosen for determining the neutral temperature in this study due to the absence of a reliable local thermal comfort standard in Indonesia. The current national standard (SNI 6390:2011) prescribes a uniform comfort temperature range (25.5°C ± 1.5°C Ta and 60% ± 5% RH) applicable nationwide (Badan Standardisasi Nasional Indonesia, 2011; Karyono, 2015). However, this standard has been deemed unreliable, as previous research indicates that inhabitants of major cities such as Jakarta, Surabaya, and Yogyakarta perceive comfort at temperatures ranging from 27°C to 29°C (Alfata et al., 2012; Feriadi & Wong, 2004), surpassing the comfort range mentioned in the national standard.

Karyono (2015) conducted his research by reanalysing 2,939 thermal comfort vote data points obtained from 12 previous studies on thermal comfort. These studies were conducted in six different cities in Indonesia: Jakarta, Surabaya, Makassar, Medan, Bandung, and Yogyakarta. To establish the Indonesian thermal comfort predictor, Karyono (2015) performed a correlation analysis between the comfort temperatures identified in these earlier studies and the average daily temperatures during which those studies were conducted. This analysis enabled him to derive a simple linear regression equation representing the Indonesian thermal comfort predictor, as illustrated in Figure 2.29.

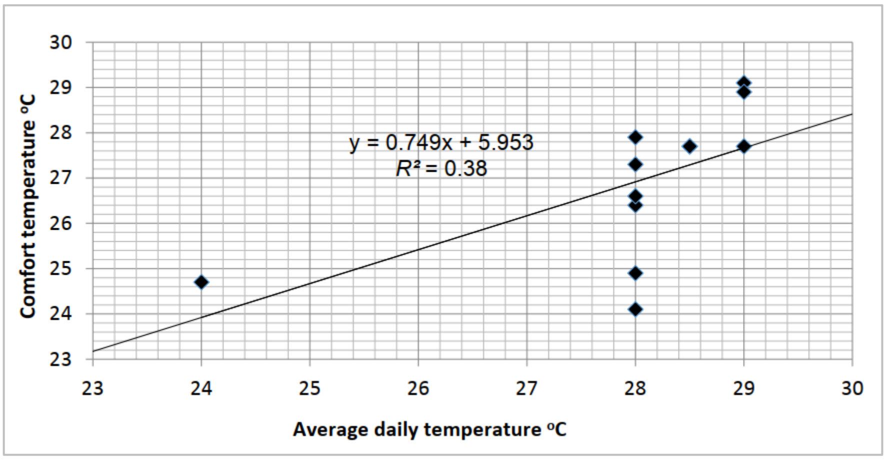


Figure 2.29 Karyono's comfort prediction equation, generated from analysing data of previous comfort studies in Indonesia. Sources: Karyono (2015)

Karyono (2015) acknowledged a potential limitation in the application of the comfort predictor equation. This limitation arises from the relatively narrow range of variation in average daily temperatures covered by the previous comfort studies. Many of these studies were conducted in big cities, primarily situated in lowland or coastal areas, characterized by high average daily temperatures. The only exception to this trend was the comfort study conducted in Bandung, a city located in the highlands, where the average daily temperature is comparatively lower. Karyono (2015) further noted that the suggested thermal comfort predictor is likely to be most applicable for predicting comfort temperatures in regions with average daily temperatures ranging between 24 and 29 °C. These temperatures align with the range in which previous comfort studies have been predominantly conducted.

This study focused on two Indonesian cities, lowland coastal Surabaya and highland Ruteng, as case studies. Surabaya is situated in a lowland coastal area, characterized by an average daily temperature of 29 °C. On the other hand, Ruteng, the second case study, is a highland city with an average daily temperature of 22 °C. Ruteng's average temperature falls below the range of average daily temperatures in cities where comfortable temperatures for inhabitants can be predicted using Karyono's equation. However, since there has been no prior research on thermal comfort conducted in the context of highland cities in Indonesia with an average daily temperature below 24 °C, this study employed Karyono's predicted thermal comfort equation (Karyono, 2015) to determine the neutral temperature in Ruteng.

Given that the Standard Effective Temperature (SET) was chosen as the comfort model for assessing thermal comfort responses in this study, the neutral temperatures of Surabaya and Ruteng were converted to SET using the CBE thermal comfort tool (Tartarini et al., 2020).

As such, in the process of converting the neutral temperatures of Surabaya and Ruteng, as calculated from Karyono's predicted thermal comfort equation, into SET values, the actual environmental thermal comfort parameters, including clothing insulation, relative humidity, air velocity, and metabolic rate, were derived from the data in prior research cited by Karyono (2015).

2.4.3 Determining the range of comfort acceptability of the students in the classrooms of both cities of the case study

After determining the SET values for neutral temperature in lowland coastal Surabaya and highland Ruteng, the next step involved defining the range of thermal comfort acceptability for students in both cities. In this study, the SET thermal comfort acceptability range was established based on the adaptive comfort criteria outlined in ASHRAE Standard 55.

Specifically, the range associated with the 80% comfort criterion, which includes a 3.5°C margin above and below the neutral temperature (ASHRAE, 2020), was selected to strike a balance between achieving acceptable comfort for most occupants and being practical and achievable in building design and operation.

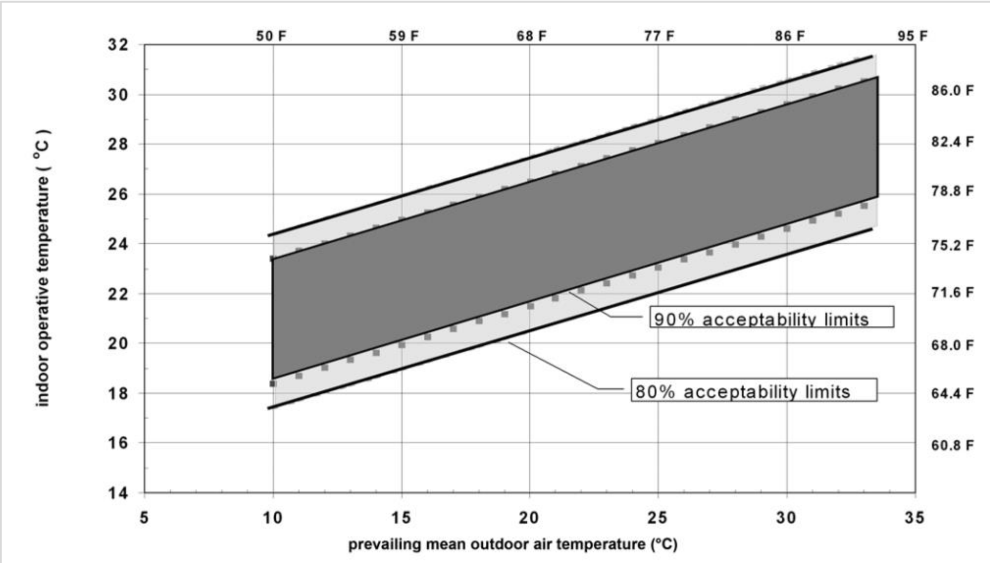


Figure 2.30 Acceptable operative temperature ranges for naturally conditioned spaces based on the adaptive comfort index (ASHRAE, 2020)

2.4.4 Calculating the percent of comfortable occupied hours in every classroom with different variations of parameters

After establishing the neutral temperature and acceptable range of thermal comfort in Standard Effective Temperature (SET) for both lowland coastal Surabaya and highland Ruteng, the subsequent step involved calculating the yearly percentage of comfortable occupied hours for each classroom under different parameter combinations.

This study utilized the percentage of yearly comfortable occupied hours as a metric to assess students' thermal comfort in Indonesian classrooms. This percentage indicates the amount of time over the year that the classroom conditions remained within the acceptable thermal comfort range for students. Considering that school hours in Indonesia span from 7:00 am to 2:00 pm, the total annual occupied hours amounted to 2920 hours. A higher percentage of comfortable hours suggested that classrooms were able to maintain acceptable thermal comfort for students for a greater portion of the year. Achieving a 100% yearly percentage of comfortable hours would mean that the classroom's thermal conditions were consistently acceptable throughout the entire school year, covering all 2920 hours.

The determination of the yearly percentage of acceptable occupied hours involved the hourly Standard Effective Temperature (SET) calculated from simulated thermal performance data from classrooms in lowland coastal Surabaya and highland Ruteng, obtained from the process explained in sub-chapter 2.4.1 of this thesis. The calculation of the acceptable occupied hours focused on hourly data falling within the acceptable comfort temperature range in Standard Effective Temperature (SET), considering the 80% range of comfort acceptability for both locations. A value of 1 was assigned if the SET value fell within the acceptability range, while a value of 0 was assigned if the SET value was outside this range. These assigned values were then aggregated to determine the total annual comfortable occupied hours.

Subsequently, an analysis was conducted using the percentage of yearly comfortable occupied hours to identify the optimal combination of building feature parameters and clothing insulation parameters that resulted in the highest percentage of comfortable occupied hours for classrooms in both lowland coastal Surabaya and highland Ruteng. This analysis facilitated the identification of the most effective design and environmental parameters for improving thermal comfort in these classroom settings.

Chapter 3 Results

This chapter offers a comprehensive overview of the collected data with the aim of enhancing the thermal comfort of Indonesian students in classrooms. The presentation of this chapter is structured around the "third skin" analogy within architectural discourse, particularly in the context of thermal comfort (Drake, 2007), which conceptualizes the built environment as a protective layer, analogous to the first and second skins enveloping the occupant’s body.

Following this analogy, sub-chapter 3.1 is focused on the second skin, specifically the thermal insulation of Indonesian Muslim school uniforms, acting as a thermal resistance between the human body’s surface and the indoor environment of the classroom. This section presents outcomes derived from measurements and calculations of the thermal insulation properties of various Indonesian Muslim school uniforms, along with an analysis of the salient factors influencing them.

Sub-chapter 3.2 delves into the role of the third skin, referring to the building envelope system as a barrier between the indoor environment of classrooms and the outdoor environment. The simulated indoor microclimates of Indonesian classrooms in Surabaya and Ruteng, representing exemplars of Indonesia’s coastal and highland climate zones respectively, are explored in this section. Analysis regarding the influence of several building feature variables on the microclimate of classrooms is also presented.

Finally, sub-chapter 3.3 seeks to understand the response of the first skin, referring to students' physiological responses in terms of thermal comfort. The findings in this section are simulated thermal comfort responses of students in Indonesian classrooms in the two selected cities, based on the Standard Effective Temperature (SET) index for a standardized and comprehensive evaluation.

By systematically presenting data from these three critical phases, this chapter contributes a nuanced understanding of the factors influencing thermal comfort in Indonesian classrooms. These analyses address the overarching aim of this research and pave the way for targeted improvements in classroom environments.

Figure 3.1 The "third skin" analogy to structure the results chapter

3.1 Clothing insulation of Indonesian Muslim school uniforms

This section presents the results from the initial phase of this research, which centres on the clothing insulation measurements of Indonesian Muslim school uniforms, based on thermal manikin tests (Tanabe et al., 1994). The primary aim is to quantitatively evaluate the influence of clothing insulation on the thermal comfort experienced by students. Furthermore, the findings from this research stage are expected to provide insights for improved designs of Indonesian school uniforms, optimizing the balance between the requirements for students' thermal comfort and the religious and cultural expectations of modesty, particularly for female students.

The specific configurations of current school uniforms selected for this study are detailed in Table 2.1 of Chapter 2 (Methodology). A total of eleven ensemble configurations, derived from fundamental Indonesian Muslim clothing uniform styles (long-sleeve shirt with pleated skirt, long-sleeve shirt with a span skirt, long-sleeve shirt with a span skirt (untucked), and long-sleeve shirt with trousers), were measured and assessed for their intrinsic clothing insulation (I_{cl}), both in standing and seated postures.

The results of the manikin measurements and calculations for the chosen uniform ensembles in standing and sitting postures are outlined in Tables 3.1 and 3.2, respectively. This presentation incorporates both total insulation I_T (i.e., clothing layer plus boundary air layer), and intrinsic clothing insulation I_{cl} (i.e., only the clothing layer without a boundary layer).

The analysis in this research explicitly focused on intrinsic clothing insulation as a pivotal factor influencing thermal comfort, as it is the type of insulation metric required for input into the comfort simulations used later in this work.

Table 3.1 Values for total and intrinsic clothing insulation of eleven ensemble configurations of Indonesian Muslim uniforms in standing postures[1]

Ensemble Category	Ensembles Code	f_{cl}	t_a (°C)	I_a (m²K/W)	I_a/f_{cl}	I_T (m²K/W)	I_{cl} standing (m²K/W)	I_{cl} standing (clo)
Long-sleeve shirt with pleated skirt (A)	A1.1	1.52	21.6	0.12	0.08	0.23	0.15	0.96
	A1.2	1.52	21.6	0.12	0.08	0.24	0.16	1.04
	A2.1	1.53	21.6	0.12	0.08	0.23	0.15	0.99
	A2.2	1.53	21.6	0.12	0.08	0.25	0.17	1.08
Long-sleeve shirt with span skirt (B)	B1.1	1.46	21.6	0.12	0.08	0.23	0.15	0.94
	B1.2	1.46	21.6	0.12	0.08	0.24	0.16	1.03
	B2.1	1.42	21.6	0.12	0.09	0.22	0.14	0.90
	B2.2	1.42	21.6	0.12	0.09	0.24	0.16	1.01
Long-sleeve shirt with trousers (C)	C1	1.35	21.6	0.12	0.09	0.21	0.12	0.78
	C2	1.35	21.6	0.12	0.09	0.22	0.13	0.83
	C3	1.46	21.6	0.12	0.08	0.66	0.11	0.73

[1] For details on the ensemble categories and codes, please refer to Table 2.1 on pages 47–50

Table 3.2 Values for total and intrinsic clothing insulation of eleven ensemble configurations of Indonesian Muslim uniforms in sitting postures[1]

Ensemble Category	Ensembles Code	f_{cl}	t_a (°C)	I_a (m²K/W)	I_a/f_{cl}	I_T (m²K/W)	I_{cl} sitting (m²K/W)	I_{cl} sitting (clo)
Long-sleeve shirt with pleated skirt (A)	A1.1	1.35	21.6	0.13	0.10	0.23	0.14	0.90
	A1.2	1.35	21.6	0.13	0.10	0.25	0.15	0.98
	A2.1	1.52	21.6	0.13	0.09	0.24	0.15	0.97
	A2.2	1.52	21.6	0.13	0.09	0.25	0.16	1.05
Long-sleeve shirt with span skirt (B)	B1.1	1.44	21.6	0.13	0.09	0.23	0.14	0.93
	B1.2	1.44	21.6	0.13	0.09	0.25	0.16	1.01
	B2.1	1.45	21.6	0.13	0.09	0.22	0.13	0.87
	B2.2	1.45	21.6	0.13	0.09	0.24	0.15	0.98
Long-sleeve shirt with trousers (C)	C1	1.29	21.6	0.13	0.10	0.21	0.11	0.70
	C2	1.32	21.6	0.13	0.10	0.22	0.12	0.76
	C3	1.36	21.6	0.13	0.09	0.20	0.10	0.66

Analysing the intrinsic clothing insulation in standing postures based on the data presented in Table 3.1, it is evident that configurations featuring long-sleeve shirts paired with skirts, irrespective of the skirt type (pleated or span skirt), consistently exhibit higher clothing insulation compared to those combining long-sleeve shirts with trousers. Notably, ensemble C3 (untucked long-sleeve shirt with trousers) records the lowest clothing insulation at 0.73 clo, while ensemble A2.2 (tucked long-sleeve shirt with pleated skirt plus leggings worn under the skirt) attains the highest clothing insulation at 1.08 clo.

Figure 3.2 Ensembles with the lowest and highest clothing insulation. a) Ensemble C3 has an intrinsic clothing insulation of 0.73 clo; b) Ensemble A.2.2 (with legging) has an intrinsic clothing insulation of 1.08 clo

3.1.1 Impact of different postures on Indonesian Muslim uniforms' clothing insulation

Considering that most activities in the classroom occur while seated, it was important to include measurements of school uniform clothing insulation in sitting positions. To replicate authentic classroom conditions, a wooden chair, typical of those found in Indonesian classrooms, was employed for the sitting position evaluations. This ensures the contextual relevance and applicability of the measurements to the actual Indonesian classroom setting.

Figure 3.3 Sitting position on a wooden stool mimicking Indonesian classroom chairs. The stool was elevated during measurements to prevent conduction effects by ensuring the soles of the feet do not touch the floor.

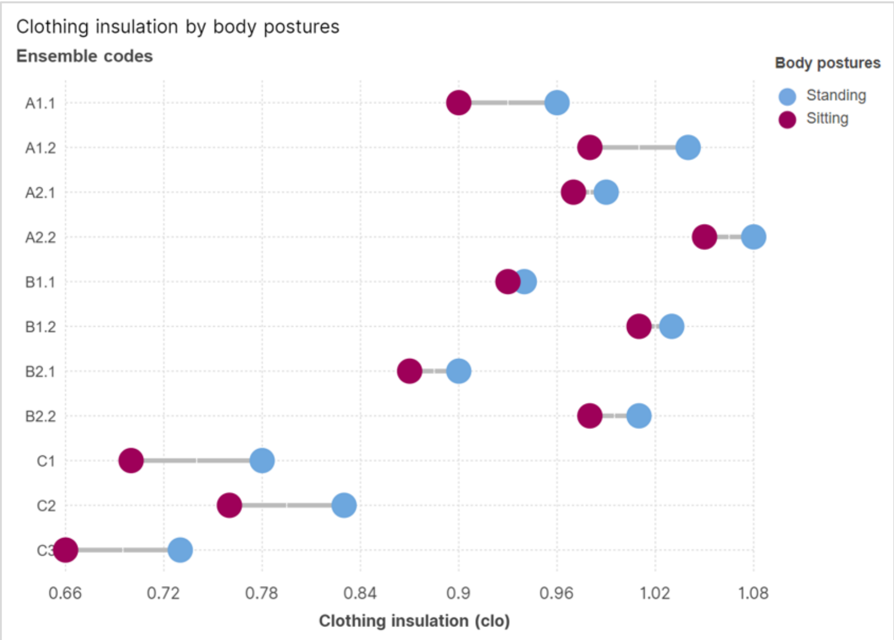


Figure 3.4 Comparison of the clothing insulation of Indonesian Muslim uniforms in standing and sitting positions

Figure 3.4 illustrates the clothing insulation for the eleven configurations of Indonesian Muslim clothing uniforms in both standing and sitting positions. The blue dots represent clothing insulation in the standing position, while the red dots represent the sitting position. Generally, clothing insulation in the standing position was higher than in the seated counterpart.

Examining the difference between standing and sitting postures, ensemble type C (long-sleeve shirt with trousers) exhibited the largest difference compared to configurations with long-sleeve shirts and skirts. Ensemble C1 (long-sleeve shirt tucked into trousers) demonstrates the highest gap at 11%, while ensemble B1.1 records the lowest gap at 1%. The decrease in clothing insulation when sitting may result from the compression of clothing in the back and thigh areas, leading to a thinner layer of air compared to when standing.

The difference in the gap between clothing insulation measurements in standing and sitting postures between skirts and trousers can be attributed to how these clothing ensembles interact with body heat and airflow in different postures. Long skirts generally provide more consistent coverage around the legs compared to trousers. When sitting, the skirt continues to cover the legs fully, which may result in less change in insulation compared to trousers. Trousers can shift or bunch up when sitting, leading to variations in insulation and air gaps. Skirts tend to have a more even distribution of fabric around the legs in both postures, which can help maintain a more consistent insulation layer.

3.1.2 Impact of wearing style on school uniform insulation values

Li et al. (2012) observed the significant impact of different ensemble wearing styles on clothing insulation, while Młynarczyk (2019) highlighted the effect of clothing apertures in reducing insulation. In the context of Indonesian students, the predominant practice involves the shirt tucked into either the skirt or trousers. This enhances the overall neatness of the uniform appearance. However, when shirts are tucked into trousers, especially with tight or medium-fitting shirts, the body's contours become more visible, a style considered inappropriate for Muslim women's clothing.

The hypothesis suggests that tucking a shirt into trousers may trap air within the ensemble layers, potentially increasing clothing insulation. Conversely, wearing shirts untucked, especially with skirts, may create apertures that facilitate circulation of the air between the body and clothing, thus enhancing convective and evaporative heat loss from the wearer’s skin surface.

To comprehensively understand the influence of tucked-in and untucked shirts on clothing insulation, measurements were conducted for both uniform configurations (long-sleeve shirt with a skirt and long-sleeve shirt with trousers) with variations in the tucking of shirts.

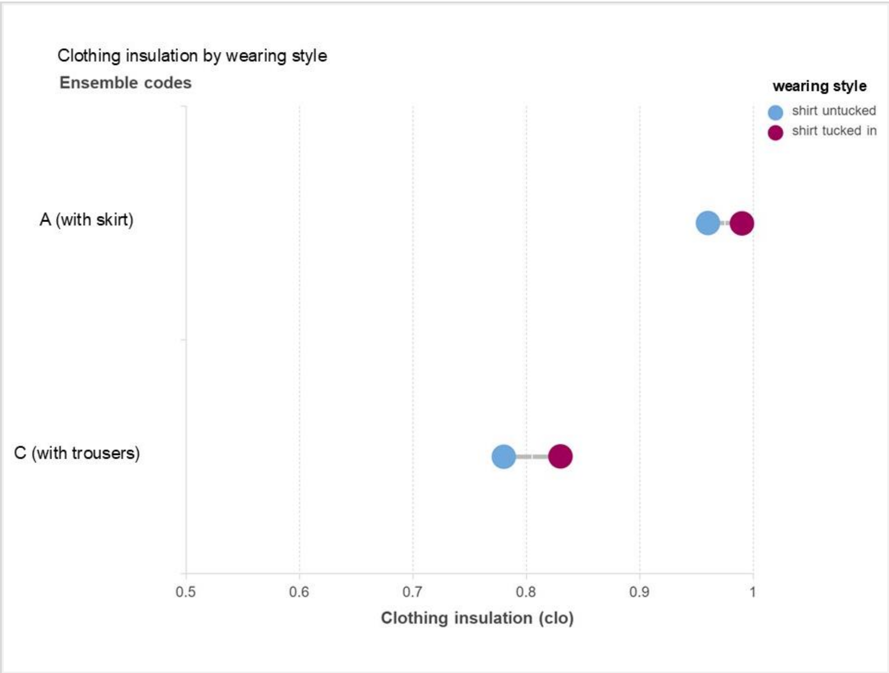


Figure 3.5 Comparison of clothing insulation of Indonesian Muslim uniforms with tucked-in versus untucked shirt

Figure 3.5 presents a comparative analysis of clothing insulation in ensemble configurations with tucked-in and untucked shirts. Ensemble code A represents long-sleeve shirts paired with skirts, while ensemble code C corresponds to long-sleeve shirts paired with trousers. In the visual representation, blue dots portray clothing insulation for ensembles with untucked shirts, while red dots depict clothing insulation for ensembles with shirts tucked into skirts or trousers. The findings consistently show higher clothing insulation for tucked-in shirts in both ensemble types A and C. The disparity between ensembles with tucked and untucked shirts is about 0.03 clo, equivalent to a 3% difference for configurations with skirts, and 0.05 clo, or 6% difference for configurations with trousers. Notably, ensemble configurations with trousers consistently exhibit lower clothing insulation compared to those with skirts, irrespective of whether the shirt is tucked or untucked.

Untucked shirts may increase airflow and ventilation by introducing additional openings in the attire, potentially contributing to cooling effects and reducing clothing insulation. In contrast, skirts might have higher clothing insulation compared to trousers, as their shape could trap more air inside, possibly creating additional insulation.

3.1.3 Impact of leggings on Indonesian school uniforms clothing insulation

In the context of Indonesian Muslim women's attire, leggings commonly serve as an inner layer beneath the skirt to provide additional coverage during activities such as climbing stairs or engaging in physically demanding actions like playful jumping. The impact of leggings on the clothing insulation was assessed through manikin measurements, comparing the clothing insulation of ensembles configured with skirts, both with and without leggings.

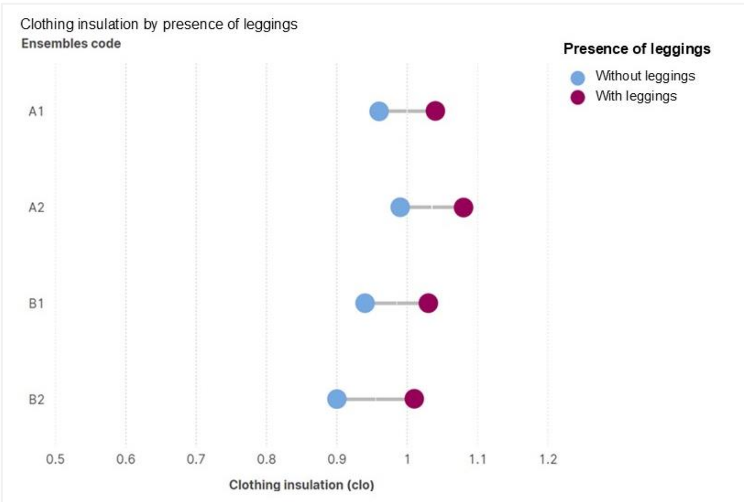


Figure 3.6 Comparison of clothing insulation of Indonesian Muslim uniforms with and without leggings

Figure 3.6 presents a comparison of clothing insulation in Indonesian Muslim uniforms with and without leggings, specifically focusing on configurations featuring long-sleeve shirts with pleated skirts (ensembles A1 and A2) and long-sleeve shirts with span skirts (ensembles B1 and B2). The blue dots depict ensemble configurations without leggings, while the red dots indicate ensemble configurations equipped with leggings. Notably, ensembles with leggings demonstrate higher clothing insulation compared to those without leggings. The smallest gap is observed in ensemble A1, accounting for 0.08 clo, equivalent to an 8% difference, while the highest difference in insulation was found for ensembles B2, with 0.11 clo, amounting to 11%. Overall, the presence of leggings results in higher clothing insulation for ensembles with pleated skirts compared to those with span skirts. Adding an additional layer of clothing to an ensemble is suggested to potentially impede air circulation within the attire, potentially leading to an increase in insulation.

3.2 Simulation of indoor microclimates of Indonesian classrooms

This sub-chapter presents the outcomes of simulations designed to comprehend the indoor microclimate of Indonesian classrooms in two distinctive cities, lowland coastal Surabaya and highland Ruteng. These cities were chosen to represent the diversity of the tropical climate in Indonesia, with Surabaya representing lowland coastal area cities characterized by higher daily temperatures, and Ruteng exemplifying highland towns and cities with comparatively lower temperatures.

The discussion within this sub-chapter is organized into two discernible sections. Section 3.2.1 delineates the results of Computational Fluid Dynamics (CFD) simulations. This section specifically focuses on the indoor air velocities simulated inside the model Surabaya and Ruteng classrooms. Section 3.2.2 presents the thermal performance of classrooms in Ruteng and Surabaya derived from thermal simulations.

3.2.1 Simulated indoor air velocity of Indonesian classroom

This section presents the outcomes of Computational Fluid Dynamics (CFD) simulations conducted within typical two-story classrooms in Indonesia, situated in the selected case study cities.

