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In-Situ hygrothermal evaluation of ventilation block as adaptive climate buffer in contemporary tropical house of Indonesia

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ABSTRACT

Within tropical urban environments, passive cooling strategies have become increasingly essential in mitigating the escalating energy consumption associated with achieving indoor thermal comfort. Among the passive cooling approaches suitable for the hot-humid tropical climate of Indonesia, comfort-oriented ventilation through the application of ventilation blocks demonstrates considerable potential. Nevertheless, the actual thermal behavior and environmental performance of ventilation blocks as an integrated system within tropical residential architecture remain insufficiently investigated. This study examines the hygrothermal performance of ventilation blocks as adaptive climatic buffers in urban housing environments. Four contemporary residential buildings in Surabaya were selected as case studies, representing the hot-humid climatic characteristics of Indonesia. Field measurements were conducted over a continuous 30-day monitoring period using temperature and humidity sensors. The instruments were positioned at a height of 1.5 m above the floor surface. Buffered hygrothermal conditions were successfully achieved within the indoor spaces of the contemporary houses. This environmental condition produced the lowest average indoor temperature (28.1°C), the longest thermal comfort duration (16 hours), and the smallest temperature and humidity fluctuations (2.7°C and 11%). Configurations incorporating high opening ratios and hygroscopic materials demonstrated greater effectiveness in moderating moisture levels. Meanwhile, configurations characterized by moderate opening ratios and material thicknesses generated the most optimal spatial heat propagation performance and the longest cooling duration.

Introduction

The global energy crisis has profoundly influenced both present conditions and future sustainability agendas. Buildings account for nearly one-third of worldwide final energy consumption, emphasizing the urgent necessity for energy-efficient architectural design strategies (Sadeghifam et al. 2015). In tropical countries, the residential sector represents a major contributor to operational energy demand, particularly for cooling purposes. The housing sector accounts for

21.6% of total energy consumption in Malaysia (Jailani et al. 2020) and nearly 50% of total electricity use in Indonesia as of 2016 (Miyamoto et al. 2024). Simultaneously, residential development in Indonesia continues to accelerate, especially within urban centers where contemporary row houses increasingly dominate new housing construction.

Passive cooling strategies that incorporate climate-responsive architectural principles (Noble 2008) significantly improve both energy performance and occupant well-being, thereby supporting the broader objectives of sustainable architecture (Olawale-Johnson, Ajwang, and Ondimu 2021; Oluwatayo and Miracle 2025; Sabina Maritza A P, Mariana, and Suharjanto 2025). The transition toward more sustainable residential practices, including the enhancement of indoor thermal comfort conditions through consideration of air temperature and humidity (hygrothermal conditions), is essential for minimizing operational energy consumption in tropical regions (Tataresteghi, Ismail, and Ishak 2018; Zakiah 2021).

In hot-humid climates, indoor air temperature reduction may also be achieved through the implementation of breathing walls, permeable walls, Trombe walls, porous walls, and breeze or ventilation blocks. Breathing walls constitute envelope systems composed of porous materials that permit either natural or mechanically assisted airflow through the wall assembly (Alongi, Angelotti, and Mazzarella 2017), thereby reducing heat absorption while improving indoor thermal conditions (Taylor and Imbabi 1998). Previous studies have demonstrated that different forms of breathing walls effectively enhance indoor thermal environments and building energy performance. A modular breathing-wall panel composed of a wrapper and dynamic insulation medium was found capable of distributing airflow uniformly (Imbabi 2006), while air-permeable concrete systems were shown to reduce energy consumption and improve indoor air quality (Wong, Glasser, and Imbabi 2007). Furthermore, an innovative hollow-block ventilation wall utilizing vertical air cavities combined with horizontal air inlets successfully reduced indoor air temperatures (Yu et al. 2018). Likewise, exhaust-air insulation walls composed of air-permeable porous materials were capable of minimizing heat accumulation and preventing heat transfer into interior spaces (Zhang et al. 2019).