As detailed in Table 2.6 of the methodology chapter, a total of 64 distinct scenarios of CFD simulations were executed, encompassing various combinations of parameters. The outdoor wind input parameters included two prevailing wind velocities corresponding to the two main prevailing wind directions (during the school occupied hours), derived from the hourly wind rose data representing wind directions and velocities in Surabaya and Ruteng (as depicted in Figures 2.17 and 2.18).

The parameters concerning the classroom model design comprised two modes of natural ventilation (cross-ventilation and single-sided ventilation), two floor levels (first-floor and second-floor), and eight window orientations (north 0°, northeast 45°, east 90°, southeast 135°, south 180°, southwest 225°, west 270°, and northwest 315°).

The CFD simulation was conducted case-by-case by rotating the building to face eight different directions, resulting in eight different window orientations (north 0°, northeast 45°, east 90°, southeast 135°, south 180°, southwest 225°, west 270°, northwest 315°), while keeping the prevailing wind directions constant (southeast 135° for the first prevailing wind direction and east 90° for the second prevailing wind direction). This method further provided an understanding of how different windows' orientations relative to wind direction affected the average indoor air velocity.

3.2.1.1 CFD simulation of indoor air velocities in classrooms: comparing lowland coastal Surabaya and highland Ruteng with southeasterly wind (135°)

Figure 3.7(a) presents wind rose diagrams illustrating the average indoor air velocity in lowland coastal Surabaya's classrooms based on building orientation, while Figure 3.7(b) shows similar diagrams for highland Ruteng. These diagrams display results from Computational Fluid Dynamics (CFD) simulations using the first prevailing wind direction from the southeast (135°) with outdoor wind speeds of 1.99 m/s in the lowland coastal area of Surabaya and 1.79 m/s in highland Ruteng. Outdoor air velocities were assumed at a height of 10 m above ground level. However, indoor air velocities near the windows (measured at 1.2 m above ground for first-floor classrooms and 4.7 m for second-floor classrooms) were lower due to downscaling effects applied by the simulation software.

In these charts, indoor air velocity in cross-ventilated classrooms is depicted in blue shades: dark blue for first-floor classrooms and light blue for second-floor classrooms. Single-sided ventilation classrooms are represented in red and pink for first- and second-floor classrooms, respectively. Each direction on the wind rose corresponds to a different window orientation. The data indicate that cross-ventilated classrooms consistently achieve higher indoor air velocities compared to single-sided ventilation classrooms. Additionally, second-floor classrooms generally exhibit slightly higher indoor air velocities than first-floor classrooms.

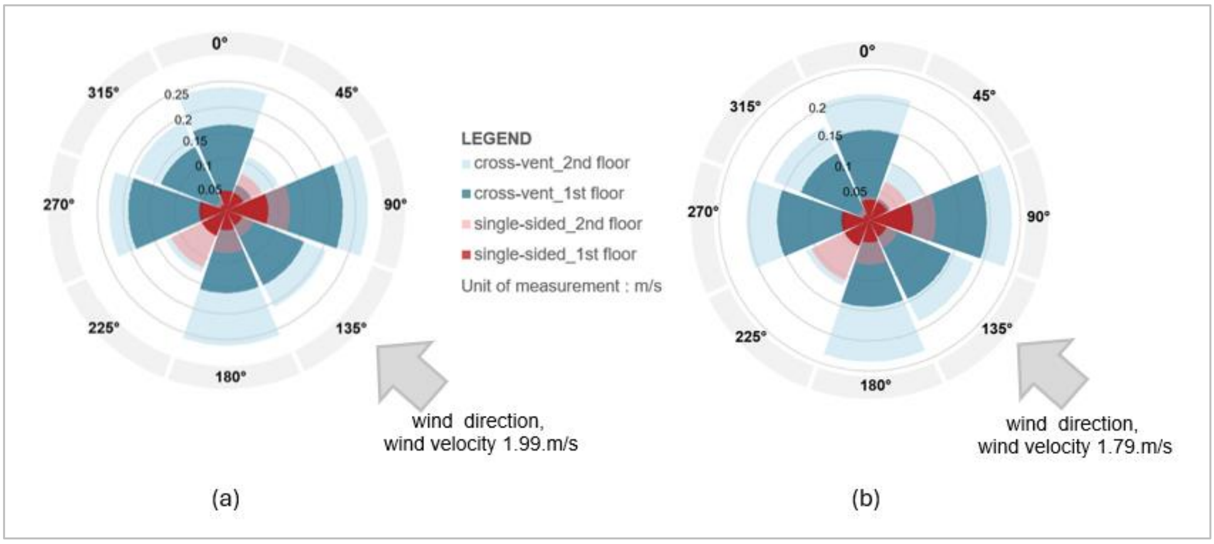


Figure 3.7 (a) Average indoor air velocity in Surabaya classrooms by window orientation, comparation of different mode of natural ventilation; outdoor wind speed 1.99 m/s; wind direction 135°. (b) Average indoor air velocity in Ruteng classroom by window orientation, comparation of different type of ventilation; outdoor wind speed 1.79 m/s; wind direction 135°

In lowland coastal Surabaya, under a wind speed of 1.99 m/s from the southeast (135°), single-sided ventilation resulted in indoor air velocities ranging from 0.01-0.12 m/s, whereas cross-ventilation yielded indoor air velocities between 0.05 and 0.27 m/s. Similarly, in highland Ruteng under an outdoor wind speed of 1.79 m/s from the same direction, single-sided ventilation produced indoor air velocities ranging from 0.01-0.11 m/s, while cross-ventilation resulted in velocities from 0.04-0.24 m/s.

The higher average indoor air velocities observed in cross-ventilated classrooms compared to the single-sided counterparts might be attributed to the increased pressure gradient between windward and leeward openings, typical of this natural ventilation type with multiple openings on opposite sides of the wall. To better illustrate this trend, Figure 3.8 shows a comparison of simulated indoor air velocities in single-sided (Fig 3.8(a)) and cross-ventilated (Fig 3.9(b)) classrooms, both with windows oriented in the same direction.

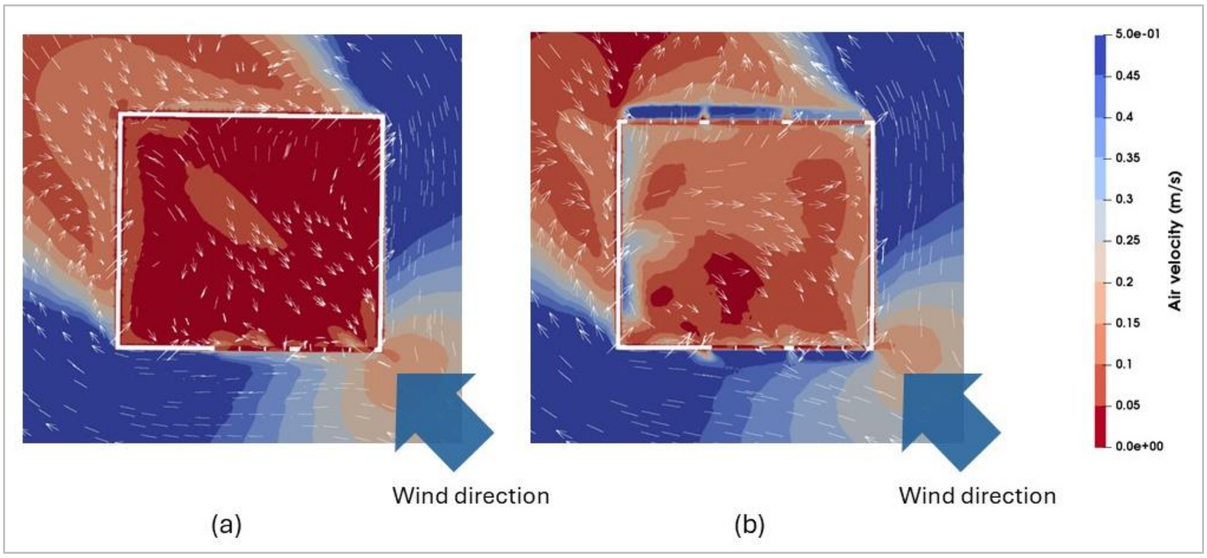


Figure 3.8 Comparison of indoor air velocity (a) in single-sided ventilated classrooms with windows oriented 180° south, and (b) in cross-ventilated classrooms with windows oriented 180° south, resulted from CFD simulation conducted under an outdoor wind direction of 135° southeast; wind velocity 1.79 m/s

Indoor air velocities were slightly higher in second-floor classrooms compared to those on the first floor. Therefore, moving classrooms from the first to the second floor without changing ventilation type or window orientation could modestly increase indoor air velocity by 0.07 m/s for single-sided ventilation in both lowland coastal Surabaya and highland Ruteng. For cross-ventilated classrooms, this relocation could potentially result in a slightly more substantial increase of 0.1 m/s in Surabaya and 0.09 m/s in Ruteng.

Indoor air velocity in second-floor classrooms is slightly higher than in first-floor classrooms due to variations in wind speed with height and the influence of ground friction. The second-floor windows, positioned approximately 4.7 m above ground level, are less affected by ground friction compared to the first-floor windows at 1.2 m. As a result, the wind entering the second-floor windows undergoes less downscaling, leading to higher indoor air velocities. This observation underscores the role of building height and wind dynamics in shaping indoor airflow in naturally ventilated spaces.

The highest indoor air velocities in cross-ventilated classrooms were observed in second-floor classrooms with windows facing east (90°), measuring 0.27 m/s in lowland coastal Surabaya and 0.24 m/s in highland Ruteng. Similarly, for single-sided ventilated classrooms, the highest indoor air velocities were observed in second-floor classrooms facing east (90°), measuring 0.12 m/s in Surabaya and 0.11 m/s in Ruteng.

In both lowland coastal Surabaya and highland Ruteng, under a southeast wind direction of 135°, both single-sided ventilation and cross-ventilation perform best in classrooms with windows oriented towards the east (90°) and south (180°). This indicates that optimal indoor air velocities for both types of natural ventilation are not achieved when windows are oriented directly windward. Instead, the best indoor air velocities occur when the windows are oriented approximately 45° relative to the prevailing wind direction.

To illustrate this trend, Figures 3.9 and 3.10 present the results of CFD simulations conducted in highland Ruteng's single-sided and cross-ventilated classrooms, respectively. Figure 3.8 (a) and (b) compares indoor air velocities in single-sided ventilated classrooms with windows oriented windward versus windows oriented at a 45° angle relative to the wind direction. Figure 3.9 (a) and (b) shows similar comparisons for cross-ventilated classrooms.

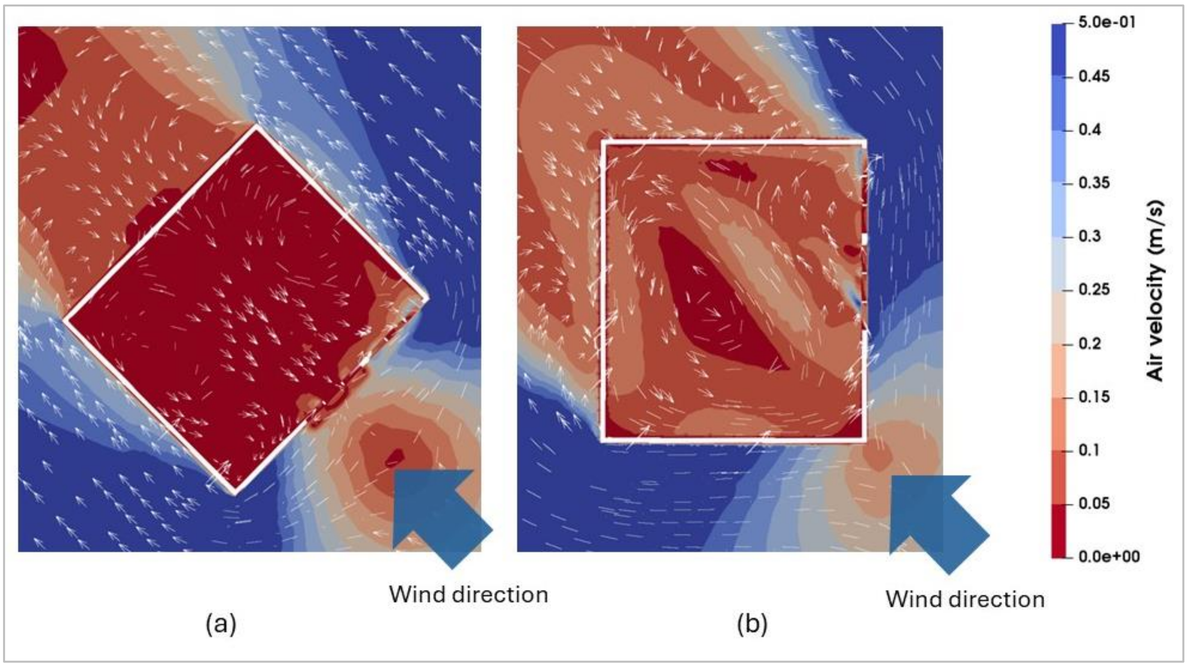


Figure 3.9 Simulated indoor air velocities in the single-sided ventilated classrooms in Ruteng under an outdoor wind direction of 135° and wind speed of 1.79 m/s: (a) when the windows are facing windward; (b) when the windows are inclined at 45° relative to the wind direction.

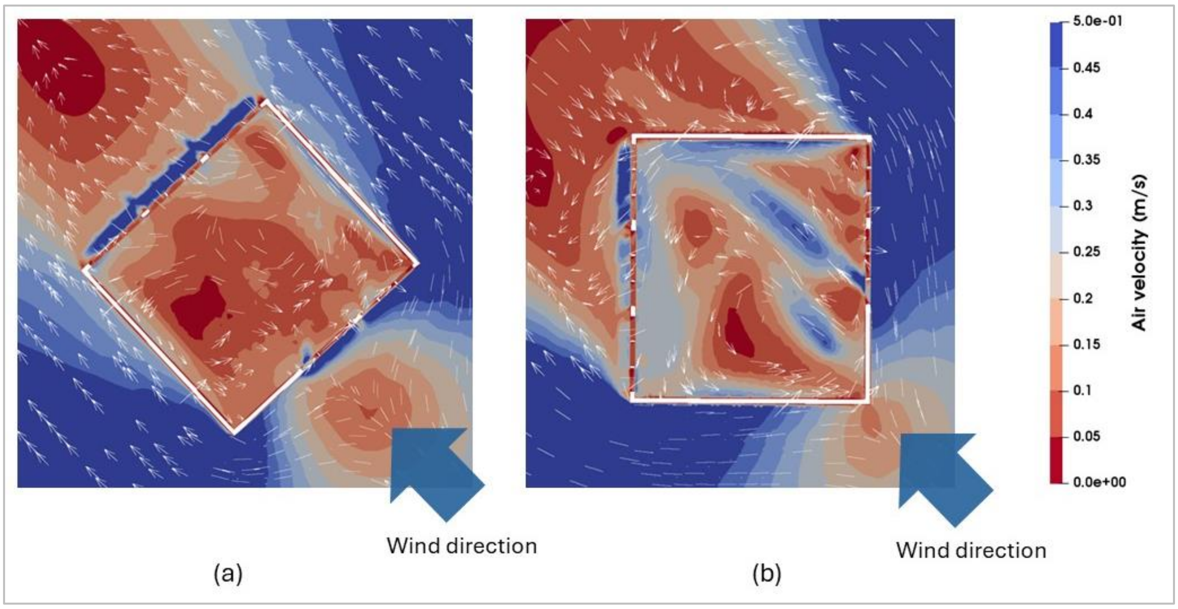


Figure 3.10 Simulated indoor air velocities in the cross-ventilated classrooms in Ruteng under an outdoor wind direction of 135° and wind speed of 1.79 m/s: (a) when the windows are facing windward and leeward; (b) when the windows are inclined at 45° relative to the wind direction.

This trend might be attributed to the design of natural ventilation in Indonesian classrooms, which predominantly utilizes top-hung windows as the primary openings. These windows feature a hinging mechanism at the top frame, allowing them to tilt outward upon opening, with the openings located at the lower and side sections of the window. As a result, the peak indoor air velocities were not achieved when the window faced directly windward; rather, optimal velocities were observed when the window was positioned at a 45° angle to the wind direction.

Regarding the worst performance of natural ventilation, Figure 3.7 (a) and (b) illustrate this trend under a prevailing southeast wind direction of 135° with wind speeds of 1.99 m/s in lowland coastal Surabaya and 1.79 m/s in highland Ruteng. The lowest indoor air velocities for cross-ventilated classrooms were observed on the first floor with windows facing northeast (45°) and southwest (225°), measuring 0.05 m/s in lowland coastal Surabaya and 0.04 m/s in highland Ruteng. The lowest indoor air velocity for single-sided ventilated classrooms occurred on the first floor with windows facing northwest (315°), registering 0.01 m/s in both cities.

This data highlights distinct trends between single-sided ventilation and cross-ventilation regarding their performance in indoor air velocity. Single-sided ventilation performs worst when windows are oriented leeward, while cross-ventilation performs worst when windows are oriented perpendicular to the wind direction. To further illustrate this observation, Figure 3.11 presents the simulated worst-case scenarios of indoor air ventilation in Ruteng's single-sided and cross-ventilated classrooms using CFD simulations.

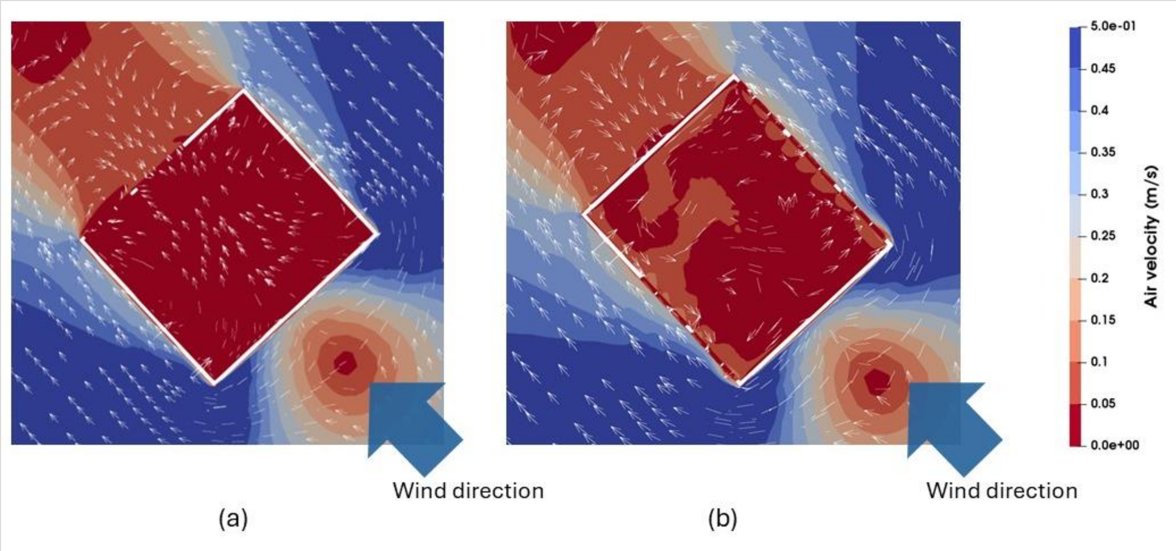


Figure 3.11 Simulated indoor air velocities in Ruteng's classrooms under an outdoor wind direction of 135° and wind speed of 1.79 m/s, illustrating the worst performance of natural ventilation: (a) single-sided ventilated classrooms with windows facing leeward, and (b) cross-ventilated classrooms with windows oriented perpendicular to the wind direction.

This trend could be explained by the characteristics of single-sided and cross ventilation systems. Single-sided ventilation classrooms typically have openings on only one side of the wall. Consequently, with the generally weak outdoor winds in Indonesia, having the opening facing the leeward side might significantly limit indoor air velocity. In contrast, for cross ventilation, when the inlet and outlet are oriented perpendicular to the wind direction, the pressure gradient between them may be reduced, potentially hindering effective air movement inside the room.

Since cross-ventilation demonstrates better performance compared to single-sided ventilation, changing the mode of natural ventilation from single-sided to cross-ventilation might lead to a potential increase in indoor air velocities. For the first-floor classrooms in both Surabaya and Ruteng, with the wind blowing from 135° at speeds of 1.99 m/s in Surabaya and 1.79 m/s in Ruteng. Transitioning from single-sided to cross-ventilation could potentially increase indoor air velocity by 0.14 m/s in Surabaya and 0.12 m/s in Ruteng. For second-floor classrooms, this change could potentially increase indoor air velocity by 0.18 m/s in lowland coastal Surabaya and 0.17 m/s in highland Ruteng.

Under the prevailing southeast wind direction of 135°, the highest potential increase in indoor air velocity resulting from switching natural ventilation modes from single-sided to cross-ventilation was observed in classrooms with windows oriented to the northwest (315°). In single-sided ventilated classrooms with leeward-facing openings, this orientation led to the lowest indoor air velocities. In contrast, cross-ventilated classrooms with openings on both leeward and windward sides established a pressure gradient across both inlets and outlets, thereby achieving higher indoor air velocities. Figure 3.12 provides a visual depiction of indoor air velocities in both single-sided and cross-ventilated classrooms in highland Ruteng under the southeast wind direction of 135°, with windows oriented towards the northwest (315°), further illustrating this trend.

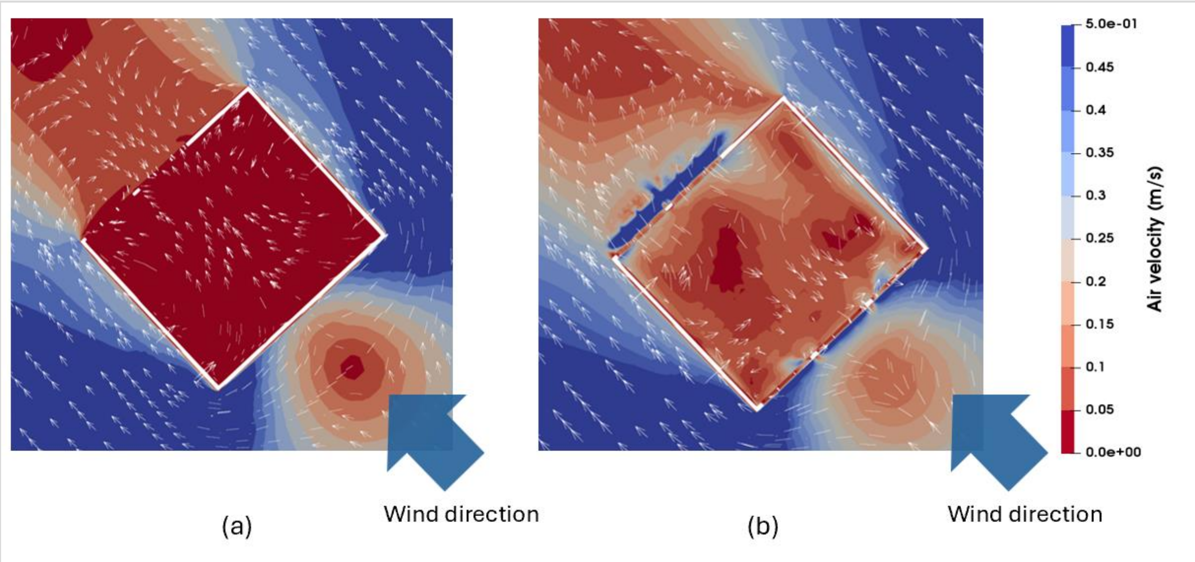


Figure 3.12 Simulated indoor air velocities in Ruteng's classrooms under an outdoor wind direction of 135° and wind speed of 1.79 m/s, highlighting the highest potential increase in indoor air velocity when switching from single-sided to cross-ventilation: (a) indoor air velocity in single-sided ventilated classrooms with openings facing leeward; (b) indoor air velocity in cross-ventilated classrooms with windows oriented windward and leeward.

In contrast, the smallest increase in indoor air velocity resulting from the shift from single-sided to cross-ventilation occurred in classrooms with windows oriented to the northeast (45°) and southwest (225°), perpendicular to the wind direction. In this orientation, both ventilation types showed nearly identical indoor air velocities, with cross-ventilated classrooms demonstrating their worst performance. This trend persisted across both first and second-floor classrooms.

Figure 3.13 illustrates the indoor air velocities in both single-sided and cross-ventilated classrooms in highland Ruteng when the windows were oriented perpendicular to the wind direction, visually depicting this observed pattern.

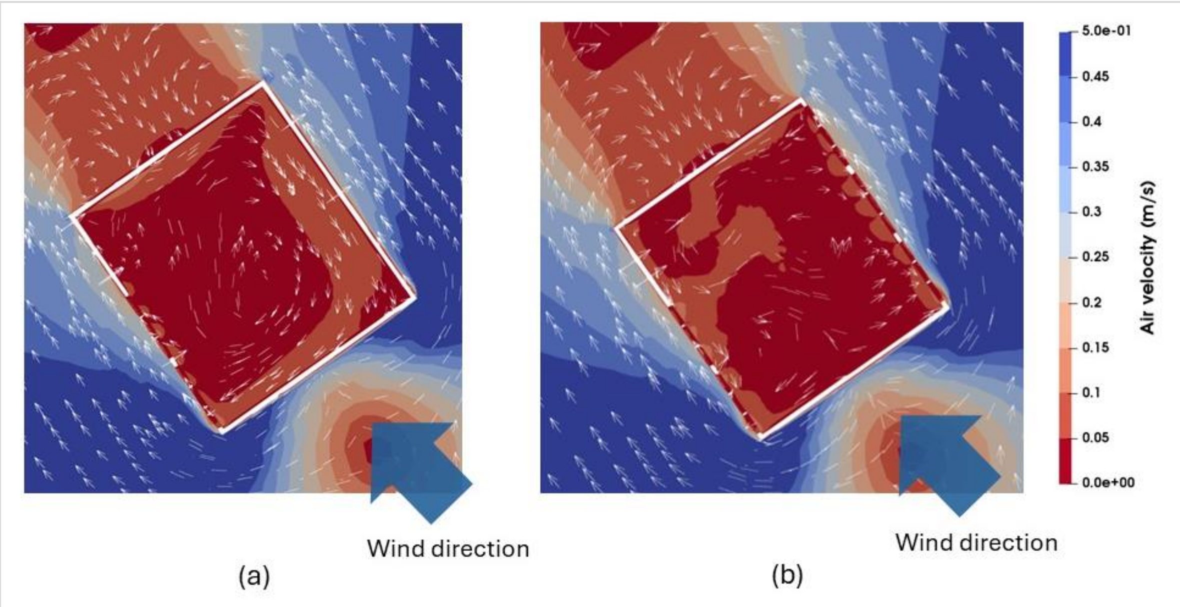


Figure 3.13 Simulated indoor air velocities in Ruteng's classrooms under an outdoor wind direction of 135° and wind speed of 1.79 m/s, highlighting the suboptimal increase in indoor air velocity when switching from single-sided to cross-ventilation, observed when the windows are oriented perpendicular to the wind direction: (a) indoor air velocity in single-sided ventilated classrooms, (b) indoor air velocity in cross-ventilated classrooms.

3.2.1.2 CFD simulation of indoor air velocities in classrooms: comparing lowland coastal Surabaya and highland Ruteng with an easterly wind (90°)

Figure 3.14 depicts the outcomes of Computational Fluid Dynamics (CFD) simulations for outdoor wind conditions from the east at 90°, with wind speeds of 2.97 m/s observed in lowland coastal Surabaya (Figure 3.14 (a)) and 1.42 m/s in highland Ruteng (Figure 3.14 (b)). Cross-ventilated classrooms are represented by varying shades of blue: dark blue denotes first-floor classrooms, while light blue signifies second-floor classrooms. Single-sided ventilation classrooms are indicated by red and pink colours for first- and second-floor classrooms, respectively. Each directional segment on the wind rose corresponds to a specific window orientation. The findings consistently show that cross-ventilated classrooms achieve notably higher indoor air velocities compared to single-sided ventilation classrooms across both cities.

Second-floor classrooms generally exhibit marginally higher velocities than those on the first floor.

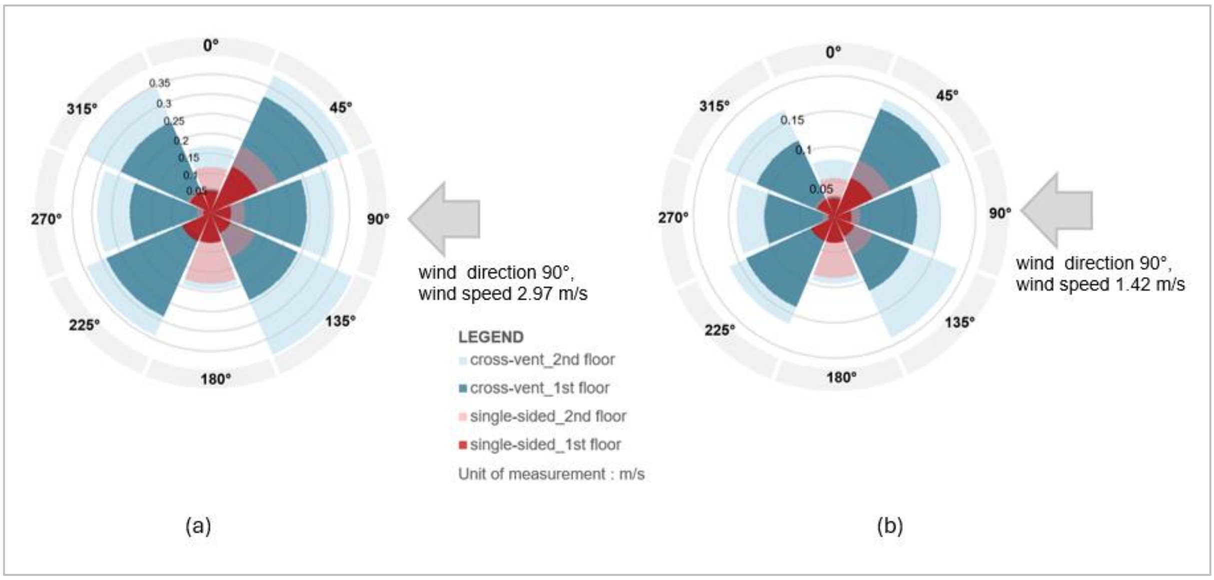


Figure 3.14 (a) Average indoor air velocity in Surabaya classrooms by window orientation, comparation of different mode of natural ventilation; outdoor wind speed 1.99 m/s; wind direction 135°. (b) Average indoor air velocity in Ruteng classrooms by window orientation, comparation of different type of ventilation; outdoor wind speed 1.79 m/s; wind direction 135°

Under prevailing 90° eastern winds with speeds of 2.97 m/s in coastal Surabaya and 1.42 m/s in highland Ruteng, single-sided ventilation resulted in indoor air velocities ranging from 0.02-0.18 m/s in lowland coastal Surabaya and 0.01 to 0.14 m/s in highland Ruteng. In contrast, cross-ventilation yielded higher indoor air velocities ranging from 0.06 to 0.39 m/s in coastal Surabaya and 0.04 to 0.19 m/s in highland Ruteng.

The observed higher average indoor air velocities in cross-ventilated classrooms might be attributed to the increased pressure gradient created between the inlet and outlet located on opposite sides of the wall. Conversely, single-sided ventilation, which typically features openings on only one side of the wall, tends to limit the pressure gradient within the opening. Figure 3.15 illustrates this trend by comparing indoor air velocities in single-sided and cross-ventilated classrooms oriented southwest (225°), as determined by CFD simulations conducted with Surabaya's outdoor wind direction of 90° and wind speed of 2.97 m/s.

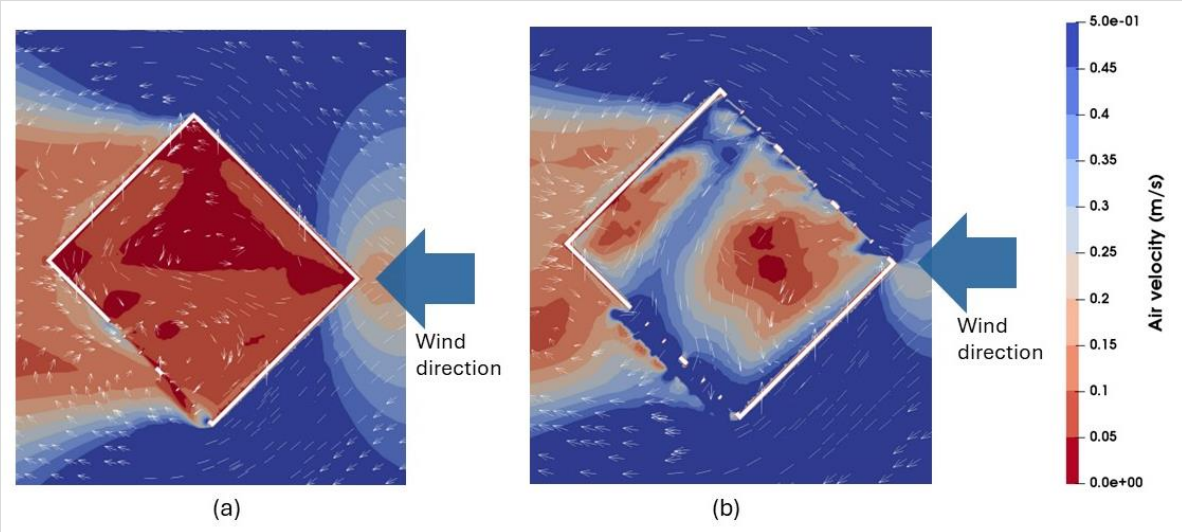


Figure 3.15 Comparison of indoor air velocity (a) in single-sided ventilated classrooms with windows oriented to 225°, and (b) in cross-ventilated classrooms with windows oriented to 225°, resulting from CFD simulation conducted with an outdoor wind direction of 90° and wind speed of 2.97 m/s in Surabaya

Figure 3.14 illustrates that under prevailing 90° eastern winds with speeds of 2.97 m/s in lowland coastal Surabaya and 1.42 m/s in highland Ruteng, the most optimal indoor air velocities were observed in second-floor classrooms with windows oriented northeast (45°) and southeast (135°). Cross-ventilated classrooms achieved the highest indoor air velocities at 0.36 m/s in coastal Surabaya and 0.19 m/s in highland Ruteng, while single-sided ventilated classrooms reached peak velocities of 0.18 m/s in Surabaya and 0.17 m/s in highland Ruteng.

These data suggest that both single-sided and cross-ventilated classrooms might achieve their best performance in indoor air velocities when windows are oriented at a 45° angle relative to the prevailing wind direction. This finding suggests that classrooms with top-hung windows might achieve optimal indoor air velocities not necessarily when the windows are oriented directly windward, but rather when they are positioned at approximately a 45° angle relative to the wind direction. This trend appears consistent with observations from the first prevailing wind direction discussed in the previous subsection.

The top-hung windows, characterized by a hinging mechanism at the top frame that tilts outward upon opening, typically feature openings located at the lower and side sections of the window. Consequently, it appears that the highest indoor air velocities may not consistently be attained when the window faces directly windward; instead, they were observed when the window was positioned at approximately a 45° angle to the wind direction. Figures 3.16 and 3.17 further illustrate this potential trend by comparing simulated indoor air velocities in classrooms with windows oriented windward versus windows oriented at a 45° angle relative to the wind direction, for both single-sided ventilation and cross-ventilation scenarios.

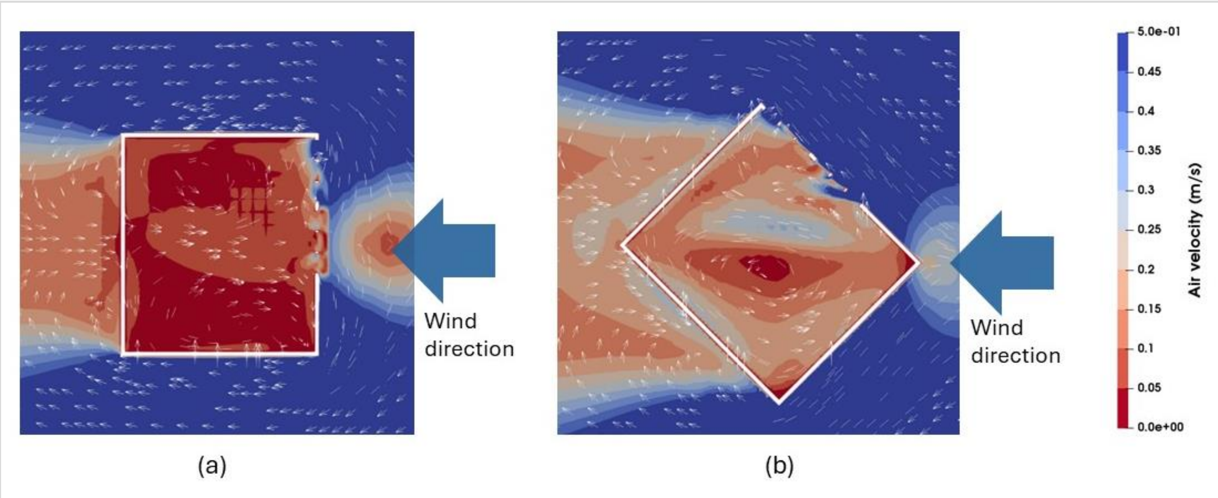


Figure 3.16 Simulated indoor air velocities in single-sided ventilated classrooms in Surabaya under an outdoor wind direction of 90° and wind speed of 2.97 m/s: (a) when the windows are facing windward; (b) when the windows are inclined at 45° relative to the wind direction

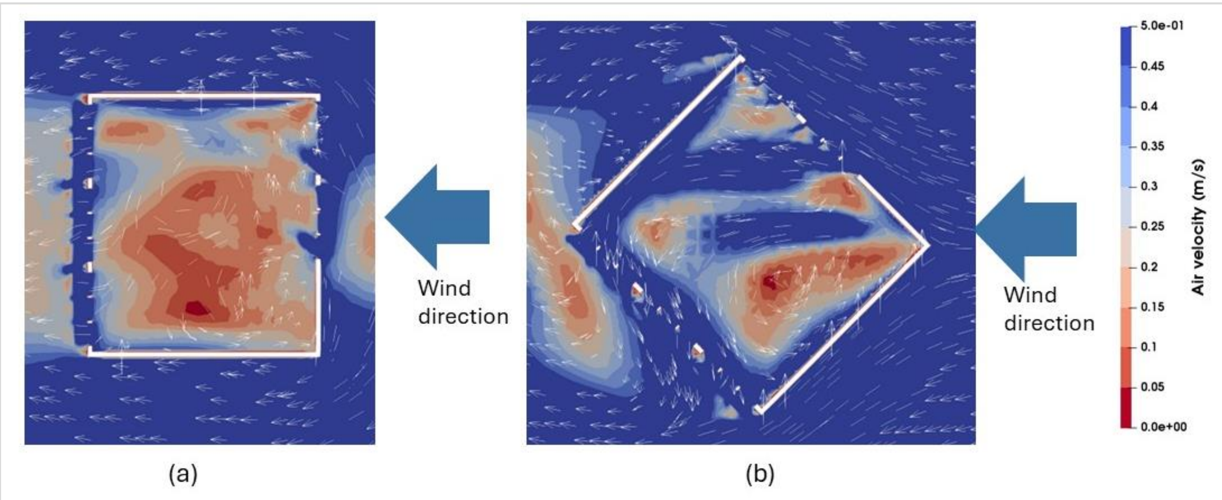


Figure 3.17 Simulated indoor air velocities in in cross-ventilated classrooms in Surabaya under an outdoor wind direction of 90° and wind speed of 2.97 m/s: (a) when the windows are facing windward and leeward; (b) when the windows are inclined at 45° relative to the wind direction

Figure 3.14 shows that under an eastward wind direction (90°) with wind speeds of 2.97 m/s in coastal Surabaya and 1.42 m/s in highland Ruteng, single-sided ventilated classrooms exhibited their worst natural ventilation performance when windows were oriented leeward (west-facing windows at 270°), resulting in indoor air velocities of 0.01 m/s in both locations. In contrast, cross-ventilated classrooms showed their lowest indoor air velocities when windows were oriented perpendicular to the wind direction (north-facing windows at 0° and south-facing windows at 180°), measuring 0.18 m/s and 0.09 m/s for Surabaya and Ruteng, respectively.

Under weak wind conditions typical in Indonesia, it appears that single-sided ventilation, characterized by openings on only one side of the wall, may result in limited indoor air velocity when the openings are oriented leeward. In contrast, cross ventilation, where the inlet and outlet are oriented perpendicular to the wind direction, seemed to show a restricted pressure gradient at the openings, potentially hindering effective air movement inside the room. This observation aligns with findings from simulated indoor air movement under an outdoor wind direction of 135° discussed in the previous subsection. To visually illustrate this potential trend, Figure 3.18 depicts simulated indoor air velocities in classrooms in coastal Surabaya, highlighting what could be perceived as the worst performance of natural ventilation under both single-sided and cross-ventilation scenarios.

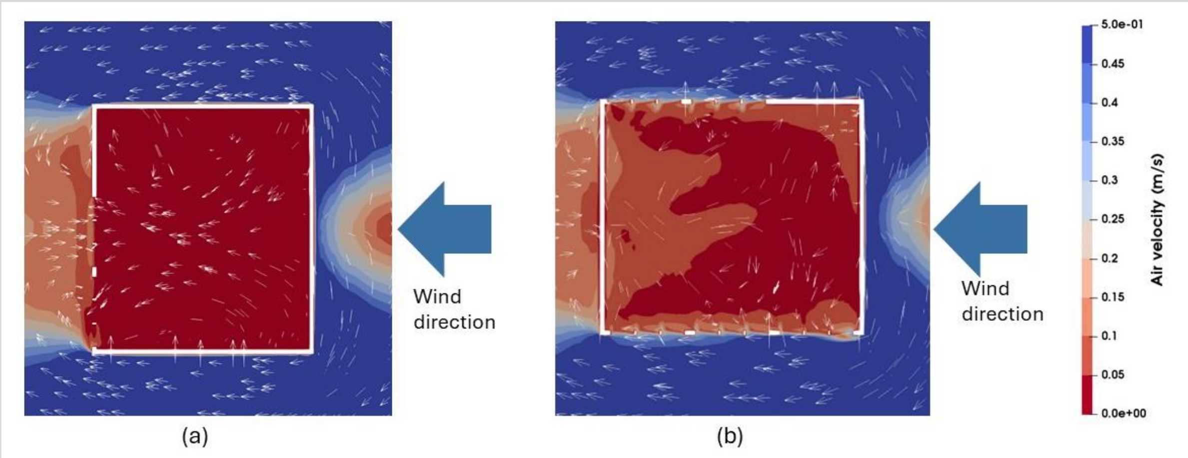


Figure 3.18 Simulated indoor air velocities in Surabaya's classrooms under an outdoor wind direction of 90° and wind speed of 2.97 m/s, illustrating the suboptimal performance of natural ventilation: (a) single-sided ventilated classrooms with windows are facing leeward, and (b) cross-ventilated classrooms with windows oriented perpendicular to the wind direction.

In the case of prevailing outdoor winds from the east (90°), it appears that the most notable improvement in indoor air velocity resulting from transitioning from single-sided to cross-ventilation was observed in classrooms with west-facing windows at 270°. Here, single-sided ventilation resulted in lower indoor velocities due to windows oriented leeward. In contrast, cross-ventilated classrooms seemed to benefit from windows facing both windward and leeward, potentially leading to significantly higher indoor velocities attributed to the increased pressure gradient between the inlet and outlet. This trend is illustrated in Figure 3.19, which depicts simulated indoor air velocities in coastal Surabaya's classrooms, suggesting a substantial increase in indoor air velocity observed when switching from single-sided to cross-ventilation, particularly when the windows were oriented leeward.

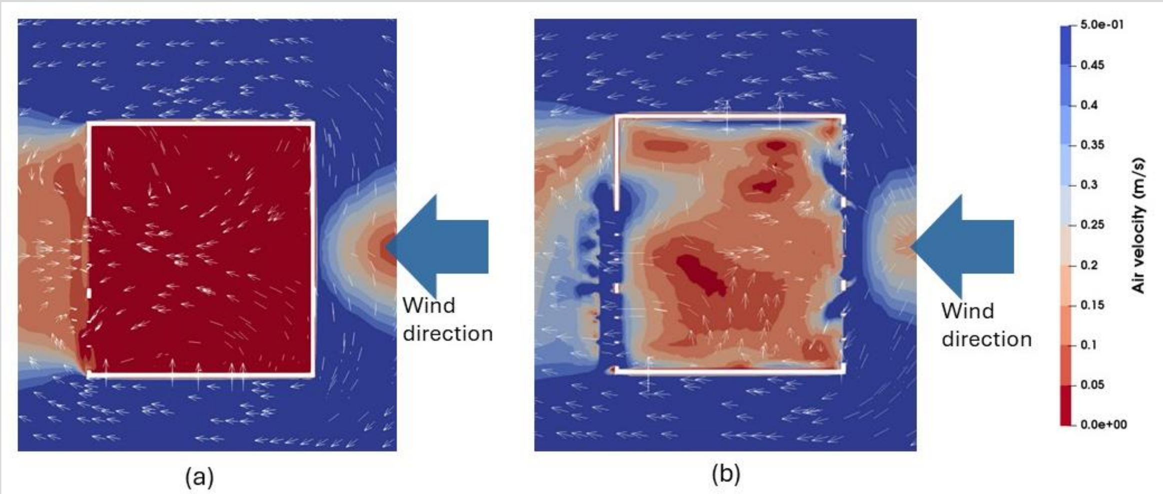


Figure 3.19 Simulated indoor air velocities in Surabaya's classrooms under an outdoor wind direction of 90° and wind speed of 2.97 m/s, highlighting the significant increase in indoor air velocity when switching from single-sided to cross-ventilation: (a) in single-sided ventilated classrooms with openings facing leeward; (b) in cross-ventilated classrooms with windows oriented windward and leeward.

Conversely, it appears that the smallest increase in indoor air velocity resulting from transitioning from single-sided ventilation to cross-ventilation may have occurred in classrooms with windows oriented perpendicular to the wind direction, specifically north at 0° and south at 180°. In these orientations, cross-ventilated classrooms seemed to exhibit lower indoor air velocities attributed to potentially limited pressure gradients in the inlet and outlet. In contrast, single-sided ventilated classrooms achieved indoor air velocities that were similar to their cross-ventilated counterparts. Figure 3.19 illustrates simulated indoor air velocities in lowland coastal Surabaya’s classrooms, suggesting a modest improvement in indoor air velocity observed when switching from single-sided ventilation to cross-ventilation, particularly when the windows were oriented perpendicular to the wind direction.

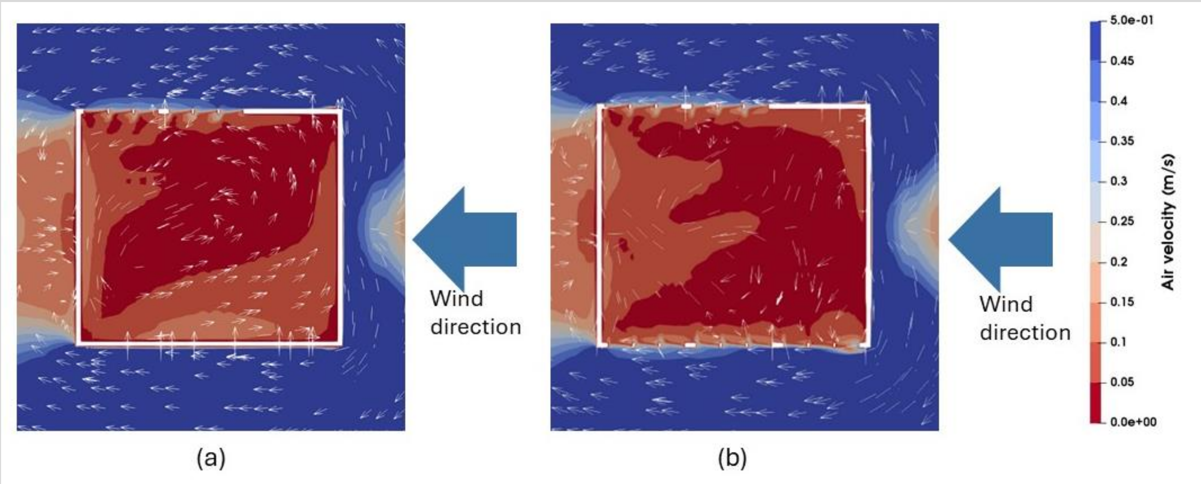


Figure 3.20 Simulated indoor air velocities in Surabaya's classrooms under an outdoor wind direction of 90° and wind speed of 2.97 m/s, highlighting the suboptimal increase in indoor air velocity when switching from single-sided to cross-ventilation, observed when the windows are oriented perpendicular to the wind direction: (a) indoor air velocity in single-sided ventilated classrooms; (b) indoor air velocity in cross-ventilated classrooms.

3.2.2 Simulated thermal performance of Indonesian classrooms

This sub-section details the outcomes derived from thermal performance simulations conducted on classrooms located in lowland coastal Surabaya and highland Ruteng, Indonesia. The parameters utilized in the thermal simulation research matrix were outlined in Table 2.10 of the methodology chapter. These parameters encompass two exemplary climate datasets corresponding to lowland coastal Surabaya and highland of Ruteng, respectively, two modes of natural ventilation (single-sided and double-sided cross ventilation), two floor levels (first and second-floor classrooms), eight building orientations (north 0°, northeast 45°, east 90°, southeast 135°, south 180°, southwest 225°, west 270°, and northwest 315°), and five combinations of wall and roof materials. Therefore, the thermal simulation research design matrix results in a total of 348 distinct scenarios.

It is important to note that the indoor air velocities included in the thermal simulation were the result of the CFD simulation of the first prevailing wind direction coming from 135° (southeast), with an outdoor wind speed of 2.99 m/s for Surabaya and 1.79 m/s for Ruteng.

This section begins with an overview of the thermal performance of Indonesian classrooms in lowland coastal Surabaya and highland Ruteng. Subsequently, a detailed analysis of the parameters defined in the simulation matrix and their influence on the thermal performance of these classrooms is performed.

3.2.2.1 Overall thermal performance of lowland coastal Surabaya and highland Ruteng's classrooms

Hourly data for indoor air temperature, operative temperature, mean radiant temperature, and relative humidity during school hours were acquired through the simulation process for each unique combination of parameters in the typical Indonesian classroom. This process utilized the Typical Meteorological Year of 2007-2021 weather data of Surabaya Gedangan and Ruteng, two selected Indonesian cities (Climate. OneBuilding, 2023). To comprehend the overall thermal performance of classrooms in Surabaya and Ruteng during school hours (from 7:00 am to 2:00 pm), average monthly operative temperature and average monthly absolute humidity are presented in Figures 3.21 and 3.22. In this study, absolute humidity was presented as variable to represent thermal performance over relative humidity. Absolute humidity directly represents the actual amount of water vapour in the air, which directly impacts thermal comfort. In contrast, relative humidity fluctuates with temperature even when moisture content remains constant.

The choice of operative temperature over air temperature alone enables a more comprehensive assessment of the thermal environment experienced by occupants. Operative temperature accounts for both air temperature and radiant temperature effects, offering a better representation of the actual thermal conditions within the classrooms.

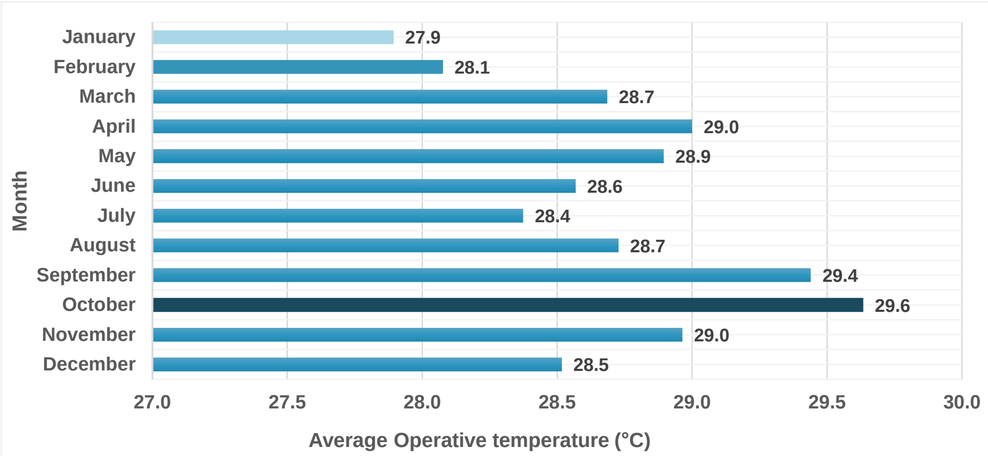


Figure 3.21 Average monthly operative temperature of Surabaya's classrooms during school hours

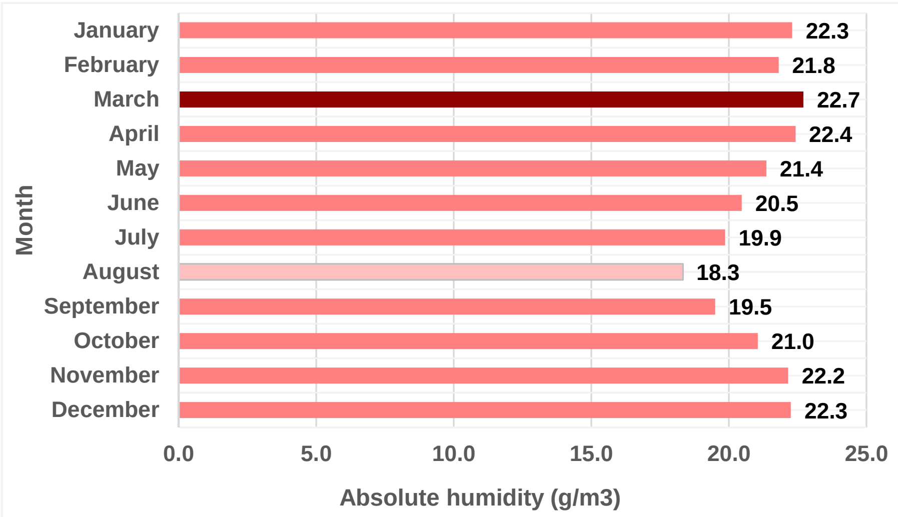


Figure 3.22 Average monthly absolute humidity of Surabaya's classroom

Figure 3.21 illustrates the occupied hour operative temperature (°C) within Surabaya's classrooms broken down by month of the typical meteorological year of 2007-2021. The simulation results indicate that the average monthly operative temperature ranges between 27.9°C in January and 29.6°C in October. Regarding the lowest and highest operative temperature during school hours, the simulation found that first-floor classrooms in lowland coastal Surabaya experienced the lowest operative temperature of 22.3°C during occupied hours, while second-floor classrooms registered the highest operative temperature at 35.6°C.