A ventilation block is a building-envelope component specifically designed to facilitate air exchange, operating similarly to a passive breathing wall by enabling the natural movement of air to improve ventilation performance, enhance indoor air quality, and reduce indoor temperature and humidity levels (Di Giuseppe and D'Orazio 2016). Ventilation blocks play an important role in lowering indoor air temperature and humidity, particularly in hot-humid climatic regions (Nugroho et al. 2020). In Malaysia, their application in public-school buildings demonstrated several advantages, including ease of maintenance, cost efficiency, and environmental sustainability, all of which potentially contribute to improved indoor air quality and thermal comfort (Nordin, Ismail, and Mohd Ariffin 2019). Roster bricks, derived from the Dutch term rooster, meaning lattice, possess hollow geometries that improve airflow and support natural ventilation, thereby enhancing indoor thermal comfort while reducing dependence on mechanical cooling systems (Yuliana et al. 2023). Nevertheless, investigations concerning the performance of ventilation blocks, particularly from a hygrothermal perspective, remain extremely limited despite their increasing application throughout Indonesia and other tropical countries. Consequently, further research examining the diverse characteristics and environmental behavior of ventilation blocks is necessary to optimize thermal comfort performance in contemporary housing.

Previous investigations have evaluated the performance of ventilation blocks through various methodological approaches. Wong, Glasser, and Imbabi (2007) and Fantucci, Serra, and Perino (2015) conducted laboratory-based experiments examining the performance of dynamic ventilation blocks and ventilated opaque double-skin façades under different pressure differentials and permeability conditions to determine their influence on heat-loss reduction and indoor air quality. Ascione et al. (2015) employed computational simulation methods to investigate the performance of insulated ventilation blocks across three distinct climatic zones. A combination of laboratory experiments and numerical simulations was also utilized to evaluate the influence of airflow velocity on thermal equilibrium and penetration time (Alongi, Angelotti, and Mazzarella 2017), as well as to examine the aerodynamic performance of ventilation blocks (ElDin, Abdou, and ElGawad

2016). Existing studies on ventilation blocks remain largely restricted to laboratory prototypes or computational simulations, leaving a significant evidence gap concerning the hygrothermal performance of ventilation blocks under actual conditions within hot-humid urban residential environments.

As a result, architectural design practice continues to lack quantitative guidance regarding appropriate porosity levels and masonry typologies capable of optimizing passive cooling performance without compromising privacy or structural stability. Therefore, this study aims to investigate the hygrothermal performance of ventilation blocks in indoor thermal environments and to formulate a hygrothermal performance index for ventilation blocks as adaptive climatic buffers within contemporary tropical housing in Indonesia based on field measurements.

This study contributes to the understanding of the hygrothermal behavior of ventilation blocks as adaptive climatic buffers in Indonesian contemporary housing under actual environmental conditions. It addresses the limited availability of in-situ measurements and the scarcity of studies conducted within hot-humid climatic contexts, while also providing insights into how different design variables, namely opening ratio, material characteristics, and wall thickness, affect environmental performance.

Methods

Profile of selected houses

Four contemporary houses designed by Andyrahman Architect and functioning as rental boarding houses were selected for field measurements. Each case study implemented different ventilation-block configurations on the façade as part of its passive cooling strategy. Constructed after 2014, all buildings are located in the Keputih Sub-district of Surabaya (7.17°S and 112.48°E), approximately 1.5 meters above sea level. Surabaya experiences a tropical savanna climate characterized by high humidity during the rainy season (December–February) and lower humidity during the dry season (June–September), with wind velocities ranging from 0.1 to 6.3 m/s (Putra et al. 2022). Monthly air temperatures fluctuate between 27.2°C and 30.3°C, particularly during November and April, while relative humidity ranges between 70% and 80%, especially throughout the wet season.

The contemporary houses are surrounded by adjacent residential buildings, as illustrated in figure 1, and are identified in this study as Contemporary House (CH) 1, 2, 3, and 4. These houses exhibit elongated spatial layouts ranging from 15 to 25 meters in depth and relatively narrow frontages between 6 and 12 meters. CH 2–4 is bordered by large open spaces at the rear side of the properties. As presented in table 1, CH 3 and CH 4 possess similar floor areas and building orientations, 150 m² with east- or west-facing orientations, whereas CH 1 and CH 2 have gross floor areas of 120 m² and 240 m², respectively, and both are oriented toward the north and south. CH 1 and CH 2 consist of two stories, while CH 3 and CH 4 are three-story buildings.

Ventilation blocks were implemented in all case-study houses, indicating a strong emphasis on natural ventilation throughout daily occupancy, as illustrated in figure 2. These ventilation blocks were installed primarily on the front façades of the buildings. Figures 3 and 4 present the floor plans and sectional configurations of the case-study houses. All buildings share a uniform floor-to-floor height of 3.7 meters and were constructed using brick masonry and reinforced concrete wall systems.

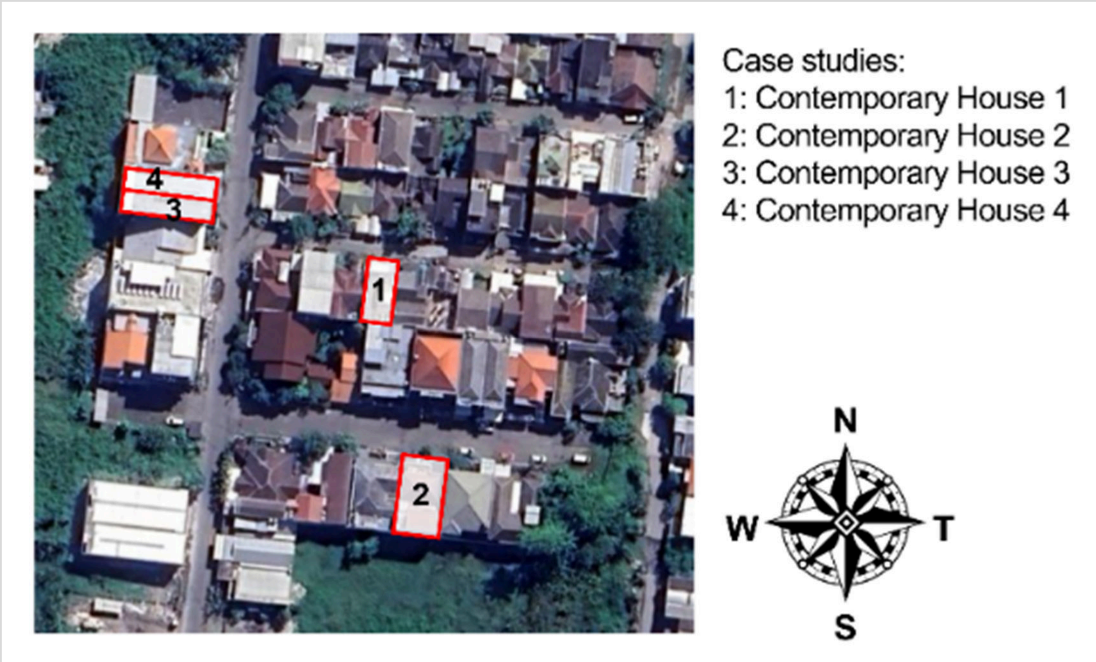


Figure 1. Location of case studies

Ventilation block designs

The four contemporary houses implemented four distinct ventilation-block designs, as illustrated in figure 5. As shown, the ventilation blocks in CH 1 and CH 2 were constructed using concrete and conventional brick materials with opening ratios of 20% and 8%, respectively. The ventilation block in CH 1 possessed a greater wall thickness than that of CH 2, measuring 15 cm and 5 cm, respectively. Furthermore, the ventilation block in CH 1 was installed on the first floor, whereas the ventilation block in CH 2 was positioned on the second floor. In contrast, the ventilation blocks in CH 3 and CH 4 were constructed from the same lightweight concrete material, possessed identical thicknesses of 10 cm, and were installed at similar locations on the second and third floors.

Table 1. The condition of case studies

Name of Building	Orientation	Size of site	Number of Floor	Shading device
CH 1	North-south	8 x 15	2	No
CH 2	North-south	12 x 20	2	No
CH 3 & 4	West-east	6 x 25	3	No