In Figure 3.22, the monthly average absolute humidity of Surabaya's classrooms during school hours over the same timeframe is depicted. August records the lowest relative humidity at 18.3

g/m^3, while March attains the highest average relative humidity at 22.7 gr/m^3. Surabaya experienced its lowest absolute humidity of 14.9 g/m^3 during occupied hours, while second-floor classrooms registered the highest operative temperature at 25.3 g/m^3.

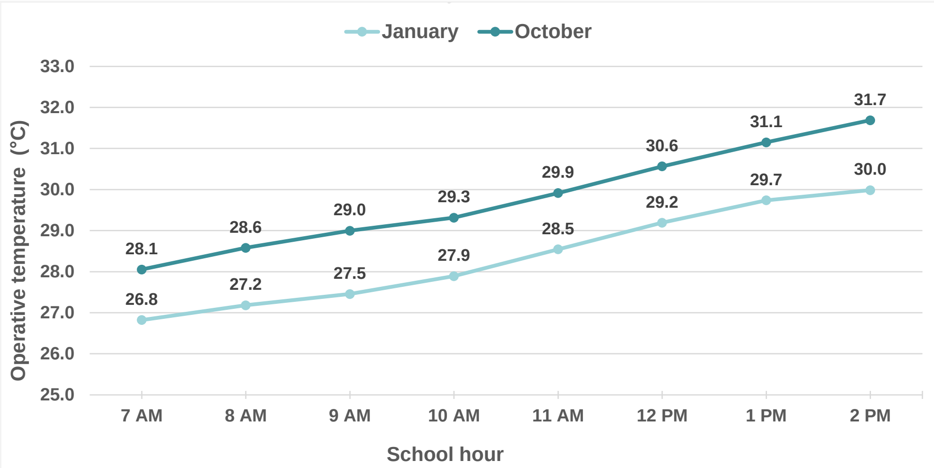


Figure 3.23 Average hourly operative temperature of Surabaya's classrooms in January and October

Figure 3.23 presents the average hourly operative temperature (°C) of classrooms in lowland coastal Surabaya during school hours in January and October, representing the months that display the lowest and highest average operative temperature over the year. It can be observed that during school hours, there are fluctuations of ± 1.5°C in operative temperature in both January and October. In January, the average operative temperature starts at 26.6°C at 7:00 am, the beginning of the school day, and gradually increases, reaching 30°C by the end of school hours at 2:00 pm. In October, the average operative temperature is 28.1°C at the commencement of the school day at 7:00 am, indicating a 1.3°C increase compared to the operative temperature in January at the same hour. The temperature then rises gradually, reaching 30.6°C at noon and ultimately reaching 31.7°C by the conclusion of the school day at 2:00 pm.

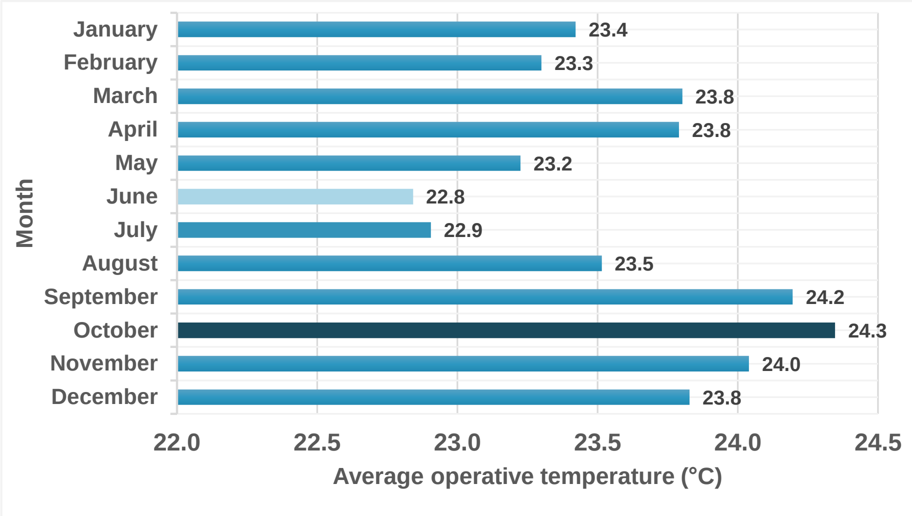


Figure 3.24 Average operative temperature of Ruteng's classrooms

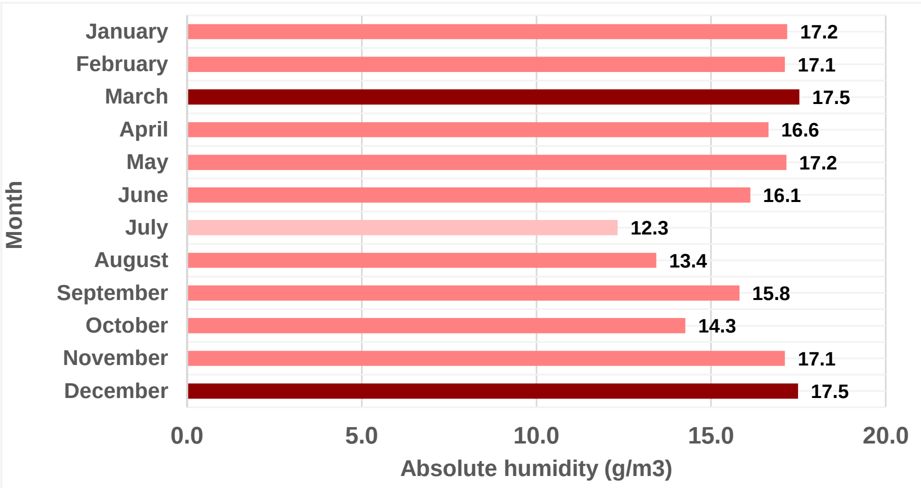


Figure 3.25 Average absolute humidity of Ruteng's classrooms

Figure 3.24 presents average operative temperature (°C) within highland Ruteng's classrooms throughout school hours, broken down by month. The thermal simulation results reveal a modest range in average monthly occupied hours operative temperature between 22.8°C in June and 24.3°C in October.

Examining the minimum and maximum operative temperature during school hours, the simulations indicate that the lowest operative temperature in highland Ruteng's classrooms was 18.9°C, observed in a first-floor classroom, whereas the highest operative temperature was 28.9°C in a second-floor classroom.

Expanding on this, Figure 3.25 illustrates the monthly average absolute humidity within highland Ruteng's classrooms during school hours over the same period. Notably, July exhibited the lowest recorded average absolute humidity at 12.3 g/m^3, while March and December marked the peak at 17.5 gr/m^3. Delving into specific values, the simulations identify the lowest absolute humidity in highland Ruteng’s classrooms during the occupied hours at 6.8 g/m^3, with the highest being 20.3 g/m^3.

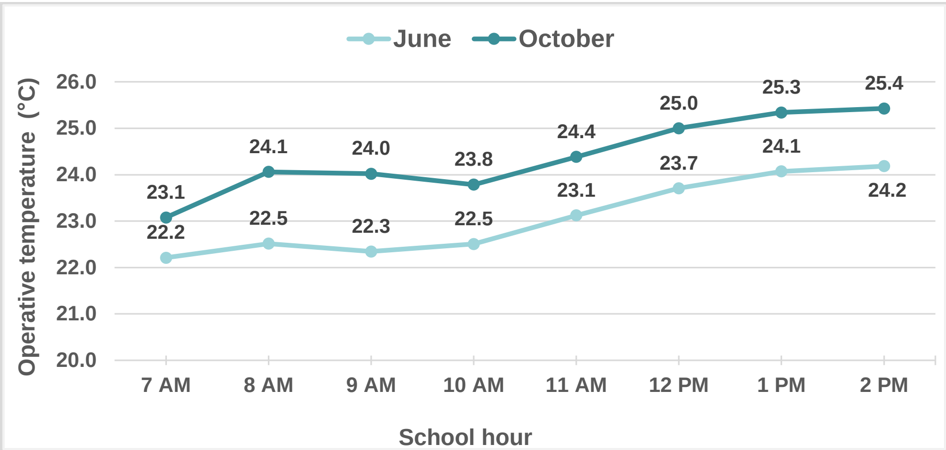


Figure 3.26 Average hourly operative temperature of Ruteng's classrooms in June and October

Figure 3.26 shows the average hourly operative temperature (°C) within Ruteng's classrooms during school hours, specifically focusing on June and October—representing months with the lowest and highest average operative temperatures throughout the year, respectively. A consistent pattern of approximately ± 1°C difference in hourly average operative temperature was observed between June and October.

It was observed that classrooms in lowland coastal Surabaya generally maintained higher temperatures compared to their highland Ruteng counterparts, with a notable temperature difference ranging between 4-5°C. Highland areas typically experience lower temperatures than lowlands primarily due to the lapse rate, where temperature decreases with altitude. In terms of absolute humidity, both lowland coastal Surabaya and highland Ruteng exhibited high levels. However, Surabaya's coastal areas had slightly higher absolute humidity, measuring 4-6 g/m^3 more than in Ruteng. This local climate difference, particularly the significant temperature disparity, highlights the necessity for tailored design strategies in each region to ensure students' thermal comfort.

The simulations indicated that classrooms in both cities experienced their highest average operative temperatures in October, during the wet season. This trend may be attributed to elevated absolute humidity levels during the wet season, influenced by monsoon winds bringing moisture from the Indian Ocean. Higher humidity levels contribute to a warmer perceived environment, as our bodies are less effective at cooling through evaporation when the air is saturated with moisture.

Conversely, the lowest simulated average operative temperature in Surabaya occurred in January, while in Ruteng, it was observed in June during the dry season. This temporal variation may be attributed to the distinct local topography of Ruteng and Surabaya, which further influences their respective local climates

3.2.2.2 The impact of building feature parameters on indoor operative temperature in Indonesian classrooms

The objective of this section is to comprehensively assess the influence of various building feature parameters, including the mode of natural ventilation (single-sided and cross-ventilation), floor level (first and second floor), window orientation, and combinations of wall and roof materials (AAC and brick walls; concrete tile, clay tile, and corrugated aluminium roof) on the operative temperature within the classrooms. Understanding these impacts is crucial, as operative temperature plays a pivotal role in determining thermal comfort.

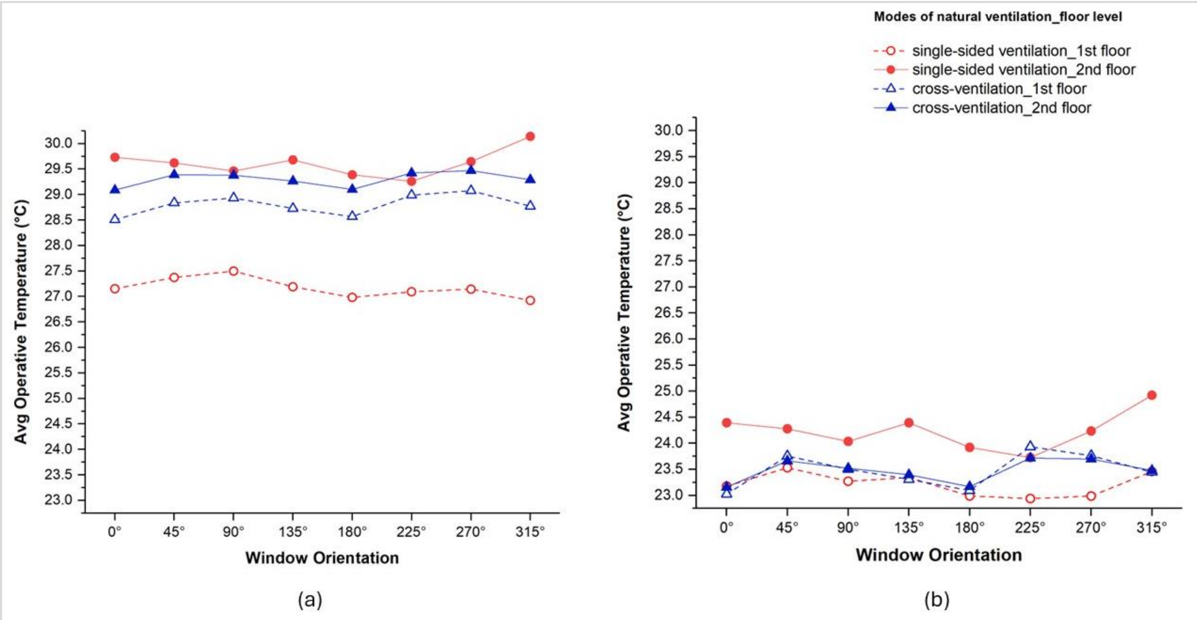


Figure 3.27 (a) Average operative temperature in Surabaya's classrooms; (b) average operative temperature in Ruteng's classrooms

Figure 3.27 compares the average indoor operative temperature of classrooms in Surabaya and Ruteng, considering variations in natural ventilation modes, window orientation, and floor level. The charts reveal both similarities and differences in observed trends.

In both cities, first-floor classrooms with single-sided ventilation consistently exhibited the lowest indoor average operative temperatures, except for those with north-facing windows (0°) in highland Ruteng. Conversely, second-floor classrooms with single-sided ventilation generally showed the highest indoor average operative temperatures, except for those with southwest-facing windows (225°). Cross-ventilated classrooms in both locations displayed indoor average operative temperatures between those of single-sided ventilated classrooms on the first and second floors.

First-floor classrooms, situated at ground level, are observed to primarily receive direct solar radiation through their walls and windows, whereas second-floor classrooms also appear to experience direct solar radiation exposure from the roof. This additional exposure could potentially result in higher indoor operative temperatures on the second floor compared to the first floor.

Higher indoor air velocities from cross-ventilation systems have the potential to improves convective heat dissipation and reduce the Standard Effective Temperature, thereby potentially enhancing thermal comfort. However, in Indonesia's hot and humid tropical climate, incoming wind tends to be warm and humid, influenced by outdoor conditions. Consequently, increased airflow may lead to higher indoor operative temperatures. This phenomenon is observed in first-floor cross-ventilated classrooms in both cities, which generally exhibit higher average indoor operative temperatures compared to classrooms with single-sided ventilation on the first floor.

Conversely, second-floor cross-ventilated classrooms may benefit from improved cooling due to cross-ventilation, allowing hot air to escape and cooler air to enter. Therefore, despite the high solar radiation exposure, these classrooms may demonstrate lower indoor operative temperatures compared to single-sided counterparts on the second floor.

In both Surabaya and Ruteng, it was observed that single-sided ventilated classrooms are more sensitive to floor location differences compared to cross-ventilated classrooms. However, classrooms in lowland coastal Surabaya show greater sensitivity to floor location differences compared to highland Ruteng, as indicated by a wider disparity in indoor average operative temperature between first and second-floor classrooms with the same natural ventilation mode. Specifically, in lowland Surabaya, the difference in indoor average operative temperature between single-sided ventilated classrooms on the first and second floors ranged from 2.2 to 3.2°C, whereas in highland Ruteng, it was narrower at 0.7 to 1.5°C. For cross-ventilated classrooms, the indoor operative temperature difference in Surabaya was 1.9 to 2.4°C, while Ruteng exhibited a smaller variance in indoor average operative temperatures between classrooms on the first and second floors. This observation suggests that relocating single-sided ventilated classrooms from the second floor to the first floor may result in a more significant reduction in indoor average temperature in lowland coastal Surabaya compared to highland Ruteng.

Cross-ventilated classrooms appear to show lower sensitivity to the effects of different floor levels compared to single-sided ventilated classrooms, possibly due to the latter's perceived lower efficiency in heat dissipation, which could result in significant heat accumulation in second-floor classrooms. Conversely, it seems that cross-ventilated classrooms may benefit from enhanced airflow and potentially more effective heat dissipation, potentially leading to a narrower temperature differential between the first and second floors.

The broader indoor average operative temperature gap observed between first-floor and second-floor classrooms with the same natural ventilation mode in lowland coastal Surabaya compared to highland Ruteng might be attributed to distinct topographical characteristics that could influence local climates in both cities. The lowland coastal area appears to experience higher ambient temperatures, lower elevation, and is influenced by warm sea breezes, which could contribute to higher humidity levels. In contrast, highland areas may benefit from cooler and more stable temperatures, lower humidity, and fewer urban heat effects, potentially resulting in a smaller temperature disparity between floors.

Analysing the impact of different natural ventilation modes on indoor average operative temperature reveals similarities between lowland coastal Surabaya and highland Ruteng. In first-floor classrooms in both cities, cross-ventilated classrooms generally showed higher indoor average operative temperatures compared to single-sided ventilated classrooms, except for those oriented north (0°) in Ruteng. Conversely, in second-floor classrooms, cross-ventilated classrooms tended to exhibit lower indoor average operative temperatures compared to single-sided ventilated classrooms, except for those with windows oriented southwest (225°) in both cities.

Second-floor cross-ventilated classrooms generally appear to have lower indoor operative temperatures compared to their single-sided counterparts due to what seems to be improved air movement, which is likely beneficial in regulating heat. However, for cross-ventilated classrooms oriented southwest (225°), where windows are oriented perpendicularly to the wind direction, this orientation appears to lead to the lowest indoor air velocities for cross-ventilated classrooms. Consequently, the lower wind speed and potentially less effective air circulation may result in slightly higher indoor operative temperatures compared to single-sided ventilated classrooms with windows oriented southwest (225°), which might experience slightly higher indoor air velocities.

There were differences in the magnitude of indoor average operative temperature variations between classrooms with different ventilation modes on the same floor level in Surabaya and Ruteng. These differences influence potential changes in indoor average operative temperature during transitions between ventilation modes. In lowland coastal Surabaya, transitioning from single-sided to cross-ventilation for first-floor classrooms could potentially result in an increase in indoor average operative temperature by approximately 1.4 to 1.9°C. Conversely, in highland Ruteng, a slight potential increase of 0.8 to 1°C might occur, particularly in classrooms with windows oriented towards 225° and 270°. For second-floor classrooms, transitioning from single-sided to cross-ventilation in lowland coastal Surabaya might lead to a minor decrease in indoor average operative temperature by 0.2 to 0.8°C, whereas in highland Ruteng, the decrease could be more pronounced, ranging from 0.8 to 1.4°C. These variations between lowland coastal Surabaya and highland Ruteng could be attributed to the diverse topographical characteristics that influence the local climate in each location.

In lowland coastal Surabaya, window orientation has a minimal impact on indoor average operative temperature compared to in highland Ruteng. Conversely, highland Ruteng shows moderate impacts of window orientation, particularly in cross-ventilated classrooms where north-facing (0°) and south-facing (180°) windows display the lowest average operative temperatures, while southeast-facing (45°) and southwest-facing (225°) windows exhibit the highest average operative temperatures, with a temperature gap of up to 1°C. Similarly, single-sided ventilated classrooms in highland Ruteng also demonstrate moderate impacts of window orientation, notably in second-floor classrooms facing southwest (225°) and northwest (315°), which show a temperature difference of 1.2°C.

The impact of window orientation on indoor operative temperature may vary significantly between lowland coastal areas and highland areas of Indonesia due to differences in climate conditions, sun path variations, and local environmental factors in each region. In lowland coastal areas, where ambient temperatures typically remain high, there is a considerable heat load regardless of window orientation. The continuous high heat and humidity appear to overshadow the potential effects of different window orientations on indoor temperatures. Conversely, highland areas generally experience cooler and more variable temperatures, which suggests they may be more sensitive to heat gains and losses influenced by varying window orientations.

Classrooms with north-facing (0°) and south-facing (180°) windows tend to experience lower temperatures due to the overhead path of the sun in tropical regions near the equator, where it predominantly moves from east to west. These orientations generally receive less direct solar radiation throughout the day, typically leading to cooler operative temperatures. Moreover, cross-ventilated classrooms oriented south (180°) exhibit higher indoor air velocities, enhancing convective heat dissipation. In contrast, classrooms oriented northeast (45°) and southwest (225°) for cross-ventilation tend to face perpendicular to the wind direction, resulting in lower indoor air velocities. This can lead to inefficient heat dissipation and potentially higher indoor operative temperatures.

For single-sided ventilation, classrooms with windows oriented southwest (225°) generally exhibited higher indoor air velocities compared to other orientations. This condition enhances convective heat transfer from the skin to the air, thereby making occupants feel cooler. Conversely, classrooms with windows oriented northwest (315°), facing leeward, experienced lower indoor air velocities. This condition lead to ineffectiveness in heat dissipation resulted in higher indoor operative temperatures

3.2.2.3 The impact of wall and roof materials on operative temperature

The thermal simulations in this study considered five distinct combinations of wall and roof materials as parameters. The selected wall materials included bricks and Autoclaved Aerated Concrete (AAC), which are common in the Indonesian public-school portfolio. For roof materials, the simulations included clay tile, concrete tile, and corrugated aluminium. Concrete and clay tiles are widely used across Indonesia, while corrugated aluminium is primarily popular in specific regions such as highland Ruteng, but less so in lowland coastal areas like Surabaya. This section focuses on gaining a deeper understanding of how different wall and roof materials influence the operative temperature of classrooms.

Figure 3.28 compares the simulated average operative temperatures in classrooms of lowland coastal Surabaya and highland Ruteng, considering variations in natural ventilation modes, floor levels, and wall and roof materials. The charts indicate that in both Surabaya and Ruteng, the choice of different materials does not appear to significantly affect average operative temperature. This observation may be attributed to the relatively minor differences in thermal properties among the selected building materials, such as bricks and AAC.

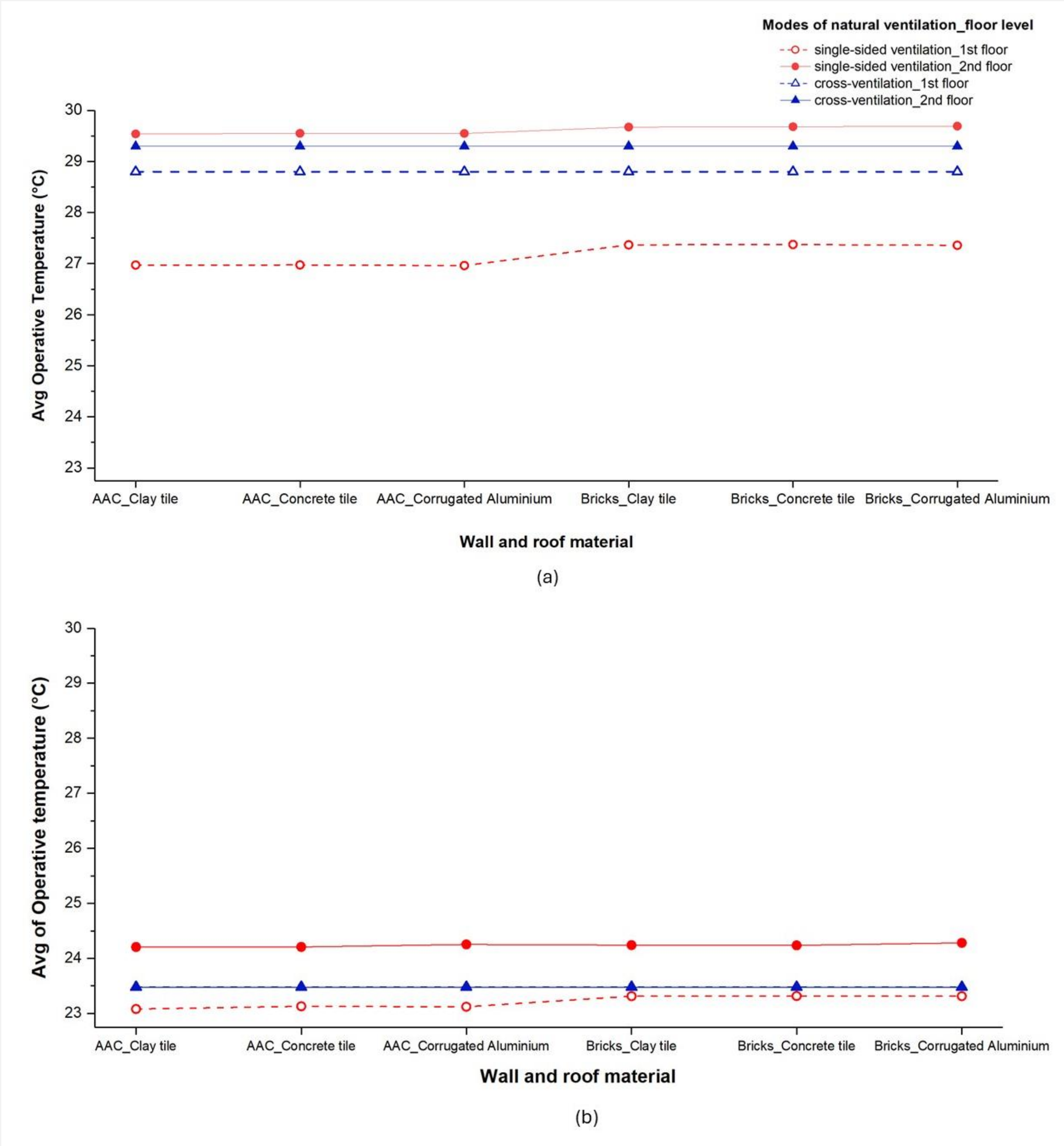


Figure 3.28 Average operative temperature according to different wall and roof material in (a) Surabaya's and (b) Ruteng's classrooms

In both cities, cross-ventilated classrooms appear to be minimally affected by variations in roof and wall materials. Conversely, single-sided ventilation classrooms showed slight sensitivity, with observable differences in operative temperature based on different wall materials (less than a 1°C temperature variation). Even more subtle differences were noted with varying roof materials, where the temperature gap was less than 0.5°C. Cross-ventilated classrooms generally exhibit better air movement, making them more effective in dissipating heat compared to single-sided ventilated classrooms. This effectiveness may explain why single-sided ventilation tends to be more sensitive to the influence of different wall and roof materials.

Regarding the influence of roof materials on classroom indoor operative temperature, this study found no significant difference between classrooms with clay or concrete tile roofs and those with corrugated aluminum roofs. The traditional pitched design of Indonesian school buildings, featuring a 35° angle with two sloping sides, appears to play a crucial role in minimizing heat transfer to the classroom interior. These sloping sides create an attic or space between the ceiling and roof, facilitating natural ventilation as hot air rises and exits through vents. This design effectively cools the attic, thereby potentially slowing the increase in operative temperature within interior spaces, which is believed to be beneficial in Indonesia's warm and humid tropical climate.

Despite the perceived minor impact of different wall and roof materials on average operative temperature, classrooms with AAC walls on the first floor in both cities exhibited slightly lower average operative temperatures compared to classrooms with brick walls. This difference may be attributed to the perceived superior insulation and lower thermal conductivity of AAC compared to conventional brick walls.