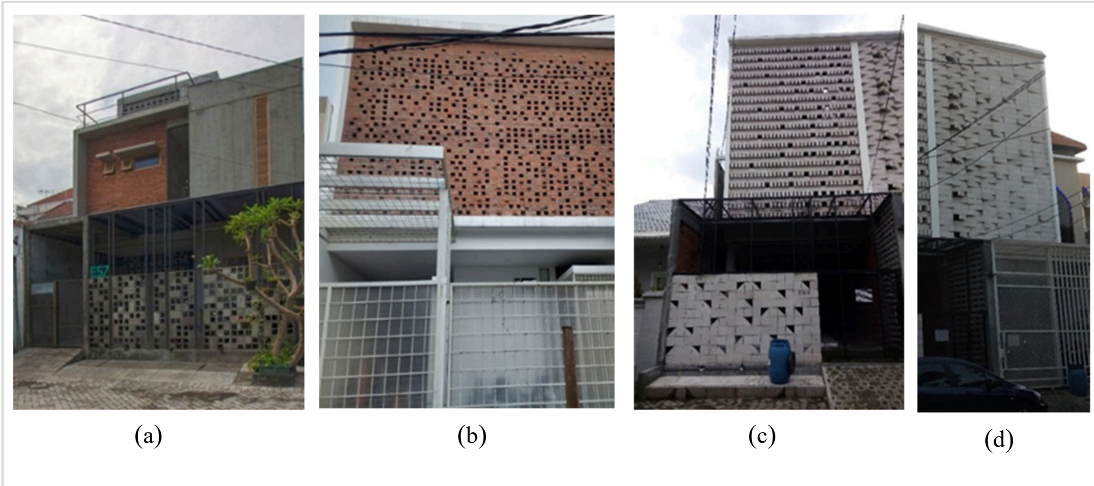


Figure 2. Front exterior view of case studies (a) CH 1; (b) CH 2; (c) CH 3; (d) CH 4

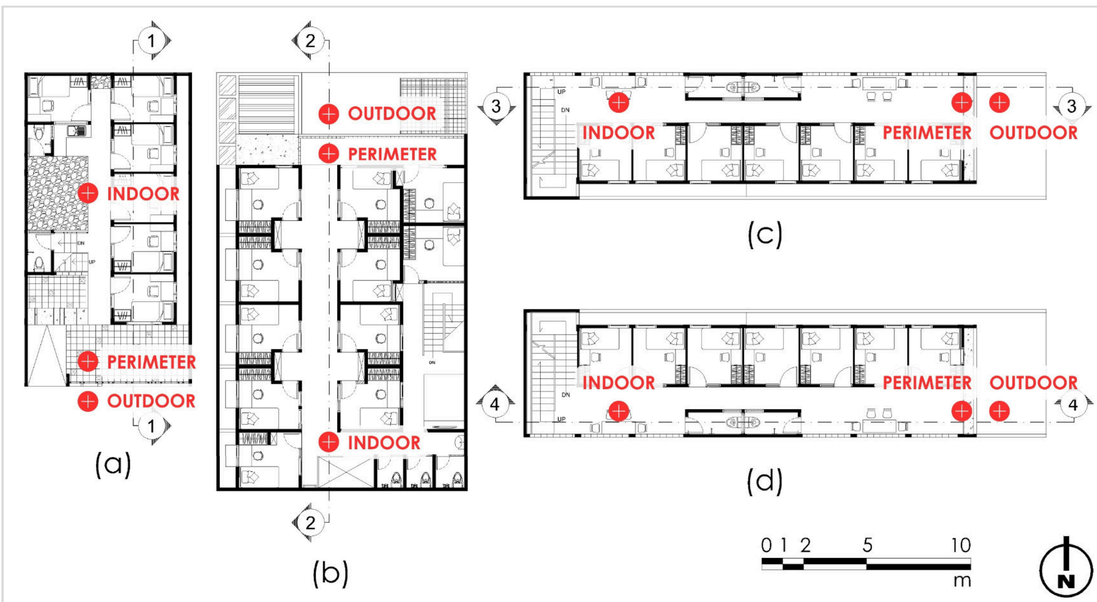


Figure 3. Floor plan and measurement point of case study (a) CH 1; (b) CH 2; (c) CH 3; (d) CH 4