Regarding diverse roof materials, classrooms with corrugated aluminum roofs appeared to show higher maximum operative temperatures, whereas those with concrete tile roofs recorded the lowest values. The elevated indoor temperatures associated with corrugated aluminum roofs could potentially be attributed to their higher thermal conductivity, which may facilitate more efficient absorption and conduction of heat. However, it is important to note that the perceived influence of different wall and roof materials on average operative temperature remains subtle.

3.3 Thermal comfort responses of Indonesian students

This chapter explores the thermal comfort responses of Indonesian students within classrooms situated in both cities of case studies. The investigation utilizes data on clothing insulation and classroom thermal performance acquired in the first and second phases of the research, with the overarching goal of providing valuable insights for enhancing the thermal comfort of Indonesian students in educational settings.

3.3.1 Neutral temperature and comfort acceptability range in Indonesia

Before delving into the assessment of thermal comfort responses, a crucial step involves defining the neutral temperature and the range of acceptable comfort temperatures. The neutral temperature represents the point at which an individual feels neither excessively hot nor cold, embodying the ideal or neutral condition for thermal comfort. The range of comfort acceptability pertains to the temperature range where individuals feel neither excessively hot nor cold, rendering it acceptable in terms of thermal comfort. Establishing these neutral temperatures and comfort acceptability ranges is pivotal as they serve as reference points for evaluating how individuals perceive and respond to their thermal environment.

As delineated in section 2.4.2 of the methodology chapter, the neutral temperature for the chosen case study cities in this research (Surabaya and Ruteng) was computed using the Indonesian thermal comfort predictor equation established by Karyono (2015). Following this calculation, the neutral comfort temperature was then converted to Standard Effective Temperature (SET) using the CBE thermal comfort tool developed by Tartarini et al. (2020).

To determine the SET comfort range of adaptability, the range of acceptability for adaptive comfort mentioned in ASHRAE Standard 55 was employed. Specifically, the range for the 80% comfort criterion, with a 3.5°C margin above and below the neutral temperature, was chosen to provide a comprehensive scope of thermal comfort.

Based on the yearly weather data of the typical meteorological year of 2007-2021, lowland coastal Surabaya exhibited an average daily temperature of 28.73°C with an average relative humidity of 75.2%. The calculated neutral temperature for Surabaya was 27.6°C or 28.6°C in SET. The 80% range of comfort acceptability for lowland coastal Surabaya was determined to be 24.1-31.1°C in SET.

In contrast, highland Ruteng displayed average daily temperatures of 22.12°C with an average relative humidity of 85.9%. The calculated neutral temperature in Ruteng was 22.5°C or 23.3°C in SET. The 80% range of comfort acceptability for Ruteng was determined to be 19.4-26.1°C in SET. These defined parameters establish the groundwork for evaluating thermal comfort responses in Indonesian classrooms, providing a standardized framework for comparison and analysis.

3.3.2 Average Standard Effective Temperature (SET) in Indonesian classrooms: impact of clothing adjustment

This section provides a comparative analysis of the average Standard Effective Temperature (SET) in classrooms located in Surabaya and Ruteng. The analysis encompasses various combinations of building-related parameters, including two modes of natural ventilation (single-sided and cross-ventilation), two different floor levels (first and second floor), and eight distinct window orientations ranging from north at 0° to northwest at 315°. The analysis was conducted hourly from 7:00 a.m. to 2:00 p.m. over the course of a year. A total of 768 classroom variations were included in the SET calculations, as detailed in Table 2.13 of the methodology chapter.

As explained in section 2.4.1 of the methodology chapter, the calculation of hourly SET in this study incorporates the highest and lowest clothing insulation values observed in Indonesian Muslim uniform ensembles. The lowest clothing insulation value is 0.66 clo, derived from ensemble C3, representing a loose-fitting shirt with trousers (shirt untucked). In contrast, the highest clothing insulation value is 1.05 clo, representing ensemble A2.2, featuring a medium-fit long-sleeve shirt with a pleated skirt and leggings as innerwear. Importantly, both measurements were obtained in the sitting position, considering that students' activities in classrooms primarily involve sitting. This comprehensive approach ensures that the thermal comfort analysis accounts for the range of clothing insulation values associated with various configurations of Indonesian Muslim clothing ensembles worn by students in classrooms.

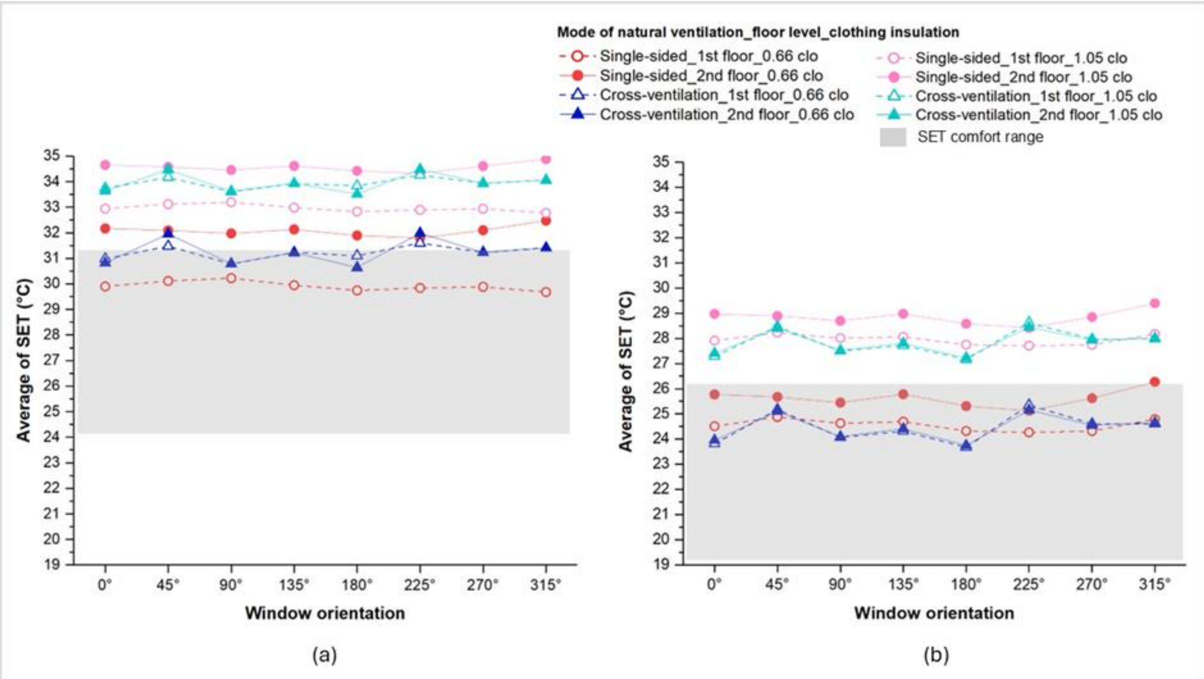


Figure 3.29 (a) Average Standard Effective Temperature (SET) in Surabaya's classrooms; (b) Average Standard Effective Temperature (SET) in Ruteng's classrooms

Figure 3.29 compares the average Standard Effective Temperature (SET) in classrooms between lowland coastal Surabaya and highland Ruteng. The analysis includes parameters such as two modes of natural ventilation, different floor levels, window orientations, and two clothing insulation values (0.66 and 1.05 clo). The data consistently demonstrates that classrooms with lower clothing insulation values exhibit notably lower SET values compared to those with higher insulation values. Specifically, reducing clothing insulation by 0.39 clo results in a decrease in SET by 2.5-3°C in Surabaya and 3.2-3.4°C in Ruteng. This underscores the significant impact of clothing insulation on thermal comfort across varied classroom environments, offering insights for optimizing comfort through standardized configurations.

Moreover, the graphs indicate that decreasing clothing insulation from 1.05 clo to 0.66 clo led to a more pronounced reduction in average SET values compared to changes in natural ventilation mode, relocating classrooms between floors, or adjusting window orientations. A reduction of 0.39 clo in insulation resulted in a decrease in SET values of approximately 3°C, whereas modifications in ventilation type or floor level yielded a maximum reduction of less than 2°C. This consistent trend is observed across classrooms in both the lowland coastal area of Surabaya and in highland Ruteng.

Tropical hot and humid climates, such as those found in Indonesia, are characterized by distinct climate features, including heightened solar heat gain, elevated humidity levels, and generally low air velocities throughout the year. These factors may pose significant challenges in designing naturally ventilated buildings that meet occupants' thermal comfort preferences, especially observed in Indonesian classrooms where mechanical systems like fans are often absent.

In this context, the significance of clothing insulation becomes evident as a crucial behavioural adaptation to potentially achieve thermal comfort. Lower clothing insulation is suggested to promote better air circulation, potentially facilitating more efficient sweat evaporation and optimal heat dissipation from the body. This improvement could enhance overall thermal comfort, particularly in hot and humid tropical regions like Indonesia. Clothing, being in direct contact with the skin, is believed to have a direct impact on the body’s ability to regulate temperature. Lower insulation clothing may support improved moisture management and airflow at the skin level, which is considered essential in hot and humid climates. Changes to building design are thought to influence air movement and temperature indirectly and might not immediately or uniformly improve thermal comfort compared to the direct impact of clothing insulation.

In lowland coastal Surabaya, the 80% range of comfort acceptability for SET was determined to be 24.1-31.1°C, while in highland Ruteng it was 19.4-26.1°C. When applying a clothing insulation value of 0.66 clo, SET values within this range were observed in all types of classrooms, except for second-floor single-sided ventilated classrooms in lowland coastal Surabaya. Conversely, with a higher insulation value of 1.05 clo, SET values exceeded the comfort range for all classrooms in both cities. In lowland coastal Surabaya, second-floor single-sided ventilated classrooms exhibited the highest indoor operative temperatures due to increased solar radiation exposure. Furthermore, the slow indoor air movement resulting from single-sided ventilation proved ineffective in dissipating heat within the classroom.

Examining the impact of different window orientations on the average SET of classrooms in both cities reveals a consistent trend. It appears that different window orientations do not significantly affect the SET of single-sided ventilated classrooms, whereas classrooms with cross ventilation show greater sensitivity to window orientation.

Single-sided ventilation typically relies on openings on one side of the room, potentially resulting in limited airflow. In these classrooms, it is hypothesized that warm air entering from outside may tend to stay longer and adapt to the room temperature. On the other hand, in cross-ventilated classrooms, it is suggested that warm air may circulate easily without fully adapting to the room temperature. This distinction could potentially explain why cross-ventilated classrooms appear to be more sensitive to the effects of different window orientations compared to those relying on single-sided ventilation.

3.3.3 Percentage of acceptable occupied hours in Indonesian classrooms

This research employs the percentage of yearly comfortable occupied hours as a metric to evaluate students' thermal comfort responses in Indonesian classrooms. The yearly percentage of comfortable occupied hours denotes the proportion of time throughout the year during which the classroom maintains acceptable thermal comfort conditions for the students.

Given that school hours in Indonesia extend from 7:00 a.m. to 2:00 p.m., the thermal simulation and SET calculations were conducted hourly within this period over the course of a year. This results in a total of 2,920 possible occupied hours annually. Consequently, a higher percentage of comfortable hours indicates that classrooms can sustain acceptable and comfortable thermal conditions for the students for a more extensive portion of the year. A 100% yearly percentage of comfortable hours signifies that the classroom's thermal conditions are deemed thermally acceptable throughout the entire school year, encompassing 2920 hours.

The determination of the yearly percentage of acceptable occupied hours involved the calculation of hourly Standard Effective Temperature (SET) based on simulated hourly thermal performance data from classrooms in lowland coastal Surabaya and highland Ruteng. This calculation specifically considered data falling within the range of acceptable comfort temperature in Standard Effective Temperature (SET), considering the 80% range of comfort acceptability for both lowland coastal Surabaya and highland Ruteng.

For an in-depth methodology on assessing student thermal comfort responses, please refer to subchapter 3.4 in the methodology chapter. The parameters involved in the SET calculation are detailed in Table 2.13 of subchapter 2.4.1 in the methodology chapter of this thesis.

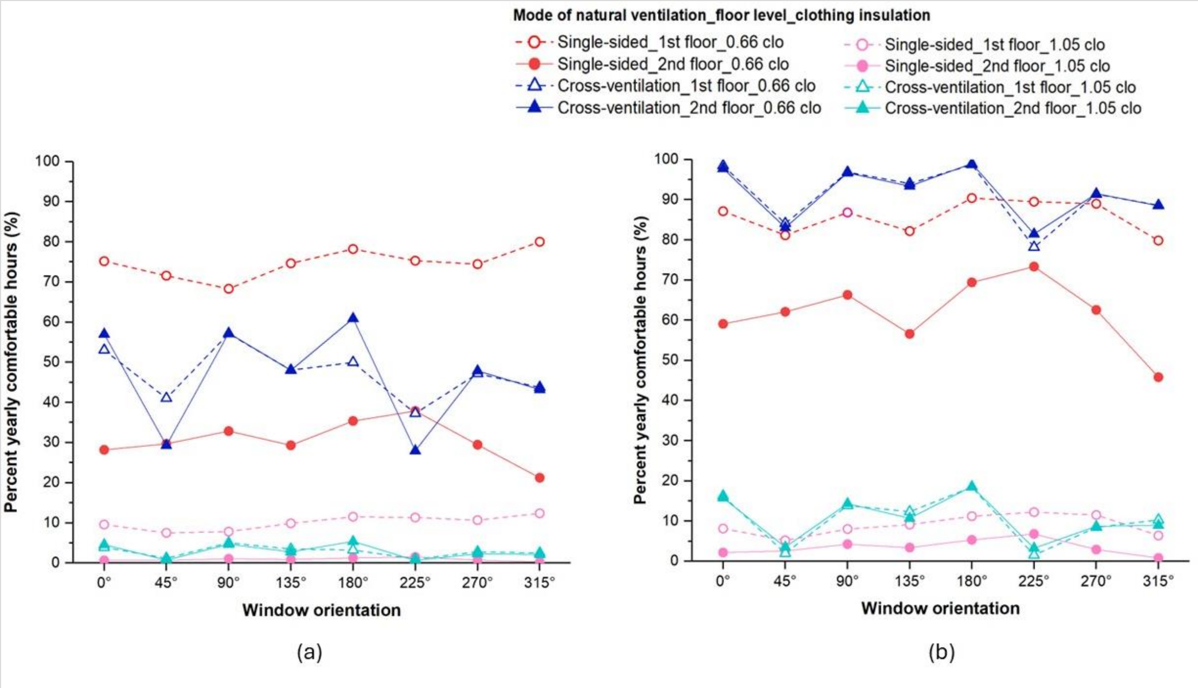


Figure 3.30 (a) Percent of yearly comfortable occupied hours in Surabaya classrooms; (b) Percent of yearly comfortable occupied hours in Ruteng classrooms

Figure 3.30 visually compares the percentage of yearly comfortable occupied hours in classrooms between lowland coastal Surabaya and highland Ruteng, considering various building-feature parameters and two clothing insulation values. The charts reveal both similarities and differences in the trends of yearly comfortable occupied hours between these two locations.

Both cities demonstrate that reducing the clothing insulation value by 0.39 clo significantly increases the percentage of yearly comfortable occupied hours in classrooms. This adjustment potentially enhances yearly comfortable occupied hours by 21-66.7% (equivalent to 612 to 1948 hours per year) in lowland coastal Surabaya and 45-83.4% (equivalent to 1314 to 2432 hours per year) in highland Ruteng. These findings highlight the crucial role of clothing insulation in enhancing students' thermal comfort, particularly in naturally ventilated classrooms.

In hot and humid tropical climates, clothing with lower insulation plays a significant role in enhancing thermal comfort by potentially facilitating sweat evaporation and improving air circulation around the body, which may aid in dissipating heat and moisture. This is considered crucial in such climates where low indoor air velocity could potentially intensify discomfort. Lower insulation clothing is thought to reduce the heat trapped against the skin, thereby potentially helping to prevent overheating and promoting a potentially more comfortable body temperature.

A notable difference between lowland coastal Surabaya and highland Ruteng lies in the ranking of classroom types based on their percentage of yearly comfortable occupied hours. In Surabaya, first-floor single-sided ventilated classrooms consistently lead with the highest yearly comfortable hours, followed by cross-ventilated classrooms. In contrast, in highland Ruteng, cross-ventilated classrooms generally show the highest yearly comfortable occupied hours (except for those facing northwest at 225°), followed by first-floor single-sided ventilated classrooms. Second-floor single-sided ventilated classrooms consistently exhibit the lowest yearly comfortable hours in both cities.

In Surabaya, first-floor single-sided ventilated classrooms exceed cross-ventilated ones in terms of yearly comfortable occupied hours by 11-38% (equivalent to 321-1109 hours). Conversely, in Ruteng, cross-ventilated classrooms generally have slightly higher annual comfortable hours, except for classrooms oriented southwest at 225°. The difference in percentage of yearly comfortable occupied hours between cross-ventilated and single-sided ventilated classrooms in Ruteng ranges from 3-12%, equivalent to 87.6-350 occupied hours per year.

In the hot local climate of lowland coastal Surabaya, it is suggested that first-floor single-sided ventilated classrooms may benefit from cooler ground-level air and possible shade provided by surrounding structures or vegetation. However, in this coastal area, it is hypothesized that cross-ventilation could potentially introduce warm air and humidity into the rooms, potentially reducing comfort hours. This could explain why first-floor single-sided classrooms generally exhibit more yearly comfortable occupied hours compared to cross-ventilated classrooms in lowland coastal Surabaya. Conversely, in highland Ruteng, where temperatures and humidity are generally perceived to be lower than in lowland coastal Surabaya, effective air circulation from cross-ventilation is suggested to potentially maximize comfortable hours compared to classrooms relying on single-sided ventilation.

Figure 3.30 highlights that the yearly comfortable occupied hours in single-sided ventilated classrooms are significantly influenced by different floor-level locations compared to cross-ventilated classrooms. This results in a notable disparity in yearly comfortable occupied hours between first-floor and second-floor single-sided ventilated classrooms in both cities, with the difference being more pronounced in lowland coastal Surabaya. In Surabaya, the gap in yearly comfortable occupied hours between first and second-floor single-sided ventilated classrooms ranges from 35.4% to 58% (equivalent to 1034 to 1919 hours per year), while in highland Ruteng, it ranges from 16% to 34% (equivalent to 467 to 993 hours per year). Conversely, for cross-ventilated classrooms in both cities, minor differences were observed in yearly comfortable occupied hours between classrooms located on the first and second floors.

Cross-ventilated classrooms are suggested to potentially offer improved capabilities in enhancing indoor air movement and regulating heat and humidity. Consequently, the thermal performance of these classrooms appears less likely to be significantly affected by variations in floor level compared to their single-sided counterparts. Given that classroom thermal performance is known to influence the percentage of yearly comfortable occupied hours, it follows that the comfortable occupied hours in cross-ventilated classrooms are also expected to be less impacted by differences in floor level locations.

Examining the impact of different modes of natural ventilation on second-floor classrooms, it was observed that in both cities, second-floor cross-ventilated classrooms generally show higher annual comfortable occupied hours compared to their single-sided ventilated counterparts, except for classrooms oriented northeast at 45° and southwest at 225° in Surabaya. Transitioning from single-sided to cross-ventilation in second-floor classrooms could potentially increase annual comfortable occupied hours by 18.4% to 29% (equivalent to 525 to 847 hours) in Surabaya, and by 8% to 47% (equivalent to 321 to 1110 hours) in Ruteng, excluding the specified orientations.

Second-floor classrooms are suggested to typically experience higher operative temperatures compared to first-floor classrooms due to the potentially increased solar radiation absorbed by the roof and walls. In this context, cross ventilation is hypothesized to potentially maximize comfortable hours better than the single-sided ventilation strategy, potentially due to its ability to enhance airflow and regulate heat and humidity within the classrooms. However, it is suggested that second-floor cross-ventilated classrooms oriented to the northeast at 45° and southwest at 225° in Surabaya may exhibit lower percentages of yearly comfortable hours compared to their single-sided counterparts, possibly due to lower indoor air velocities. At these orientations, it is hypothesized that the inlet and outlet of cross-ventilated classrooms face perpendicular to the prevailing wind direction, potentially resulting in reduced indoor air movement.

Window orientation has a negligible effect on the annual comfortable occupied hours in single-sided ventilated classrooms across both cities. However, cross-ventilated classrooms are more influenced by window orientation. Trends show that classrooms with windows facing north (0°), east (90°), and south (180°) generally have higher comfortable hours, whereas those with windows facing northeast (45°) and southwest (225°) tend to have lower comfortable hours. The greatest variation in annual comfortable hours is observed in first-floor cross-ventilated classrooms in Surabaya, with differences reaching up to 33% (963 hours per year).

This phenomenon may potentially be related to the performance of natural ventilation. In single-sided ventilated classrooms, where airflow is limited, warm air entering the room tends to linger and potentially adjust to the classroom's temperature. Conversely, in cross-ventilated classrooms, effective air movement potentially allows for more efficient circulation without immediate adjustment to indoor temperatures, making them more susceptible to the influence of different window orientations.

Classrooms oriented towards the east (90°) and south (180°) experience higher indoor air velocities, potentially contributing to higher yearly comfortable occupied hours. Additionally, classrooms facing north (0°) may exhibit higher yearly comfortable occupied hours because their windows are not necessarily oriented towards the sun's path, which may reduce the amount of solar radiation received throughout the day. In contrast, cross-ventilated classrooms oriented towards northeast (45°) and southwest (225°) typically may have the lowest yearly comfortable occupied hours due to the potentially low indoor air velocities achieved.

Chapter 4 Discussion

This chapter interprets the empirical findings, revealing their implications to further address the primary goal of enhancing the thermal comfort of Indonesian students in classrooms. Maintaining consistency with the organisation of the preceding chapter, the discussion in this chapter is structured around the "third skin" metaphor within architectural discourse and thermal comfort (Drake, 2007).

Sub-chapter 4.1 strives to comprehend the second skin, specifically exploring the clothing insulation of Indonesia’s Muslim school uniforms and their impact on students' thermal comfort in the classroom.

Subsequently, sub-chapter 4.2 delves into the role of the third skin, referencing the building system as a barrier between the indoor environment of classrooms and the outdoor environment. This section engages in an analysis and interpretation of the simulated thermal performance results from Indonesian classrooms, with a particular focus on lowland coastal Surabaya and highland Ruteng, the cities chosen as case studies. The discussion systematically examines the influence of various design aspects—including ventilation type, window orientation, floor level, and construction materials—on thermal performance.

Finally, sub-chapter 4.3 examines the first skin, referring to students' physiological responses and thermal comfort. The discussion concentrates on the thermal comfort responses of Indonesian students, quantified through the index of Standard Effective Temperature (SET). The overarching objective is to identify strategies for enhancing the thermal comfort of Indonesian students within educational environments.

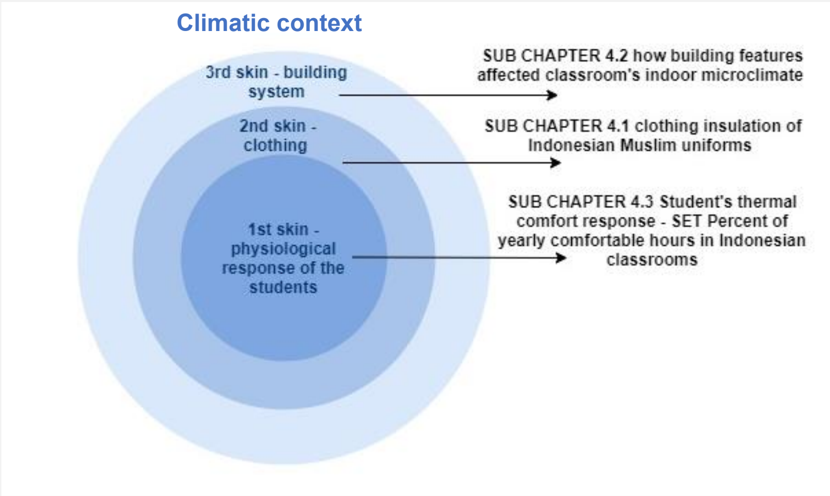


Figure 4.1 The "third skin" analogy used to structure the discussion chapter

4.1 Finding thermally comfortable uniform designs for Indonesian Muslim students

Clothing serves as a boundary influencing the exchange of heat and humidity between the human body and the environment, thereby affecting human heat balance (Havenith et al., 2002; Udayraj et al., 2016; Voelker et al., 2009). In conventional thermal comfort theory, clothing is conceptualized as a single layer of thermal insulation uniformly placed between the human subject's body surface and their immediate thermal environment (Morgan & de Dear, 2003).

Previous research underscores the crucial role of clothing in thermal comfort, emphasizing that adaptation of clothing to varying climate conditions is an affordable and effective means of achieving thermal comfort (Bouden & Ghrab, 2005; Parsons, 2002). Further amplifying this importance, ASHRAE (2020) and Huang et al. (2013) assert that, for individuals engaged in near-sedentary activities (approximately 1.2 met metabolic rate), the effect of changing clothing insulation on the optimum operative temperature is approximately 6 °C per clo (ASHRAE, 2020). Classroom learning activities predominantly occur in a sitting posture, characterized by near-sedentary activities with a metabolic rate of about 1.2 met (ASHRAE, 2020). However, during school hours, Indonesian students are required to wear a specific uniform, restricting the possibility of thermal adjustment by changing clothing.

In Indonesia, deeply influenced by Islamic culture, female students predominantly wear a specific uniform, differing from those worn by male and non-Muslim female students. This uniform covers almost all parts of the body, excluding the face and palms. Given Indonesia's hot and humid tropical climate, coupled with naturally ventilated public schools and classrooms, the role of the uniform in providing thermal comfort becomes paramount.

Notably, previous research on thermal comfort in Indonesian classrooms has primarily relied on the clothing insulation database published by ASHRAE (Baharuddin et al., 2017; Hamzah et al., 2016, 2018; Latif et al., 2016). However, ASHRAE only furnishes values for Western-style ensembles, which diverge from those worn by Indonesia’s Muslim students. Consequently, utilizing ASHRAE's clothing insulation values in Indonesian thermal comfort research may not accurately represent the actual insulation value of the clothing. Therefore, considering different details of ensembles, measuring clothing insulation with a thermal manikin allowed this study to obtain more accurate results.

Distinct uniform styles are worn by different categories of Indonesian students, yet there has been no prior research comparing the thermal comfort responses of male students, non-Muslim female students, and Muslim female students. This research aims to assess the impact of clothing insulation in the uniforms worn by Indonesian Muslim students, providing insights that could enhance the understanding of thermal comfort preferences among Indonesian students. Moreover, this investigation could contribute to the refinement of information derived from ASHRAE and offer invaluable insights for the design of Muslim school uniforms, aligning with both thermal comfort preferences and religious-cultural expectations.

This section presents a comprehensive analysis and interpretation of data derived from the measurement of clothing insulation in eleven configurations of Indonesian Muslim uniforms worn by students. The ensembles were classified into three categories: (A) long-sleeve shirt with pleated skirt, (B) long-sleeve shirt with span skirt, and (C) long-sleeve shirt with trousers. Each category included primary ensembles and supplementary ensembles, which were modified based on factors identified in previous research as influential. These factors included worn style (tucked-in vs. untucked shirt) and the presence of leggings. A detailed list of ensembles is presented in Table 2.1, with the measurement methodology described in Section 2.2 of the methodology chapter.

4.1.1 Comparison of clothing insulation among three categories of Indonesian school uniform

Students attending public schools in Indonesia are mandated to adhere to a standardized uniform, outlined in official regulations (Kemdikbudristek Republik Indonesia, 2022; Kwartir Nasional Gerakan Pramuka, 2012). The prescribed clothing for Muslim female students comprises a long-sleeve shirt, long skirt, headscarf, and tie (Kemdikbudristek Republik Indonesia, 2022). Notably, the regulations do not designate a long-sleeve shirt with trousers as an alternative uniform for female Muslim students. This research, recognizing the potential suitability of this configuration for Indonesia's hot and humid tropical climate, includes it as a category for measurement.

Clothing insulation values resulting from manikin measurements for eleven configurations of uniforms, taken in both standing and sitting positions, are detailed in Tables 3.1 and 3.2 of the Results chapter. The outcomes reveal that ensembles of configuration type C (long-sleeved shirt with trousers) generally had lower clothing insulation values compared to ensembles of categories A and B (long-sleeved shirt with skirts). This aligns with observations from previous research conducted by Havenith et al. (2013).

Havenith et al. (2013) conducted manikin measurements on various Eastern ensembles, including office and school uniforms from Indonesia. The configurations G2 and G3 in

Havenith et al. (2013) correspond to ensembles B.1.1 and C.1 in the current research, albeit with subtle differences in detail, especially in relation to the inner hijab and leggings. The results of Havenith et al. (2013) also indicate that the configuration of a long-sleeved shirt with a skirt exhibited higher clothing insulation compared to the configuration of a long-sleeved shirt with trousers. The potential explanation lies in the length of the skirt entrapment of more air, creating additional insulation under the skirt. The shape of the skirt allows more air to be trapped inside the skirt, in addition to that, the length of the skirt, reaching the ankle, hinders air circulation, thus resulting in higher insulation compared to the trousers.

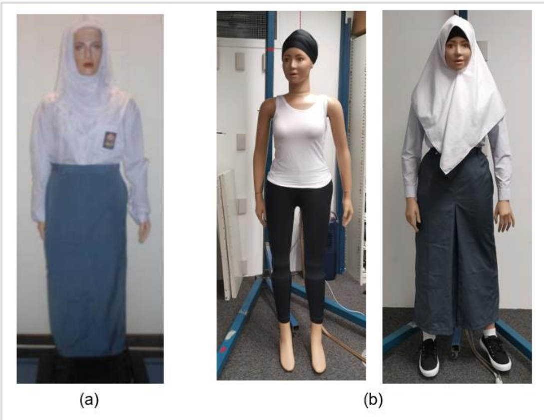


Figure 4.2 Comparation of configuration of clothing ensemble with skirt, measured in Havenith et al. (2013) and in this research. (a) Measured in Havenith et al. (2013) – 0.97 clo, an ensemble without legging and inner scarf/hijab. (b) Ensemble measured in this research (equipped with inner hijab/scarf, including two different measurements, with and without leggings).

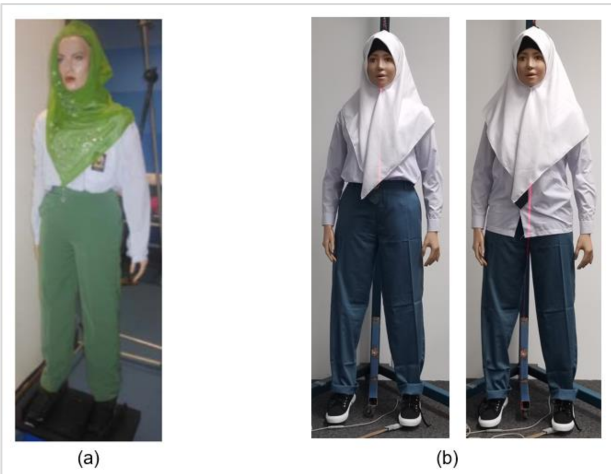


Figure 4.3 (a) Ensemble measured in Havenith et al. (2013), clothing insulation 0.7 clo; (b) Ensembles measured in this research, featuring different styles of hijab/scarf, and two different measurements of shirt (tucked-in (0.83 clo) and untucked (0.78 clo)).

Apart from the same trend shown, there is a 7% difference in clothing insulation between this research and the research of Havenith et al. (2013). This variation might arise from differences in manikin body shapes, fit of the clothing, and ensemble details, such as the inclusion of a cotton undershirt in this research (Havenith et al., 2013).

Comparing ensemble A (long sleeves with pleated skirt) and ensemble B (long sleeves with span skirt), the ensemble with the pleated skirt had a 9% higher clothing insulation. The fuller design of the pleated skirt allows for more air to be trapped compared to the span skirt, which is tighter fitting. As such, the pleated skirt contributes to increased clothing insulation. This finding aligns with the research of Chen et al. (2004) and Havenith et al. (1990), which found that loose-fitting ensembles exhibited greater clothing insulation under various wind speeds. Chen et al. (2004) found that loose-fitting ensembles, with a larger air gap between the garment and the body, demonstrated increased insulation, peaking at approximately 1-7.5 cm of difference in girth between the garment and the body.

However, excessively loose-fitting ensembles can compromise thermal insulation and moisture vapor resistance due to larger openings at the neck, waist, wrists, and ankles allowing for free ventilation of the sub-clothing air layer (Chen et al., 2004). This is particularly evident during windy conditions and with body movement. In the comparison of ensembles A and B in this research, the key difference lies in the type of skirt, affecting the fit on the lower body. The shirt material and fit remain consistent for both categories. Considering the length of the skirt in both configurations hinders effective air circulation, it is reasonable to expect increased clothing insulation in ensembles incorporating pleated skirts, particularly in situations characterized by still air. In conclusion, this research demonstrates the subtle impact of configuration on clothing insulation, providing evidence for the bioclimatic design of school uniforms that are appropriate to the specific cultural context.

4.1.2 The impact of different body postures on clothing insulation

Examining the influence of different body postures on clothing insulation, this study revealed a consistent trend, with ensembles measured in the sitting position generally exhibiting lower insulation compared to the standing position. This finding aligns with prior research by Gao et al. (2021), Havenith et al. (1990), and Nishimura et al. (1994).

While these studies agree that clothing insulation in the sitting position is lower, there are variations in the magnitude of the effect. This study found that the clothing insulation between standing and sitting positions differs by 1-10% across different ensembles. However, Havenith et al. (1990) noted a 6-31% difference, Nishimura et al. (1994) observed a 14% reduction in clothing insulation, and Gao et al. (2021) reported a 15% difference.

Nishimura et al. (1994) found that transitioning from standing to sitting decreased total clothing insulation by 1.4%, with boundary air insulation increasing by 8%, resulting in a 14% reduction in intrinsic insulation. In this study, the boundary air insulation in the sitting position increased by approximately 7%, while the intrinsic insulation in the sitting position decreased within the range of 1-10% across different ensemble types.

Discrepancies in the reported gap between standing and sitting clothing insulation may arise from variations in chair types used in previous studies (Havenith et al., 1990). Previous studies reported using a stool for measuring clothing insulation in the sitting position; however, they did not specify the design nor material insulation. Gao et al. (2021) employed a net chair to minimize the incremental insulation of the chair itself on clo measurements. Material differences in chairs can influence insulation through factors such as heat transfer coefficients and transparency to airflow (Havenith et al., 1990). Additionally, variations in chair shapes may affect the contact area between the body and the chair, also potentially influencing heat transfer. A larger contact area can lead to increased heat transfer between the chair material and the body, resulting in decreased total insulation.

Gao et al. (2021) claimed that the reduction in clothing insulation during the sitting position was attributed to the compression of clothing in the back and thigh areas, creating a thinner air layer compared to the standing posture. This explanation aligns with ISO 9920:2009 (British Standards Institution, 2009). Gao et al. (2023) further confirmed this interpretation, noting that while intrinsic clothing insulation was generally greater in most body segments for the standing posture, statistically significant differences were only observed in the pelvis and thigh regions due to the compression of the enclosed air layer of the clothing in the sitting posture.

As previously noted, this study revealed variations in the gap between clothing insulation in the standing and sitting positions, ranging from 1-10% across different ensembles. Generally, configurations with trousers exhibit a larger difference in clothing insulation between standing and sitting positions compared to ensembles with skirts. This discrepancy can be attributed to the distinct drape of the material used in skirts and trousers. In the sitting position, specific body parts such as the knees undergo flexion, influencing the drape behaviour of garments with different materials. Fabrics with a high drape coefficient (such as combination of cotton and polyester, as observed in the measured skirts) are less prone to collapsing onto the body. The stiffer fabric maintain larger air gaps at certain body sites, as the folds of the garment act like cantilevers (Atasagun et al., 2019). The increased air gap enhances insulation, thereby reducing the disparity in insulation between standing and sitting postures.

4.1.3 The impact of wearing styles on insulation of school uniforms

According to Ke and Wang (2020), the way in which an ensemble is worn can significantly impact ensemble clothing insulation. The findings of this study corroborate this, revealing that ensembles with shirts tucked into skirts and trousers exhibited higher clothing insulation by 3% and 6% respectively compared to configurations with untucked shirts.

The tucked-in style reduces the number of openings in the ensemble compared to the untucked style. Untucked shirts introduce more openings in the ensemble, facilitating airflow and promoting ventilation, thereby contributing to cooling effects and a subsequent reduction in clothing insulation. Additionally, openings in clothing allow heat to dissipate from the body through convection and radiation, particularly when a temperature differential exists between the body and the surrounding environment. Such conditions prove advantageous in warm climates, such as that of Indonesia.

4.1.4 The impact of leggings on insulation of school uniforms

As previously mentioned, it is customary for most women in Indonesia to wear leggings beneath their skirts as an additional measure of modesty. Therefore, when formulating a uniform involving a skirt, the inclusion of leggings in the calculation of ensemble clothing insulation becomes imperative. This study found that the presence of leggings contributes an additional 8-11% to the intrinsic clothing insulation of the girls' school uniform. This outcome can be interpreted as an additional layer of clothing to an ensemble impeding air circulation within the clothing layers and thereby augmenting insulation (Bouskill et al., 2002; Havenith et al., 1990). Moreover, each clothing layer within the ensemble acts as a barrier, trapping and retaining air, which functions as the main insulating medium.

The 3% variation in the difference between ensembles with and without leggings across different configurations in this research might be attributed to differences in the drape behaviour of the skirt material during measurement, or due to differences in clothing area factor (f_{cl}) measurement with a photographic method (McCullough et al., 2005).

4.1.5 Implications for the case of Indonesian schools

Achieving thermal comfort in naturally ventilated buildings poses significant challenges, especially in hot and humid tropical regions such as Indonesia (Al-Tamimi et al., 2011). Public schools and classrooms in Indonesia are typically designed for natural ventilation, limiting students' ability to regulate the indoor microclimate based on personal preferences. Consequently, adjusting clothing represents a crucial and cost-effective behavioural adaptive opportunity for thermal comfort (Ogulata, 2007). Given that students must adhere to specific uniform requirements during school hours, it is crucial to design school uniforms that address contextually relevant thermal comfort needs of Indonesian students. However, designing thermally comfortable school uniforms for Indonesian students, particularly for female Muslim students adhering to Islamic cultural norms of modest attire, presents challenges. Balancing these cultural requirements with the need for low-insulation clothing suitable for a hot and humid tropical climate is essential.

Tight-fitting ensembles afford lower insulation, but such designs are deemed inappropriate for Muslim women, as they accentuate the female form. The formal uniform prescribed for Muslim female students in Indonesia typically comprises a long-sleeve shirt tucked into a long skirt, accompanied by a headscarf. Contrary to expectations, this research reveals that the configuration of a shirt and long skirt does not yield the lowest clothing insulation. Additionally, when Muslim women wear skirts, they often add leggings for modesty, thereby increasing insulation.

According to ASHRAE (2020), the impact of changing clothing insulation on the optimally comfortable operative temperature is approximately 6 °C per clo. Considering Indonesia's high humidity and consistently high operative temperatures, the research findings suggest that a lower insulation school uniform contributes to enhanced thermal comfort for students. Specifically, this study recommends a uniform comprising an untucked long shirt paired with trousers as it affords the lowest insulation, making it a more climatically adapted. The inclusion of trousers eliminates the need for leggings as an additional layer, and the loose fit of the untucked shirt facilitates sub clothing layer ventilation, enhancing convection and evaporative cooling. This recommendation aligns with Islamic clothing standards for women while minimising thermal discomfort in a tropical climate.

4.2 Impact of building features on simulated thermal performance of Indonesian classrooms

In addition to clothing insulation, students' thermal comfort in classrooms is influenced by factors such as their metabolic rate and the thermal performance of the school building, as it affects classroom air temperature, mean radiant temperature, relative humidity, and air velocity within the occupied zone. Given their initial design as naturally ventilated buildings, the indoor microclimate of Indonesian classrooms closely correlates with prevailing external weather conditions. The architectural features of the school building facades play a pivotal role as the "second skin", regulating heat exchange between the interior and exterior environments, thus influencing indoor thermal performance (Drake, 2007; Givoni, 1998). Therefore, comprehending how these architectural elements affect the indoor microclimate in Indonesian classrooms is a prerequisite to evaluating students' thermal comfort and devising design principles for its optimisation.

This section examines how various building facade parameters influence the simulated indoor microclimate of Indonesian classrooms, focusing on lowland coastal Surabaya and highland Ruteng as representative exemplars of the Indonesian climate. By examining the implications of ventilation types, window orientations, floor levels, and construction materials, this section provides insights for occupant-centric future design considerations.

This sub-chapter is structured as follows: Section 4.2.1 discusses the simulated natural ventilation performance in Indonesian classrooms, while Section 4.2.2 addresses their thermal performance.

4.2.1 Impact of natural ventilation modes, floor level, and window orientation on natural ventilation performance

The significance of air movement in shaping individuals' perception of thermal comfort has been firmly established (Croome & Roberts, 1975; Givoni, 1969). Building ventilation plays a fundamental role in ensuring health and comfort. In warmer climates, particularly those with elevated humidity levels like the Indonesian climate, comfort depends not only on the quantity of fresh air supplied to a room but, more critically, on the velocity of air circulation around occupants in what is referred to as the “occupied zone,” facilitating effective cooling through convection and evaporation (Prianto & Depecker, 2002).

Classrooms in Indonesian public schools are typically designed with natural ventilation. However, designing naturally ventilated classrooms in warm and humid climates like Indonesia presents significant challenges, particularly in achieving students' thermal comfort (Al-Tamimi et al., 2011). Encouraging adequate air movement within buildings in densely populated urban areas of tropical, humid regions with low wind speeds can be particularly complex (Meteo, 2001, as cited in Prianto & Depecker, 2002).

The CFD model of Indonesian classrooms in this research was based on the standard Indonesian classroom described in Kementrian Pendidikan dan Kebudayaan Republik Indonesia (2018). The present models incorporated two modes of ventilation: single-sided ventilation and cross-ventilation through top-hung windows with a 30° opening angle and clerestory components situated above the windows. It is important to note that the classroom models were not equipped with fans, as the guidelines do not mention the requirement for fans in classrooms (Kementrian Pendidikan dan Kebudayaan Republik Indonesia, 2018).

As illustrated in Figure 4.4, the dimensions of the classrooms were 7 x 8 x 3.5 m^3, resulting in a 6.30% opening ratio for classrooms with single-sided ventilation and a 14.8% opening ratio[2] for those with cross-ventilation. This opening ratio is higher than 5% minimum opening ratio recommended by the Australian Building Codes Board (2020). Further details regarding the classroom design and dimensions can be found in Chapter 2, particularly in Section 2.3.1.2 and Tables 2.3 and 2.4.

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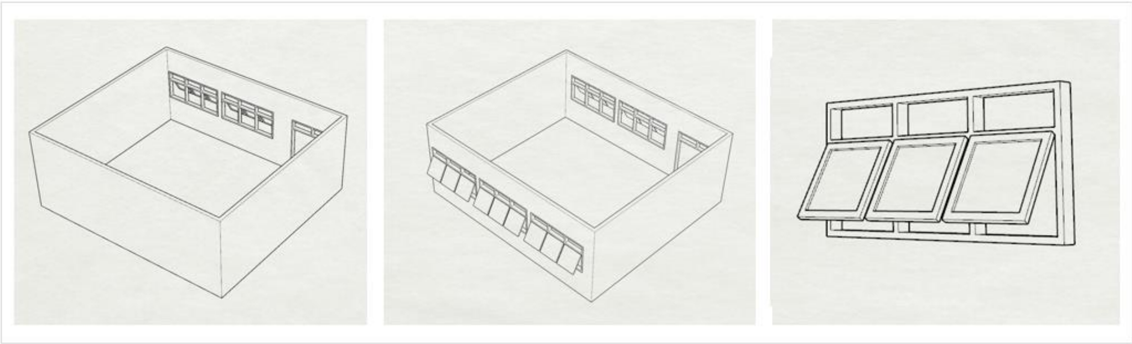
[2] Opening ratio is defined as the ratio of the total area of openings to the floor area of a building or specific floor.



(a) (b) (c)

Figure 4.4 (a) Single-sided ventilated classroom; (b) cross-ventilated classroom; (c) detail of the window opening

The CFD simulation employed two prevailing wind speeds and directions during school occupied hours (7.00 am – 2.00 pm) for lowland coastal Surabaya and highland Ruteng, extracted from hourly wind-rose data from the Typical Meteorological Year of 2007-2021 for Surabaya Gedangan and Ruteng (Climate. OneBuilding, 2023). In lowland coastal Surabaya, the first prevailing outdoor wind velocity was 1.99 m/s from a southeast (135°) direction, while the second prevailing wind velocity was 2.97 m/s from an eastern (90°) direction. For Ruteng, the first prevailing outdoor wind velocity was 1.79 m/s from a southeast (135°) direction, and the second prevailing wind velocity was 1.45 m/s from an eastern (90°) direction. These wind velocities were categorized as weak or low based on the Beaufort scale (Rizk et al., 2018).

The simulation revealed that indoor air speed in Indonesian classrooms, particularly those with single-sided ventilation, consistently fell below the recommended values set by ASHRAE (2020) and Nor Azli et al. (2023) in their study of hot and humid Malaysia's climate. ASHRAE (2020) specifies an acceptable air speed of 0.2 m/s for an operative temperature range of 23–25.5°C, with sedentary activities below 1.3 met and clothing insulation of 0.65 clo. In contrast, this study found that simulated indoor air velocity[3] for single-sided ventilation scenarios generally remained very low, below 0.08 m/s, while cross-ventilated scenarios yielded

[3] The calculations of indoor air velocity were conducted at three distinct heights: 0.1 m, 0.6 m, and 1.1 m above the floor, aligning with the measurement standards for sitting occupants specified in ISO 7726:2001 (British Standard Institution, 2002).

velocities ranging from 0.05 to 0.27 m/s, depending on window orientation. The ASHRAE (2020) airspeed recommendations may not be applicable to Indonesian classrooms, particularly for Indonesian female Muslim students, whose national school uniform clothing insulation ranges from 0.87 to 1.05 clo, exceeding ASHRAE's specified clothing insulation level. Higher insulation might prevent air from circulating around the body, thus reducing convective heat loss and resulting in thermal discomfort (Nielsen et al., 1985). Additionally, ASHRAE's recommended airspeed might not be suitable for lowland Surabaya, where indoor operative temperatures can reach up to 35°C in the afternoon, surpassing the outlined temperature range (ASHRAE, 2020).

Regarding preferred indoor air velocity in classrooms in hot and humid tropical climates, Nor Azli et al. (2023) conducted a study in naturally ventilated classrooms in Malaysia equipped with ceiling fans, where the mean indoor operative temperature was 28.4°C. The study evaluated the thermal comfort and learning performance of students under three different ceiling fans speed (18.0 m/s, 19.5 m/s, and 21.0 m/s) during the peak temperature period of the school session. The findings indicated that optimal learning performance was achieved when students felt "slightly cool" and the indoor air velocity exceeded 0.95 m/s (achieved with the maximum fan’s speed). Additionally, Nor Azli et al. (2023) found that hotter environments and a lack of air movement contributed to declining student performance. They suggested that the comfort zone in a naturally ventilated classroom for school students should be set within the thermal sensation scale of -1 (slightly cool) with an air velocity greater than 0.76 m/s (Nor Azli et al., 2023). These indoor air velocities were achieved with the assistance of ceiling fans in the classrooms.

Considering the similar culture and climate region, the indoor airspeed suggested by Nor Azli et al. (2023) might be more applicable for Indonesian classrooms, particularly for lowland coastal Surabaya’s climate. However, achieving this indoor air speed may be challenging under the conditions of weak equatorial outdoor wind speeds in Indonesia, unless ceiling fans become mandatory to maintain comfortable air speeds within the occupied zone. Additionally, this research suggests that exclusive reliance on single-sided ventilation is not advisable for Indonesian classrooms unless supplementary ceiling fans are employed to enhance airflow. When single-sided ventilation is unavoidable, it is essential to implement several strategies to optimize its performance. Ceiling fans have been demonstrated to significantly enhance thermal comfort when compared to scenarios where natural ventilation is the sole ventilation strategy (Kubota & Hooi Chyee, 2010; Omrani et al., 2021).

The simulation results indicated that, irrespective of window orientation and floor level, cross-ventilation generally led to higher indoor air velocities compared to single-sided ventilation in both Surabaya and Ruteng. This finding aligns with observations by Omrani et al. (2017), Rizk et al. (2018), and Givoni (1994), who asserted that cross-ventilation typically provides superior indoor air velocities compared to single-sided ventilation. The superiority of cross-ventilation in achieving higher average indoor air velocities can be attributed to the increased pressure gradient between the windward and leeward openings (Givoni, 1994; Gough et al., 2020; Omrani et al., 2017; Ulrike & Battaglia, 2015). Furthermore, cross-ventilation is deemed more effective than stack ventilation in tropical regions such as Indonesia, where there is generally no significant temperature difference between indoor and outdoor environments (Givoni, 1994). Additionally, the cross-ventilation system offers superior natural ventilation compared to single-sided ventilation because it ensures a more even distribution of air across various parts of a room or building (Givoni, 1994; Ulrike & Battaglia, 2015). This distribution helps prevent localized hotspots or areas with poor air quality. In single-sided ventilation, air may only enter and exit from the same side, leading to stagnant air in certain zones. Cross-ventilation, on the other hand, minimizes these stagnant zones by creating a more uniform air movement throughout the space.

In this study, cross-ventilation was generally associated with higher indoor air velocities compared to single-sided ventilation. However, even with the optimal indoor air velocities achieved through cross-ventilation, these velocities may still not meet the thermal comfort needs of students, especially in lowland Surabaya where high operative temperatures are prevalent during occupied hours. Additionally, the high insulation values provided by Indonesian school uniforms may require higher indoor air velocities to achieve thermal comfort. Therefore, in addition to optimizing cross-ventilation designs to improve indoor air velocities, incorporating fans into cross-ventilated classrooms is crucial to enhance natural ventilation performance as necessary.

The Australian Building Codes Board (2020) recommends a minimum opening ratio of 5% of a room's floor area for natural ventilation. The model designs used in this study for Indonesian classrooms exceed these standards, with openable areas of 6.30% for single-sided ventilation and 14.8% for cross-ventilated classrooms, as detailed in Tables 2.3 and 2.4 in Chapter 2. Nevertheless, the resulting indoor air velocities, particularly in single-sided ventilation, remain very low, failing to meet the minimum recommendations for indoor air speed during sedentary activities set by ASHRAE (2020). This highlights the inadequacy of the 5% openable area standard, particularly in conditions characterized by low outdoor wind speeds and high ambient temperatures typical of Indonesian cities. It underscores the necessity for Indonesia to develop its own building codes tailored to its unique climate characteristics.

The simulation results also indicated that classrooms situated on the second floor generally experience slightly higher indoor air velocities compared to those on the first floor. This increase is attributed to the effects of wind speed variation with height and ground friction (Givoni, 1998). However, the simulations found that relocating classrooms from the first to the second floor does not guarantee prolonged comfort hours, as top-floor classrooms may face higher operative temperatures due to solar heat gain from the roof, as well as heat from walls and windows. Therefore, this study suggests that for Indonesian classrooms in both lowland Surabaya and highland Ruteng, transitioning from single-sided to cross-ventilation may provide superior natural ventilation performance and comfort compared to moving classrooms from the first floor to the second floor.

In hot, humid environments with weak outdoor wind speeds such as Indonesia, ensuring optimal performance of both single-sided and cross-ventilation is crucial. The study found that the highest indoor air velocities for both ventilation types occurred when windows were oriented approximately 45° relative to the prevailing wind direction, rather than directly facing windward. This finding aligns with Givoni (1994) and Wang and Yan (2015), who observed improved natural ventilation performance when buildings were exposed to oblique winds. Givoni (1994) specifically noted that the best ventilation performance occurs when windows are oriented obliquely 30-60° to the wind direction, while Wang and Yan (2015) found optimal rates with a 45° angle wind approach. This orientation creates a pressure gradient along the windward wall, enhancing indoor air velocities (Givoni, 1994).

Conversely, the worst performance of cross-ventilation was observed when windows were oriented perpendicular to the wind direction. Givoni (1994) explained that in such scenarios, both openings experience similar pressures, reducing the airflow into the room. This phenomenon limits the effectiveness of cross-ventilation when the inlet and outlet orientations do not facilitate adequate pressure gradients for efficient air movement (Sacht & Lukiantchuki, 2017).

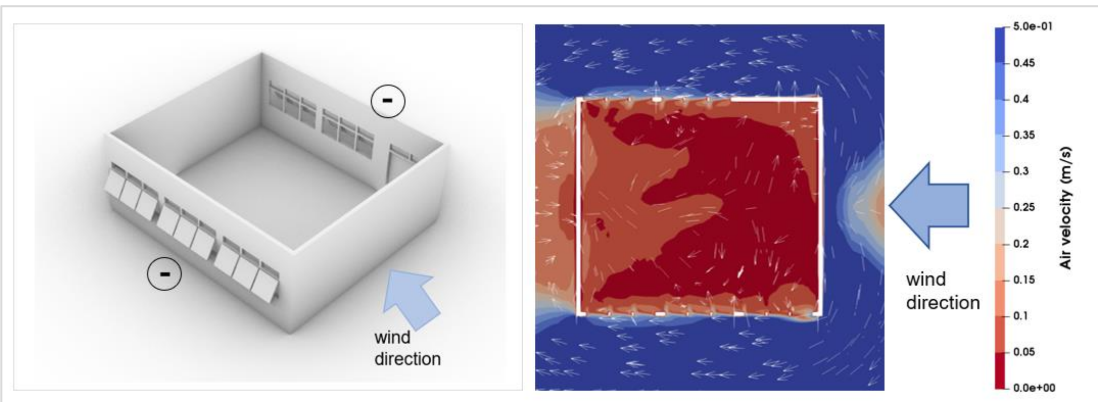


Figure 4.5 The worst performance of natural ventilation for cross-ventilation scenarios occurred when windows were oriented perpendicular to the wind direction

This research found that single-sided ventilation performed worst when the window was oriented leeward to the prevailing outdoor wind. Conversely, Evola & Popov (2006) found that in conditions of strong outdoor wind velocity, positioning single-sided ventilation openings on the leeward side could actually enhance indoor natural ventilation. However, in areas with weak outdoor wind velocity, such as is prevalent in Indonesia, this orientation is suboptimal. This finding underscores the importance of considering wind climatology, especially the prevailing wind direction of a location, when designing for natural ventilation in buildings.