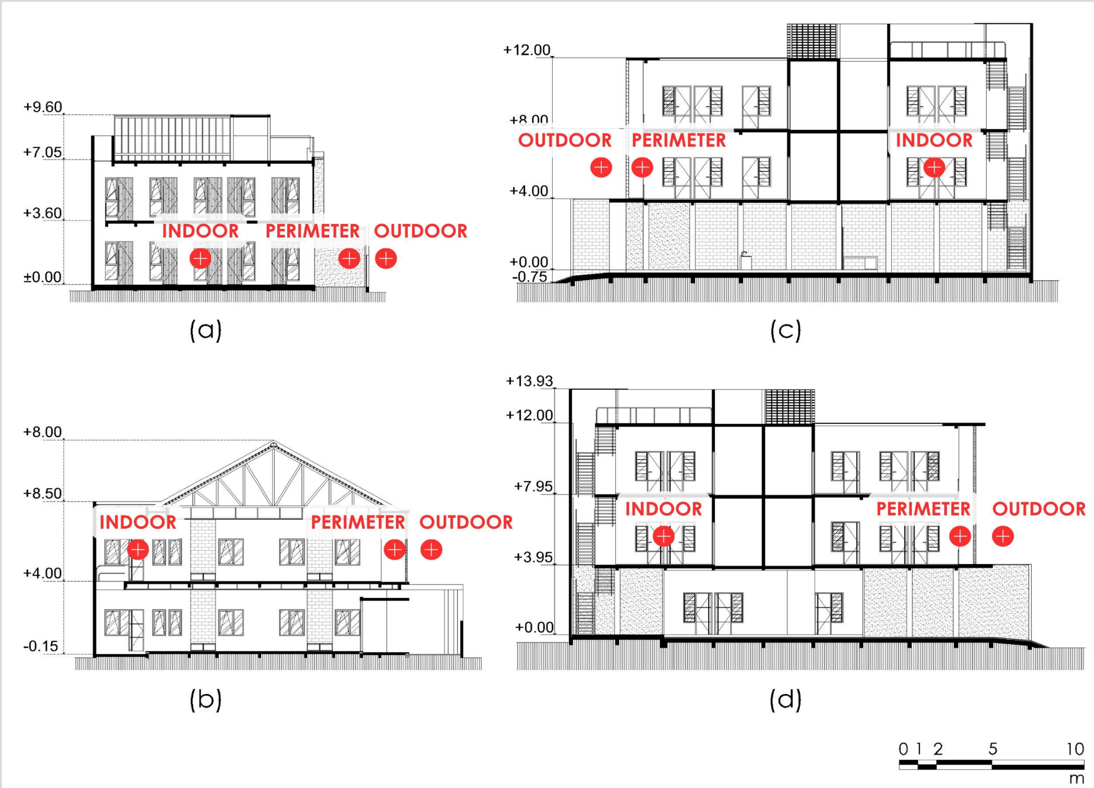


Figure 4. Section plan and measurement point of case study (a) CH 1; (b) CH 2; (c) CH 3; (d) CH 4