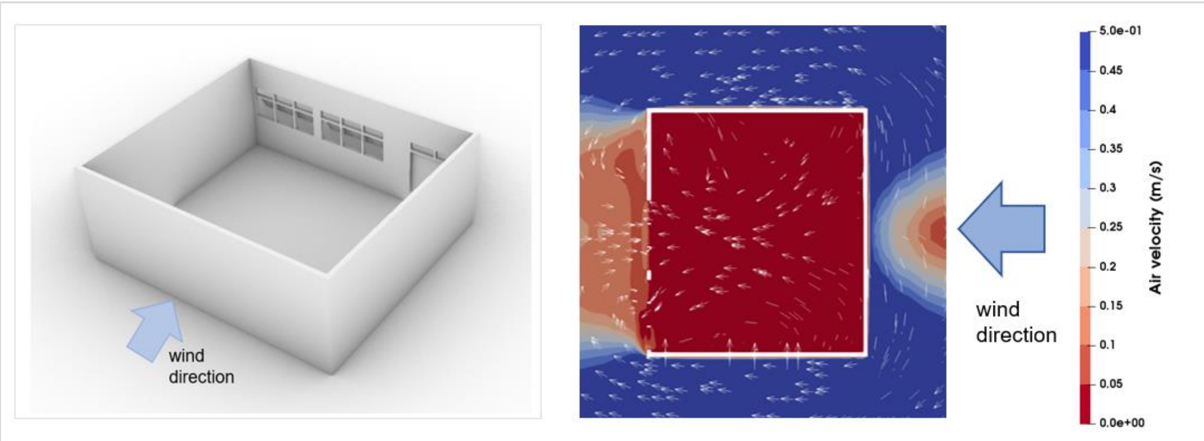


Figure 4.6 The worst performance of natural ventilation for single-sided ventilation occurred when windows were oriented leeward to the prevailing wind direction

In addition to orienting windows towards the prevailing wind, the choice of window type in this investigation likely influenced natural ventilation performance (Gao & Lee, 2011; Heiselberg et al., 2001; Wang & Yan, 2015; Zhang et al., 2023). The primary window type used in the classroom models of this study were top-hung with a 30° opening angle. These windows pivot outward from the top of the frame, with the opening located at the lower and side sections of the window. As a result, peak indoor air velocities were not achieved when the window directly faced the wind; instead, optimal airflow occurred when the window was positioned at a 45° angle to the prevailing wind direction. The characteristics of window types influence indoor air velocities. Consequently, the optimal window orientation suggested in this research may not be applicable if window types other than top-hung windows are used. Increasing the openable area of windows could enhance indoor airflow. Further research is necessary to investigate the specific effects of different window types on indoor air velocities in Indonesian classrooms.

4.2.1.1 Optimising natural ventilation performance of Indonesian classrooms – considering other building features

This study suggests windows should be oriented at a 45° angle towards the prevailing wind to optimize natural ventilation performance in Indonesian classrooms. However, under certain design constraints, single-sided ventilation may sometimes be unavoidable. Previous research has highlighted various building features such as window types (Gao & Lee, 2011; Heiselberg et al., 2001; Wang & Yan, 2015; Zhang et al., 2023), size and placement of openings (El-Agouz, 2008; Evola & Popov, 2006; Tantasavasdi et al., 2001), and the use of wing walls (Givoni, 1994, 1998), all of which influence natural ventilation performance. Integrating these features into building design has the potential to improve natural ventilation effectiveness, stet of whether cross-ventilation or single-sided ventilation strategies are employed.

The choice of window type significantly influences natural ventilation performance in buildings (Gao & Lee, 2011; Heiselberg et al., 2001; Wang & Yan, 2015; Zhang et al., 2023). Indonesian classrooms typically utilize top-hung windows with clerestory openings. However, research indicates that top-hung windows generally exhibit poorer natural ventilation performance compared to alternative types such as bottom-hung, slider, awning, and casement windows (Gao & Lee, 2011; Heiselberg et al., 2001; Wang & Yan, 2015; Zhang et al., 2023). Studies by Wang and Yan (2015) and Zhang et al. (2023) highlight that casement windows achieve higher average indoor wind velocities than top-hung and sliding windows.

Gao and Lee (2011) conducted a comparative analysis of natural ventilation performance among top-hung, side-hung, and slider windows. They found that end-slider windows outperformed side-hung windows by 17.2% in terms of the weighted average mean age of air

(MAA), while top-hung windows exhibited the least effective natural ventilation (Gao & Lee, 2011). Despite their drawbacks, top-hung windows offer the advantage of facilitating natural ventilation while protecting against rain ingress. Given Indonesia's tropical climate and frequent heavy rainfall, the prevalence of top-hung windows may reflect the need for rain protection.

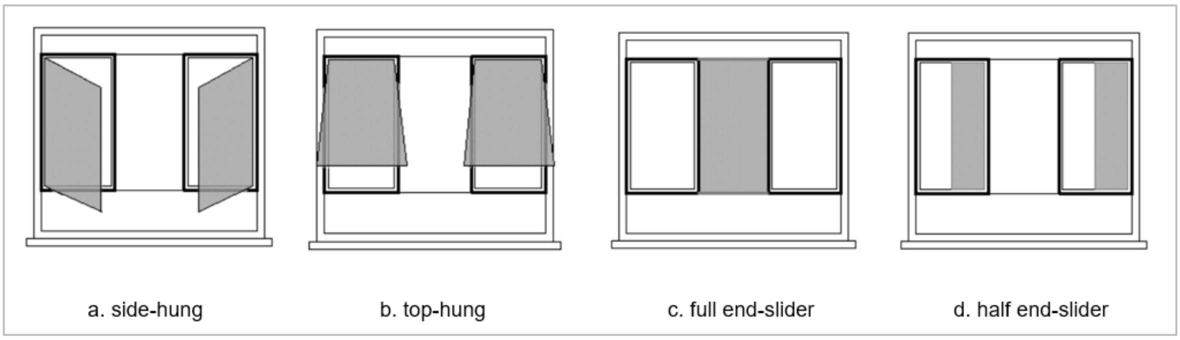


Figure 4.7 Window types (Gao & Lee, 2011)

Despite the suboptimal natural ventilation performance, Zhang et al. (2023) suggest that top hung window type effectively guides airflow upwards. However, this upward airflow may not directly enhance thermal comfort in the occupied zone where most activities occur while seated. In a sitting position, air velocities are measured at 1.1 m above the floor (British Standard Institution, 2002), while the top-hung window is positioned slightly higher at 1.2 m above the floor (see Figure 4.8). Nonetheless, the window's ability to direct airflow upwards may help reduce the stagnation of warm air in the upper part of the room, decreasing localized heat buildup and indirectly improving overall comfort at seating height. Therefore, enhancing the natural ventilation performance of Indonesian classrooms could involve considering alternative window types suggested by previous research or strategically placing top-hung windows.

Figure 4.8 The position of the top-hung window relative to the occupied zone of Indonesian classrooms (Source: Admin SMAN1 Banyuwangi, 2024)

The size, position, and arrangement of openings are critical factors influencing natural ventilation performance (El-Agouz, 2008; Evola & Popov, 2006; Hellwig et al., 2019; Tantasavasdi et al., 2001). In this study, the cross-ventilated classroom model maintained identical sizes and arrangements for inlet and outlet openings, with the outlet positioned opposite the inlet. However, prior research indicates that varying the size and arrangement of inlets and outlets can enhance the Venturi effect, a fluid dynamics phenomenon in which the velocity of a fluid increases as it passes through a constriction, leading to decreased pressure (Tantasavasdi et al., 2001).

The Venturi effect is significant in building design for natural ventilation, optimizing airflow by influencing the dimensions and positions of inlet and outlet openings (Givoni, 1969; Prianto & Depecker, 2002; Tantasavasdi et al., 2001). Tantasavasdi et al. (2001) demonstrated that using a smaller inlet size compared to the outlet can induce a Venturi effect, maximizing indoor air velocity. Furthermore, placing the inlet on the windward side and the outlet on the leeward side enhances indoor air velocity.

Givoni (1969) investigated the influence of the inlet-to-outlet openings width ratio on indoor air velocity, finding that a 1:1 ratio could achieve an average indoor air velocity of 36% of the wind speed, suitable for regions with strong winds. Conversely, a 1:3 ratio was more suitable for weak wind regions like Indonesia, achieving an average indoor air velocity of 44% of the wind speed, with maximum velocities reaching 137-152% of the outdoor wind speed (Givoni, 1969). In this study, the cross-ventilation model for classrooms employed a 1:1 ratio for inlet to outlet openings. Adjusting this ratio in cross-ventilated classrooms in Indonesia could optimize natural ventilation performance and potentially reduce the window-to-wall ratio, mitigating solar heat gain.

Wing walls, as identified by Givoni (1994, 1998) and Moore (1993), also impact natural ventilation performance. Studies indicate that incorporating wing walls at strategic positions relative to openings can influence the pressure gradient in single-sided ventilation, thereby improving indoor ventilation performance (Givoni, 1994; Moore, 1993). Thoughtful integration of wing walls has the potential to further enhance single-sided ventilation performance.

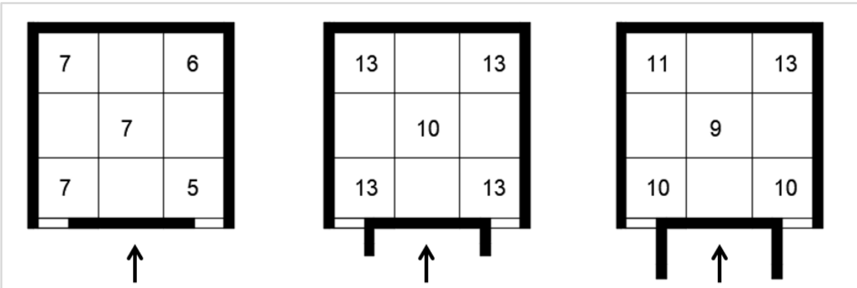


Figure 4.9 Effect of wing walls on indoor air speed as a percentage of outdoor airspeed, redrawn from Givoni (1994)

4.2.2 Simulated indoor operative temperature of Indonesian classrooms

This subsection examines the impact of various building features on the simulated indoor average operative temperature of typical Indonesian classrooms. The model used for simulation adhered to classrooms design guidelines outlined by Kementrian Pendidikan dan Kebudayaan Republik Indonesi (2018). The features included two modes of natural ventilation (single-sided and cross-ventilation), different floor levels (first and second floor), varied window orientations from north (0°) to northwest (315°), and six combinations of wall and roof materials (Autoclaved Aerated Concrete (AAC) and brick walls; concrete tile, clay tile, and corrugated aluminium roof). The classroom model utilized concrete structures, featuring top-hung windows oriented at 30° with clear glass materials and clerestory openings at the top.

The thermal simulations incorporate average indoor air velocities and ventilation rates derived from CFD simulations, utilizing the initial prevailing wind direction from the southeast (135°), along with outdoor wind speeds of 1.99 m/s for lowland Surabaya and 1.79 m/s for highland Ruteng, as input parameters.

The simulation results are consistent with previous research, indicating that building features such as modes of natural ventilation, floor levels, and window orientation affect indoor operative temperature (Al Tamimi & Fadzil, 2010; Al-Tamimi et al., 2011; Givoni, 1998; Wong et al., 2006). However, the impact of each building feature on indoor operative temperature may vary between the lowland coastal area of Surabaya and the highland region of Ruteng due to differences in geographic characteristics, which also influence local climate conditions. Consequently, distinct design strategies should be employed for lowland coastal areas and highland regions to achieve optimal indoor operative temperatures.

In both lowland coastal Surabaya and highland Ruteng, single-sided ventilated classrooms seem to be more sensitive to floor level temperature differences compared to cross-ventilated classrooms. Specifically, there appears to be a notable difference in average indoor operative temperature observed between first-floor and second-floor single-sided ventilated classrooms, whereas the temperature variation between different floor levels in cross-ventilated classrooms was less pronounced. Additionally, first-floor classrooms generally exhibit lower indoor operative temperatures compared to their second-floor counterparts.

The disparity in floor-level temperatures is likely to be the result the varying solar radiation intensity absorbed by the building facade. First-floor classrooms, at ground level, likely receive direct solar radiation through walls and windows, but second-floor classrooms also have direct solar exposure on the roof, potentially leading to higher indoor operative temperatures on the upper floors (Givoni, 1998).

Single-sided ventilated classrooms appear to be more susceptible to floor-level effects due to less ventilative heat flushing dissipation, allowing heat accumulation in second-floor classrooms. Conversely, cross-ventilated classrooms have more effective convective heat dissipation, narrowing the temperature differential between floors.

Indonesia sits within the hot and humid tropical climate zone, so its building stock is exposed to direct solar radiation throughout the year. In both lowland coastal Surabaya and highland Ruteng, situating classrooms on the ground floor can significantly reduce indoor operative temperatures compared to placing them on upper floors, especially when cross-ventilation is not feasible. Conversely, for classrooms located on upper floors, implementing cross-ventilation is essential to optimize natural ventilation and airflow. Effective cross-ventilation facilitates the purging of hot air and its replacement by cooler outdoor air, thereby enhancing thermal comfort (Givoni, 1994; Ulrike & Battaglia, 2015).

For lowland Surabaya, which experiences significantly higher daily temperatures and humidity compared to highland Ruteng, this research found that placing single-sided ventilation classrooms on the ground floor resulted in notably lower indoor operative temperatures compared to using cross-ventilation. Conversely, for highland Ruteng, where daily temperatures are lower than in Surabaya, this study found no significant difference in indoor average temperatures between classrooms with single-sided ventilation and those employing cross-ventilation on the ground floor, except for classrooms with windows oriented southwest (225°) and west (270°). This variation may be attributed to the distinct local climate characteristics of Surabaya's lowland coastal area and Ruteng's highland environment.

In the hot and humid local climate of coastal Surabaya, the incoming wind tends to be warm and humid, influenced by the regional scale climatic context. Consequently, increased airflow from warm outdoors via cross-ventilation, particularly in ground floor classrooms, may lead to higher indoor operative temperatures compared to single-sided ventilation. Additionally, the use of single-sided and cross-ventilated systems is associated with an increased window-to-wall ratio (WWR), which can enhance solar exposure through windows (Givoni, 1998). Cross-ventilated classrooms have windows on two adjacent walls, doubling the WWR compared to single-sided ventilated classrooms. The heat gained through windows is a significant contributor to total heat accumulation, particularly exacerbated by clear glass that permits solar radiation transmission while trapping longwave radiation indoors (Al-Tamimi et al., 2011; Givoni, 1998; Hien & Liping, 2006; Yu et al., 2008). This phenomenon explains why, in the hot lowland coastal area of Surabaya, ground floor classrooms with single-sided ventilation exhibit considerably lower indoor operative temperatures compared to cross-ventilated counterparts, potentially offering better thermal comfort to students.

Moreover, the difference in indoor operative temperature between the first and second-floor classrooms was notably larger in lowland coastal Surabaya compared to highland Ruteng. In Surabaya, single-sided ventilated classrooms on the first floor experienced a temperature differential ranging from 2.2 to 3.2°C compared to those on the second floor, whereas in Ruteng, the difference was narrower at 0.7 to 1.5°C. For cross-ventilated classrooms in lowland Surabaya, the temperature gap between first- and second-floor classrooms ranged from 1.9 to 2.4°C, with no significant difference observed in Ruteng. This observation suggests that relocating single-sided ventilated classrooms from the second floor to the first floor may lead to a more significant reduction in indoor average temperature in coastal locations like Surabaya compared to high-elevation sites like Ruteng.

The variation in temperature gaps between first-floor and second-floor classrooms in Surabaya and Ruteng can be attributed to their distinct local geographical characteristics. Ruteng, situated at a higher altitude (1,118 meters above sea level), experiences a decrease in temperature with altitude, with an average lapse rate of 6.5°C per kilometre (Schnelle, 2003). In contrast, Surabaya, located on the coast and characterised by flatter terrain, may exhibit more pronounced temperature variations between different surface types (Oliver & Hidore, 2021). The lowland coastal area is also influenced by warm sea breezes, contributing to higher humidity levels. These geographical and climatic differences likely contribute to a greater variation in temperature between the first and second floors of classrooms in Surabaya compared to Ruteng.

Windows serve multiple functions in buildings, including providing visual and auditory contact with the outdoors, natural ventilation, and daylighting. They also play a role in passive solar heating and cooling. Givoni (1998) notes that window orientation affects both solar exposure and ventilation potential. In equatorial regions such as Indonesia, buildings with west and east-facing windows tend to experience higher solar exposure due to their orientation relative to the sun-path, potentially resulting in elevated indoor operative temperatures compared to buildings with windows oriented north and south (DeKay & Brown, 2014; Givoni, 1969, 1998). Conversely, in relation to wind direction, this study reveals that top-hung windows oriented obliquely at 45° to the prevailing wind direction optimize natural ventilation performance, driving increased indoor average air velocities. This finding reinforces the generalisations from earlier research by Givoni (1998) and Wang and Yan (2015). Additionally, the research found that classrooms with cross-ventilation windows oriented perpendicular to the wind direction and single-sided ventilated windows on the leeward facade delivered suboptimal ventilation performance and higher indoor operative temperatures as a result.

The impact of window orientation on indoor operative temperature was observed to be more pronounced in highland Ruteng compared to coastal Surabaya, likely due to differences in topography and local climate between the two cities. In lowland coastal regions, where high ambient temperatures and humidity prevail, there is unrelenting heat load, irrespective of window orientation. This bioclimatic burden overwhelms any effects of window orientations on indoor temperatures (Karthick et al., 2023). Conversely, highland areas experience generally cooler, variable temperatures, making them more sensitive to heat gains and losses resulting from window orientation and other factors.

Specifically for highland Ruteng, this study found that classrooms with windows oriented to the north (0°) and south (180°) consistently sustained lower indoor operative temperatures, regardless of the natural ventilation mode employed. This can be explained by reduced solar exposure on the northern and southern facades, which are not directly exposed to insolation at low solar angles (Givoni, 1998). Furthermore, classrooms oriented southwards at 180° experience optimal natural ventilation performance, further contributing to cooler indoor operative temperatures. Conversely, classrooms with southeast-facing (45°) and southwest-facing (225°) windows in cross-ventilated scenarios, and southeast-facing (45°) and northwest-facing (315°) windows in single-sided ventilation scenarios, experience the highest indoor average operative temperatures. These classrooms generally exhibit poorer natural ventilation performance due to windows oriented perpendicular to the wind direction in cross-ventilated systems, and leeward-facing windows in single-sided ventilation. These findings underscore the importance of window orientation in relation to both solar exposure and airflow on indoor operative temperatures.

In the context of a hot and humid tropical climate, prioritizing design strategies that enhance natural ventilation and mitigate solar heat gain on building facades is crucial for achieving lower indoor operative temperatures and higher indoor air velocities (Al-Tamimi et al., 2011; Givoni, 1998), thereby enhancing thermal comfort and facilitating optimal learning environments. It is recommended to orient classroom windows at oblique 45° angles towards the prevailing wind direction to optimize natural ventilation performance. In addition to that, avoiding east and west orientations is advised, as these may expose classrooms to higher solar radiation intensity due to the path of the sun.

Givoni (1998) highlights that the equatorial zone, situated within the Trade Wind belt, predominantly experiences winds from the east. Consequently, eastern-facing windows are highly beneficial in this zone for optimizing natural ventilation, which is crucial for comfort in high-humidity environments. This generalisation is supported by this research, where the primary wind directions prevailing in both lowland Surabaya and highland Ruteng were from 135° (southeast), with the secondary prevailing wind direction being from the east. Givoni additionally recommends that when there is a conflict between optimizing natural ventilation and avoiding solar radiation exposure, priority should be given to windows for optimal natural ventilation. Architectural features such as shading devices can be employed to mitigate direct solar exposure to windows effectively (Givoni, 1998). The classrooms modelled in this study lacked effective shading. First-floor classrooms had no shading devices attached to their windows, while second-floor classrooms relied solely on roof overhangs for shading.

Despite their benefits in reducing solar heat gain, the effectiveness of shading devices in enhancing natural ventilation remains debated. Their application can impact indoor airflow, air speed, and air change rates, with effects that may be either beneficial (Pourshab et al., 2020; Prianto & Depecker, 2002) or detrimental (Hassanli et al., 2019; Mohamed et al., 2014). Previous research has found that the impact of shading devices on natural ventilation performance is influenced by several factors, including the types and configurations of shading devices, window types (Grussa et al., 2019; Hien & Istiadji, 2023; Kannan et al., 2018), geographical location (Alhuwayil et al., 2019), and climatic conditions (Alhuwayil et al., 2019; Calama-González et al., 2019). However, there is currently a lack of comprehensive studies on the integration of shading devices with various types of windows (Yusoff et al., 2023). Therefore, careful consideration of shading device application is essential to avoid impeding natural ventilation and adversely affecting thermal comfort.

Regarding the influence of building materials on indoor operative temperature, this research examines the differential impact of five common combinations of wall and roof materials used in Indonesian public-school buildings, specifically in lowland Surabaya and highland Ruteng.

The chosen wall materials are bricks and Autoclaved Aerated Concrete (AAC), while the roof materials include concrete tile, clay tile, and corrugated aluminium.

Bricks has traditionally been used for wall construction throughout Indonesia, but Autoclaved Aerated Concrete (AAC) is gaining prominence as an alternative wall material, particularly in major urban centres such as Surabaya. The preference for AAC is driven by several advantages, including its lightweight composition, insulation properties, fire resistance, acoustic insulation capabilities, durability, and environmental benefits. AAC is considered environmentally friendly compared to conventional bricks due to its manufacturing process (Narayanan & Ramamurthy, 2000; Qu & Zhao, 2017).

Concerning roof materials, concrete and clay tiles emerge as the predominant choices in most Indonesian cities, including the lowland coastal area of Surabaya. The advantage of clay and concrete roofs is driven by their capacity to extend the roofing system's lifespan and their minimal maintenance requirements compared to other roofing materials (Roslan et al., 2016). In contrast, corrugated aluminium is popular only in specific Indonesian cities, with highland Ruteng being one notable example. The popularity of corrugated aluminium in Ruteng is attributed to its lower construction costs and easier application, despite its poorer thermal performance. This thermal conductivity enables corrugated aluminium to transfer heat more efficiently (Badan Standardisasi Nasional, 2011). Consequently, this roofing material is less favoured in lowland cities with higher temperatures.

The simulation results indicate that in both Surabaya and Ruteng, the use of different materials shows negligible impact on indoor operative temperature. This finding can be attributed to the relatively small variations in thermal properties, specifically thermal conductivity and thermal mass, among the chosen building materials such as bricks and AAC. Both brick and AAC are materials characterized by relatively high thermal mass which helps stabilize indoor operative temperatures throughout the day, contributing to a more comfortable and consistent learning environment.

Although corrugated aluminium has higher thermal conductivity than clay and concrete tile roofs, this study found no significant difference in indoor operative temperatures between classrooms with these roofing materials. This result may be influenced by the particular roof design commonly used in Indonesian school buildings. The conventional pitched roof design in Indonesian school buildings features a 35° angle between the two sloping sides. This design creates an attic or space between the ceiling and roof that is ventilated through a stack effect. As hot air rises, it exits through vents, cooling the attic and slowing the increase in operative temperature within the interior space. This finding aligns with studies by Ramly and Hussain (2006) and Roslan et al. (2016), underscoring the importance of an optimal roof pitch. Additionally, the pitched roof provides effective rainwater drainage, preventing accumulation and water damage. Moreover, it affords shading to external walls, windows, and doors, minimizing direct exposure to intense sunlight and maintaining a cooler indoor environment in tropical climates.

4.3 Assessing students' thermal comfort response in Indonesian classrooms

This sub-chapter discusses students' responses to thermal comfort in Indonesian classrooms, providing valuable insights into the interaction between the building façade, clothing, and the human body. Understanding these responses is crucial for developing strategies to enhance students' thermal comfort in the classroom. A thermally comfortable learning environment is essential, as optimal thermal comfort positively influences educational achievements, learning performance, and cognitive tasks (Barbhuiya & Barbhuiya, 2013; Haverinen-Shaughnessy et al., 2015).

In this research, the Standard Effective Temperature (SET) was the chosen index for assessing students' thermal comfort in naturally ventilated Indonesian classrooms. SET was selected for its ability to account for air velocity's impact on convective heat exchange and sweat evaporation (Ji et al., 2022), making it suitable for naturally ventilated buildings in hot and humid tropical climates (Karyono, 2015; Zhang et al., 2010).

In this research, SET values were calculated for each occupied hour across 768 simulated classroom variations in lowland coastal Surabaya and highland Ruteng. These variations include different building features such as two modes of natural ventilation (single-sided and cross-ventilation), two floor levels (first and second floor), and eight window orientations ranging from north (0°) to northwest (315°). Additionally, the SET calculation incorporates the highest and lowest clothing insulation values observed in Indonesian Muslim uniform ensembles. The lowest insulation value (0.66 clo) comes from ensemble C3, which includes trousers and an untucked, loose-fitting shirt. In contrast, the highest insulation value (1.05 clo) is from ensemble A2.2, featuring a medium-fit long-sleeve shirt with a pleated skirt and leggings as innerwear. This comprehensive approach ensures that the thermal comfort analysis accounts for the range of clothing insulation values associated with different configurations of uniforms by students in classrooms.

The neutral temperature for lowland Surabaya and highland Ruteng, which forms the basis for thermal comfort assessment in this study, was derived using the Indonesian thermal comfort predictor equation presented by Karyono (2015). This equation was developed based on an analysis of 2,939 thermal comfort vote data points from twelve previous studies conducted in six Indonesian cities including Jakarta, Surabaya, Makassar, Medan, Bandung, and Yogyakarta (Karyono, 2015).

Karyono's equation was selected for calculating neutral temperature in this research because Indonesia currently lacks a reliable thermal comfort standard grounded in local research. The existing national standard (SNI 6390:2011) specifies a single comfort temperature range (25.5°C Ta, with a range of +1.5°C Ta and a relative humidity of 60% + 5% for workplaces) to be applied nationwide (Badan Standardisasi Nasional Indonesia, 2011; Karyono, 2015). However, this standard has been found unreliable as previous studies indicate that residents in major cities like Jakarta, Surabaya, and Yogyakarta find comfort in temperatures ranging from 27°C to 29°C (Alfata et al., 2012; Feriadi & Wong, 2004), which extends beyond the specified comfort range.

To provide a comprehensive scope of thermal comfort, the 80% comfort criterion was used, with a 3.5°C margin above and below the neutral temperature, aligning with the adaptive comfort range mentioned in ASHRAE Standard 55 (ASHRAE, 2020).

The calculated neutral temperature for lowland Surabaya, experiencing an average daily temperature of 28.7°C and average relative humidity of 75.2%, was 27.6°C (or 28.6°C in SET). The 80% range of comfort acceptability for Surabaya fell within 24.1°C to 31.1°C in SET. For highland Ruteng, with average daily temperatures of 22.1°C and average relative humidity of 85.9%, the calculated neutral temperature was 22.5°C (or 23.3°C in SET). The 80% range of comfort acceptability calculated for Ruteng was within 19.4°C to 26.1°C in SET. These ranges serve as the basis for calculating the percent yearly comfortable occupied hours, a metric used to evaluate thermal comfort responses in Indonesian classrooms.

The significant difference in neutral comfort temperature and the range of comfort acceptability between lowland Surabaya and highland Ruteng highlights the need for further research to establish tailored comfort standards for different local climates in Indonesia. Applying a uniform thermal comfort standard across diverse regions with varying climatic conditions could overlook the influence of thermal history and acclimatization, which are crucial in shaping people's thermal comfort preferences (Brager & de Dear, 1998; De Dear et al., 1997; Jowkar, de Dear, et al., 2020). Moreover, this approach may lead to thermal discomfort among occupants and potentially increase energy consumption.

4.3.1 Thermal comfort in Indonesian classrooms: effects of clothing insulation, modes of natural ventilation, floor levels, and window orientation Clothing insulation significantly impacts thermal comfort across diverse classroom environments. In both Surabaya and Ruteng, reducing clothing insulation from 1.05 clo to 0.66 clo led to a more substantial decrease in average SET values and a notable increase in comfortable hours compared to changes in natural ventilation modes, floor levels, or window orientations. These findings provide valuable insights for improving students' thermal comfort in Indonesian classrooms.

In tropical regions with a hot and humid climate, such as Indonesia, distinct climate features include heightened solar heat gain and elevated humidity levels. Additionally, air velocities remain consistently low throughout the year. These climatic attributes pose significant challenges in designing naturally ventilated buildings that meet occupants' thermal comfort preferences (Al-Tamimi et al., 2011). Achieving thermal comfort in naturally ventilated buildings becomes notably challenging when inadequate indoor air movement fails to provide sufficient cooling effects. This issue is particularly evident in Indonesian classrooms lacking mechanical systems like fans. In this context, clothing adjustment emerges as a critical behavioural adaptation for achieving thermal comfort (Newsham, 1997; Ogulata, 2007; Parsons, 2014).

Lower clothing insulation promotes enhanced air circulation, facilitating efficient sweat evaporation and optimal heat dissipation from the body (Havenith, 2002; Newsham, 1997). This improvement in airflow and moisture management contributes significantly to overall thermal comfort (Bouskill et al., 2002; Havenith, 2002; Ogulata, 2007), particularly in hot and humid tropical regions like Indonesia. Clothing, being in direct contact with the skin, directly influences the body’s ability to regulate temperature. In contrast, changes in building design, while influencing air movement and temperature indirectly, may not always provide immediate or consistent improvements in thermal comfort compared to the direct impact of clothing insulation.

Designing school uniforms that ensure thermal comfort for Indonesian students, particularly for female Muslim students who observe Islamic cultural norms of modest dress, poses considerable challenges. These norms require covering most of the body except for the face and hands. It is crucial to balance these cultural expectations with the need for clothing that offers low insulation, suitable for the hot and humid tropical climate. Such low-insulation ensembles promote better heat dissipation and enhance airflow around the body (Havenith, 2002; Newsham, 1997), thus improving thermal comfort in these environments.The study found that clothing ensemble C3, with a clothing insulation of 0.66 clo measured in the sitting position, provides better thermal comfort for students compared to ensemble A2.2, which has an insulation of 1.05 clo. Ensemble C3 consists of a loose-fitting, untucked long-sleeve shirt paired with long trousers and a hijab or head cover. In comparison, ensemble A2.2 represents the formal school uniform for Muslim female students in Indonesia, which features a long-sleeve shirt tucked into a long skirt.

Figure 4.10 Ensemble C3 which has a clothing insulation value of 0.66 clo and ensemble A2.2 which has a clothing insulation value of 1.05 clo

The official school uniform designed for Indonesian Muslim female students typically comprises long-sleeved shirts tucked into long skirts. The skirt's design allows more air to be trapped inside, effectively hindering heat transfer and enhancing thermal insulation for the body. Moreover, ensembles with long skirts often include leggings, commonly worn as underskirts by Indonesian women. The presence of leggings as an underskirt may increase insulation for ensembles featuring long skirts. Leggings add an extra layer within the ensemble, acting as a barrier that traps and retains air, serving as an insulating medium. This impedes air circulation within the ensemble, thereby augmenting insulation (Bouskill et al., 2002; Havenith et al., 1990).

Muslim attire and uniforms have gained popularity in Indonesia over the past decade, with the regulation officially addressing Muslim school uniforms introduced in 2022. Consequently, the designers of Indonesian Muslim school uniforms likely have no personal experience wearing such uniforms during their own school years. To ensure optimal thermal comfort, it is advisable to evaluate the performance of the uniforms in naturally ventilated classrooms while incorporating feedback from students who have firsthand experience wearing them.

This research proposes an alternative clothing ensemble configuration that combines untucked long-sleeved shirts with long trousers, aiming to achieve lower clothing insulation compared to configurations involving skirts. Ensembles featuring trousers are lighter and offer less insulation without the additional layer of leggings, thereby reducing the risk of overheating and discomfort from excessive sweating. Additionally, the untucked style of ensembles with trousers, as advocated in this study, promotes better air circulation, facilitating sweat evaporation and maintaining dryness, thereby further enhancing thermal comfort.

Furthermore, the observed impact of changing clothing insulation aligns with ASHRAE Standard 55, which asserts that altering clothing insulation affects the optimum operative temperature by approximately 6°C per clo (ASHRAE, 2020). This research found that reducing clothing insulation by 0.36 clo could potentially decrease SET by 2-3°C, significantly increasing yearly comfort hours in Indonesian classrooms. These findings underscore the pivotal role of clothing insulation in achieving thermal comfort.

In assessing the impact of building features on yearly comfortable occupied hours in Indonesian classrooms, this study identified distinct trends between lowland Surabaya and highland Ruteng. In Surabaya's hot and humid coastal climate, first-floor single-sided ventilated classrooms consistently recorded the highest percentage of yearly comfortable occupied hours compared to other types of classrooms. Conversely, in the cooler highland climate of Ruteng, cross-ventilated classrooms demonstrated higher annual comfort hours.

These divergent trends can be attributed to regional topographical variations that influence local climate conditions. In Surabaya's lowland coastal areas, ground-floor classrooms with single-sided ventilation are likely to enhance thermal comfort by limiting the entry of humid, warm air into the classrooms. However, cross-ventilation strategies in the hot local climate of lowland coastal Surabaya may increase indoor air velocity, potentially introducing warmer air and humidity, thereby reducing the duration of comfortable conditions. Additionally, the implementation of single-sided ventilation benefits from significantly lower Window-to-Wall Ratio (WWR), reducing solar heat gain through glass windows. First-floor classrooms in Surabaya may also benefit from shading provided by upper floors or surrounding vegetation, contributing to their thermal comfort. In contrast, Ruteng's highland climate, characterized by lower temperatures and humidity levels, suggests that effective natural ventilation and increased air movement from cross-ventilation may maximize comfortable hours compared to classrooms relying solely on single-sided ventilation.

In terms of classrooms with the lowest annual comfort hours, in both lowland Surabaya and highland Ruteng, second-floor classrooms with single-sided ventilation experience the least annual comfortable occupied hours. Despite differing local climates, both regions share the characteristic of receiving high solar radiation throughout the year. Consequently, second-floor classrooms generally have higher indoor operative temperatures due to increased solar radiation exposure on both façades and roofs (Kocagil & Koçlar, 2016). The use of single-sided ventilation on these top floors may result in suboptimal natural ventilation performance, with limited air movement hindering the escape of warm air and humidity, thereby leading to lower annual comfortable occupied hours.

In both cities, single-sided ventilated classrooms appear more sensitive to the impact of different floor levels, while cross-ventilated classrooms are less affected by floor location. This sensitivity is reflected in the larger discrepancy in yearly comfortable occupied hours between first and second-floor single-sided ventilated classrooms compared to cross-ventilated ones. This disparity can be attributed to the less efficient air circulation in single-sided ventilated classrooms, which hinders effective heat dissipation and leads to significant heat accumulation (Givoni, 1994; Ulrike & Battaglia, 2015), particularly in second-floor rooms exposed to additional solar heat gain from the roof. In contrast, cross-ventilation benefits from improved airflow, facilitating better heat dissipation and potentially resulting in narrower temperature variations between different floor levels.

In assessing the impact of window orientation on yearly comfortable occupied hours in classrooms, this study finds that cross-ventilated classrooms are more responsive to different window orientations compared to single-sided ventilated classrooms. Single-sided ventilated classrooms rely on windows on one side of the wall, restricting airflow to a more stagnant and less effective movement, which allows warm air to linger and gradually adjust to the classroom's temperature. In contrast, cross-ventilated classrooms benefit from effective air movement, promoting more efficient circulation and potentially making them more responsive to various window orientations.

Window orientation plays a critical role in indoor operative temperatures by influencing both sun exposure and natural ventilation dynamics (Givoni, 1998). In both lowland Surabaya and highland Ruteng, regardless of the ventilation mode, classrooms with windows oriented to the south (180°) and north (0°) demonstrate higher annual comfortable occupied hours. This is likely due to reduced solar heat gain compared to east and west orientations, which directly face the sun's path. This finding aligns with prior research by Al-Tamimi et al. (2011), which identified 0° and 180° orientations as optimal for hot and humid tropical climates. Additionally, despite receiving higher solar heat intensity, this research found that classrooms facing east (90°) also experience high annual comfortable occupied hours. This can be attributed to effective natural ventilation and significantly higher indoor air velocities, as the east (90°)

orientation is oblique at 45° to prevailing wind directions, resulting in optimal indoor air velocity. To mitigate the effects of higher solar radiation received by eastern windows, this study recommends implementing effective shading devices. These devices can reduce the impact of direct solar radiation, thereby lowering the potential increase in indoor operative temperature in classrooms and increasing annual comfortable occupied hours.

Regarding classrooms that experienced the lowest yearly comfortable occupied hours, this research found that classrooms with windows perpendicular to the prevailing wind direction exhibited the lowest annual comfortable occupied hours. This is likely due to poor natural ventilation performance observed in classrooms with windows facing perpendicular to the wind direction. This trend underscores the critical importance of understanding local climate conditions, especially prevailing wind patterns, in the design of naturally ventilated buildings. Moreover, the findings support Givoni's (1998) argument to prioritize window orientation based on wind direction to optimize natural ventilation performance, rather than solely avoiding orientations with high solar radiation exposure. This approach is particularly relevant when there is a conflicting objective between enhancing natural ventilation and minimizing solar heat gain (Givoni, 1998). Additionally, reducing solar heat gain on windows facing the sun-path can be achieved through architectural interventions such as shading devices, which effectively reduce direct solar exposure (Givoni, 1994, 1998; Hien & Liping, 2006).

Chapter 5 Conclusion

5.1 Main findings

In this research, strategies are proposed to optimise thermal comfort for students in Indonesian classrooms. Creating a thermally comfortable learning environment is essential, as previous research has demonstrated that thermal comfort significantly affects students' health, productivity, and academic performance. Thermal discomfort can reduce attention and concentration, thereby hindering students' learning outcomes and achievements. This issue is particularly critical for Indonesia, where studies have reported widespread dissatisfaction among students regarding the thermal conditions in their classrooms.

Indonesian public-school classrooms are generally designed for natural ventilation, relying on outdoor climate conditions to manage indoor thermal environments. However, the hot and humid climate of Indonesia presents significant challenges to maintaining thermal comfort in school buildings. These challenges are further exacerbated by the lack of occupant-centred guidelines for school and classroom design and the absence of reliable thermal comfort standards specific to Indonesia's local climatic conditions. Moreover, the school uniforms worn by Indonesian Muslim female students, which cover the entire body except for the face and palms, are likely to increase clothing insulation, thereby intensifying discomfort in hot and humid conditions.

The strategies proposed in this study to optimise thermal comfort in Indonesian classrooms are divided into two main categories: the first focuses on the design of school uniforms, particularly for female Muslim students, and the second involves modifications to classroom design that account for the unique climatic conditions of Indonesia's coastal lowlands and highland regions within the hot and humid tropics.

In this research, the clothing insulation of various Indonesian school uniforms was measured using a thermal manikin. The findings indicate that a uniform ensemble comprising a loose-fitting, untucked long-sleeve shirt, long trousers, and a hijab provides significantly lower clothing insulation than that of the official school uniform for female Muslim students in Indonesia, which consists of a long-sleeve shirt tucked into a long skirt along with a hijab. Therefore, incorporating trousers into the uniform can substantially improve thermal comfort for students.

The design of the skirt tends to trap more air, thereby impeding heat transfer and increasing thermal insulation for the wearer. Additionally, long skirts are often worn with leggings, which serve as underskirts. The presence of leggings adds an extra insulating layer within the ensemble, which further inhibits air circulation and enhances insulation. Without legging as an additional layer underneath, ensembles that include trousers are lighter and offer less insulation. This reduced insulation helps to lower the risk of overheating and discomfort from excessive sweating. Moreover, the untucked style of trousers, as recommended in this study, enhances air circulation, aids in sweat evaporation, and helps maintain dryness, thereby further improving thermal comfort.

The study also revealed that adjusting clothing from the official school uniform, featuring long skirts and leggings, to an ensemble incorporating trousers resulted in a more substantial increase in comfortable occupied hours in classrooms compared to modifications in building features such as natural ventilation modes, floor levels, window orientations, and wall and roof materials. Clothing, through direct contact with the skin, has a primary effect on the body's temperature regulation. Conversely, modifications in building design affect air movement and temperature indirectly and may not consistently or immediately enhance thermal comfort to the same extent as adjustments in clothing insulation.

Designing school uniforms that ensure thermal comfort for Indonesian students, particularly for female Muslim students who adhere to Islamic cultural norms of modest dress, presents significant challenges. It is essential to reconcile these religion and cultural expectations with the need for clothing that offers low insulation, appropriate for the hot and humid tropical climate. Uniforms with lower insulation facilitate better heat dissipation and improve airflow around the body, thereby enhancing thermal comfort in such environments. Therefore, to optimise students' thermal comfort in Indonesian classrooms, this study recommends revising the official school uniform design for Indonesian Muslim female students. Instead of the current official ensemble of a long-sleeve shirt paired with a long skirt and hijab, the study suggests adopting a configuration of a long-sleeve shirt (untucked) paired with trousers and a hijab. This revised design would not only adhere to Islamic cultural requirements but also provide improved thermal comfort in naturally ventilated classrooms within Indonesia's hot and humid tropical climate.

The effectiveness of different school design strategies in achieving optimal thermal comfort for students is influenced by variations in local climates in Indonesia, which are affected by the topographical characteristics of lowland coastal and highland regions. Given that Indonesia currently uses uniform classroom design across the country, this research suggests that adapting classroom designs to align with local climate characteristics—such as those specific to coastal or highland regions—could significantly enhance thermal performance and extend the duration of comfortable occupied hours for students. In Indonesia, accounting for the climatic conditions of both lowland coastal and highland regions is crucial when designing naturally ventilated classrooms to ensure a thermally comfortable indoor environment. This consideration is especially important as Indonesia, the world's largest archipelagic nation, consists predominantly of lowland coastal areas (located at an elevation of less than 500 meters above sea level) alongside numerous highland regions (situated at elevations above 500 meters). These distinct topographical features contribute to variations in the local climate, which in turn shape individual thermal comfort preferences through acclimatization processes that enhance tolerance to specific temperature ranges. Figure 5.1 illustrates the locations of these lowland coastal and highland regions across Indonesia.

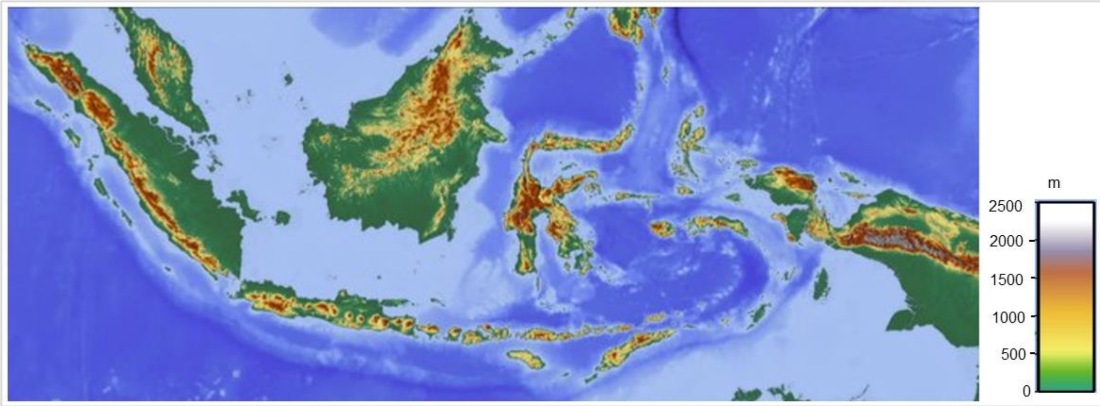


Figure 5.1 Indonesian topographic map showing the location of lowland and highland regions in Indonesia (edited from https://upload.wikimedia.org/wikipedia/commons/9/9d/South_east_asia_topographic_map.svg)

This research suggests that, in the hot and humid lowland coastal climate of Indonesia, implementing single-sided ventilation in first-floor classrooms would significantly increase the number of yearly comfortable occupied hours compared to other strategies, such as cross-ventilation on the first or second floors. In this climate, cross-ventilation strategies for first-floor classrooms may inadvertently introduce warmer air and higher humidity, reducing the duration of comfortable conditions. However, if classrooms must be located on the top floor, a cross-ventilation system is essential. Top-floor classrooms, exposed to higher solar radiation, experience considerably higher operative temperatures. The use of cross-ventilation in these classrooms enhances air movement, improving heat dissipation. Conversely, in the highland climate with lower daily temperatures, employing cross-ventilation rather than single-sided ventilation in classrooms—regardless of floor level—may result in greater comfortable occupied hours.

In a hot and humid tropical climate such as Indonesia, it is crucial to prioritise building design strategies that enhance natural ventilation and reduce solar heat gain. These approaches are critical for achieving lower indoor operative temperatures and increased air velocities, which in turn enhance thermal comfort. To minimise higher solar exposure, it is advisable to avoid window orientations directly facing the sun at times of low solar elevation angle, particularly in the east and west directions. However, if such orientations conflict with the prevailing wind direction, this research recommends prioritising window orientation based on the prevailing wind to optimise natural ventilation. Specifically, orienting classroom windows at oblique 45° angles towards the prevailing wind is suggested to maximise ventilation performance. Additionally, incorporating architectural features such as shading devices and blinds could be done to effectively reduce direct solar exposure to windows. These findings underscore the importance of understanding local climate characteristics, including prevailing wind directions and velocities, when designing strategies for naturally ventilated buildings.

In the climatological setting of Indonesia with its proximity to the Equatorial "doldrums," where wind resources are meagre, it is recommended that fans should be mandated in all new classroom designs, and retrofitted in all existing classrooms that don't already have them, especially when single-sided natural ventilation is the only feasible option. The addition of fans can increase air movement, thereby enhancing sweat evaporation and heat dissipation, which leads to improved thermal comfort.

5.2 Implication for practices

This research has important implications for improving practices aimed at optimising students' thermal comfort in Indonesian classrooms. In the absence of occupant-centric guidelines for schools and classrooms in Indonesia, the findings propose strategies for enhancing thermal comfort in educational environments. The strategies are categorised into those focused on school uniform design and those focused on classroom-specific design.

Related to the school uniform design, this study suggests revising the design of the official school uniform for female Muslim students from a configuration of long-sleeve shirt tucked into a long skirt, to a climatically more appropriate ensemble consisting of an untucked long-sleeve shirt paired with trousers and accompanied by a hijab. Changing the long skirt to trousers and adopting an untucked shirt style significantly reduces whole-ensemble insulation, thereby enhancing thermal comfort for Indonesian students in the classroom.

The suggested strategies for classroom design are divided into two categories: those tailored to local climates based on topographical features (such as lowland coastal or highland regions in Indonesia), and those applicable to the broader hot and humid Indonesian climate.

Classrooms design strategies suggested specifically for lowland coastal and highland regions of Indonesia include:

- For the design of classrooms situated in **lowland coastal cities** characterised by high daily temperatures and humidity, prioritising ground-floor locations with single-sided ventilation over top-floor placements is advisable to maximise the percentage of comfortable occupied hours. If constraints necessitate classrooms on higher floors, implementing a cross-ventilation system becomes imperative. This system ensures adequate airflow, facilitating a cooling effect to lower indoor operative temperatures and promote sweat evaporation and heat loss through convection.
- In **highland areas**, where daily temperatures are relatively lower compared to lowland regions, implementing a cross-ventilation system for classrooms is recommended regardless of their floor level. This approach can increase the percentage of comfortable hours throughout the year, compared to single-sided ventilation, thereby enhancing students' thermal comfort.

Strategies suggested for the hot and humid climate of Indonesia, regardless of the topographical characteristics of the region, include:

- Understanding the prevailing wind direction and local wind velocities is essential before designing a naturally ventilated building at a specific site. This study confirms that window orientations relative to predominant wind direction exert a major influence on the air speeds experienced within the occupied zone inside the classroom, which in turn exerts an overriding influence on the thermal comfort experienced by occupants.

- To optimise indoor air velocity, particularly inside rooms with top-hung windows as the main openings, it is advisable to orient the façade containing the windows oblique, i.e. at a 45° angle towards the predominant wind direction. The term "predominant wind direction" refers to the prevailing wind direction throughout the year. In hot and humid tropical regions like Indonesia, the climate remains consistently hot and humid year-round. While the daily temperature is only slightly higher during the dry season compared to the rainy season, humidity levels are higher in the rainy season than in the dry season. These hot and humid conditions necessitate enhanced air movement to facilitate sweat evaporation and convective heat dissipation, thereby improving thermal comfort.

- To minimise excessive solar exposure, it is advisable to avoid window orientations that face the sun directly during periods of low solar elevation angles, especially in the east and west directions. However, if this orientation conflicts with the prevailing wind direction, this research recommends prioritising window orientation based on the prevailing wind to optimise natural ventilation, because judiciously specified external shading devices and blinds can be employed to mitigate direct solar exposure through windows, while exerting minimal attenuation of ventilation effectiveness.

- It is recommended that natural ventilation of classrooms in the equatorial region of Indonesia should be supplemented with fans, particularly when cross-ventilation is not feasible and single-sided ventilation is unavoidable. State-of-the-art ceiling fan technology can move large volumes of air within the occupied zone at minimal electricity power demand. The enhanced air movement effectively improves convective heat dissipation. Additionally, increased air movement within the occupied zone enhances sweat evaporation from the skin, which helps maintain the body's heat balance and improves thermal comfort in a humid equatorial climatic setting such as that of Indonesia.

- This study recommends using wall materials with low conductivity and high thermal mass, such as Autoclaved Aerated Concrete (AAC) and bricks. Materials with high thermal mass absorb and store heat during the day, preventing the immediate transfer of external heat to interior spaces. Introduction of this thermal lag avoids incrementing indoor heat load when classrooms are in use and outdoor temperatures are at their highest during the diurnal cycle.

This study highlights the importance of maintaining the traditional pitched roof design of Indonesian school buildings, which features a 35° angle with two sloping sides. This specific roof design effectively minimizes heat transfer from the roof to the classroom interior, as it creates an attic space between the ceiling and the roof, promoting natural ventilation as hot air rises and exits through vents. Consequently, the attic remains cooler, which slows the increase in operative temperature within interior spaces, making it well-suited to Indonesia's warm and humid tropical climate.

5.3 Future research directions

This study suggests directions for future research. These future research directions are categorised into two main areas: first, advancing thermal comfort research in Indonesia, and second, developing strategies to optimise students' thermal comfort in Indonesian classrooms.

5.3.1 Future research directions in the topic of thermal comfort in Indonesia

The findings of this research highlight the urgent need for Indonesia to establish reliable thermal comfort standards based on comprehensive research conducted within the local climate. Currently, Indonesia applies a uniform range of comfort temperatures nationwide, despite evidence indicating its unreliability. Previous studies across various Indonesian cities have shown that Indonesians experience thermal comfort within temperature ranges that exceed those prescribed by the national standard.

Given that numerous Indonesian cities are located either in lowlands with higher daily temperatures or highlands with lower daily temperatures, it is essential to conduct thermal comfort research in both geographical contexts. The result research will then form the basis for developing localized thermal comfort standards which are more suitable for the Indonesian context, and thus should be prioritized as a future research direction.

The prevalent use of naturally ventilated buildings in Indonesia underscores the importance of adopting locally derived thermal comfort standards based on rigorous research, rather than relying on a single national standard. In naturally ventilated building, occupants have limited ability to adjust the indoor microclimate based on their preference. As thermal comfort preferences are also influence by personal thermal history, customizing comfort standards to specific geographical contexts holds promise for informing design strategies that better accommodate occupants' thermal preferences. Additionally, implementing more appropriate standards or guidelines for Indonesian comfort temperatures could lead to substantial energy savings in building operations.

5.3.2 Future research directions to optimize thermal comfort in Indonesian classrooms

- This study utilized a dry thermal manikin to measure and evaluate the clothing insulation of various school uniforms worn by Indonesian Muslim female students. For future research, it is suggested to employ a sweating manikin (Ooka et al., 2010; F. Wang, 2017), which offers several advantages, particularly for the hot and humid climatic conditions of Indonesia. A sweating thermal manikin can simulate human sweating, a critical component of thermoregulation in such environments. Additionally, sweating thermal manikin has the ability to evaluate the performance of different fabrics (Morton & Hearle, 2008; Murthy, 2016) and clothing systems in terms of their ability to wick moisture away from the body and allow for efficient evaporation. This is crucial for designing garments suited for hot and humid climates.

- This research found that the natural ventilation standard of Australian building codes, which requires a minimum window opening size of 5% of the floor area (Australian Building Codes Board, 2020), is ineffective for providing thermal comfort in typical Indonesian cities due to low outdoor wind velocity, high ambient temperatures, and high humidity. Therefore, further research is recommended to develop building codes tailored to Indonesia’s unique climatic conditions, specifically regarding the standard window openable area to floor area ratio. Additionally, this study highlights the necessity of further research into preferred indoor airspeed in Indonesian classrooms, as indoor airspeed significantly impacts the yearly comfortable occupied hours in Indonesian classrooms.

- Understanding how various building facade features impact indoor thermal performance in classrooms is essential for developing strategies that enhance students' thermal comfort. In a hot and humid tropical climate, prioritising design strategies that improve natural ventilation and reduce solar heat gain on building facades is crucial for achieving lower indoor operative temperatures and higher indoor air velocities. The classroom model used in this research was based on the architectural drawings of a typical Indonesian classroom, as outlined in Appendix 4 of the Operational Guidelines for the Procurement of Buildings and Educational Facilities in Indonesia, issued by Indonesia’s Ministry of Education and Culture (Kementrian Pendidikan dan Kebudayaan Republik Indonesia, 2018). Therefore, the building features involved in the research were limited to different modes of natural ventilation, floor levels, and window orientations. This research suggests further investigations incorporating a wider range of building features, such as shading devices, wing walls, the size and placement of window openings, and various window types. These features have been proven to mitigate solar heat gain and enhance natural ventilation performance. The findings will aid in developing detailed strategies to improve thermal comfort for students in Indonesian classrooms.

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