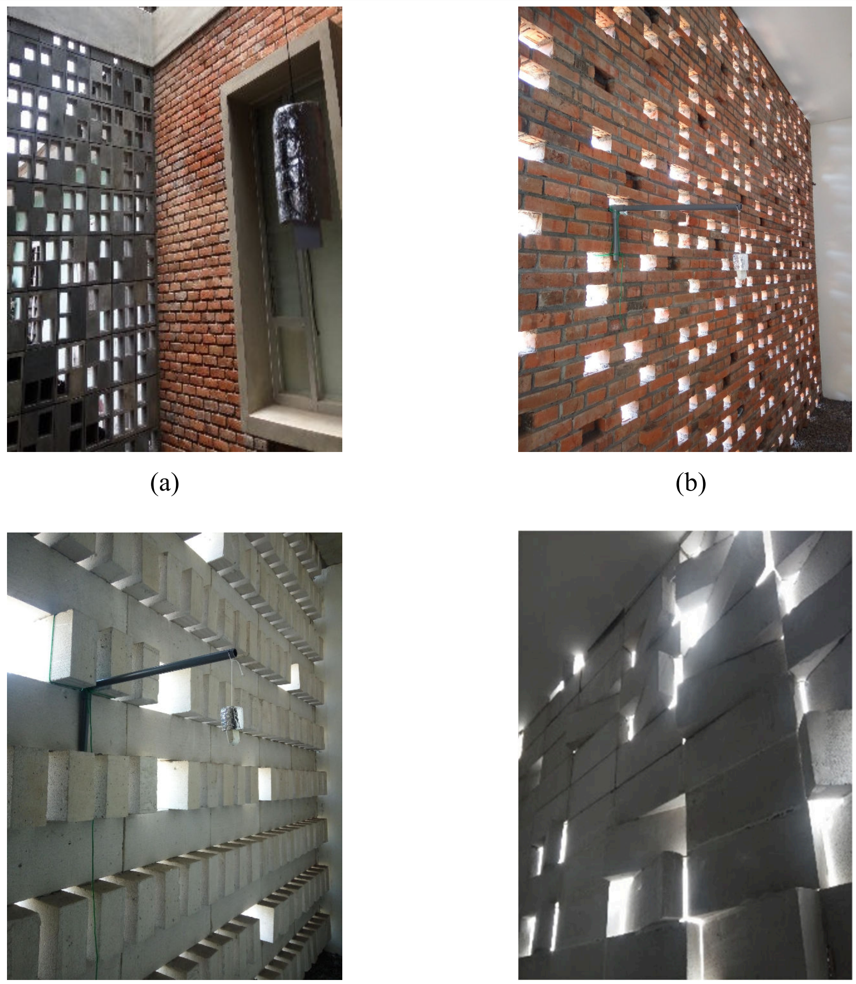
Field measurements and data analyses

Field measurements were conducted continuously and simultaneously over a 30-day period during the dry season (May 2019). Each case-study house was monitored consecutively for 30 days. The data-collection procedures referred to the Indonesian National Standard (SNI) 7061:2019 and ISO 7726. SNI 7061 specifies that thermal-environment measurements must include air temperature and relative humidity as the primary thermal parameters, accompanied by systematic measurement procedures, representative observation points, and calibrated instruments.

The measurement locations are illustrated in figures 3 and 4. Three spatial zones were established for the field measurements: the indoor zone (located at the center of the building), the perimeter zone (positioned inside the façade approximately 75 cm from the ventilation block), and the outdoor zone (located outside the façade approximately 75 cm from the ventilation block). This arrangement enabled the investigation of the hygrothermal performance of the ventilation blocks across the different spatial zones. Bedrooms were excluded from the measurements due to the absence of occupant consent.

Two thermal parameters, namely air temperature and relative humidity, were measured at a height of 1.5 m above floor level, representing the primary activity zone of building occupants according to ISO 7726, as presented in figure 5. Hygrothermal sensors and RC-4HC Elitech data loggers were utilized to record these thermal parameters. The sensors possessed an accuracy of ±0.5°C within a temperature range of -30°C to 60°C, while the data loggers were capable of collecting data continuously and simultaneously. To minimize the influence of direct and reflected solar radiation, the sensors were protected using aluminum-foil shielding cups. Measurements were recorded at one-hour intervals to capture the temporal variations associated with the diurnal cycle.

The field-measurement results were subsequently analyzed quantitatively to examine the relationship between ventilation-block configurations and hygrothermal performance. Variables including ventilation-block opening ratio, material type, orientation, and installation position were considered influential factors affecting the hygrothermal performance of the buildings. Meanwhile, hygrothermal performance was evaluated through several indicators, including air temperature performance (temperature difference, minimum temperature, and maximum temperature), relative humidity performance (humidity difference, minimum humidity, and maximum humidity), time lag, damping ratio, and duration of hygrothermal comfort. Thermal comfort evaluation was conducted using the adaptive thermal comfort standard established by ASHRAE 55.



(a) (b) (c) (d)

Figure 5. Placement of the measurement equipment in (a) CH 1; (b) CH 2; (c) CH 3; and (d) CH 4

Descriptive analysis was employed to evaluate the hygrothermal performance of each house. The results were subsequently compared using several performance indicators, including cooling effect (CE), moisture effect (ME), spatial propagation effect (SPE), and damping ratio (DR), to investigate the hygrothermal influence of ventilation blocks on environmental performance (see equations 1–5).

$$CE = T_{out} - T_{in} \quad (1)$$

$$ME = RH_{out} - RH_{in} \quad (2)$$

$$SPE = T_{peri} - T_{in} \quad (3)$$

$$DR_t = \frac{\Delta T_{in}}{\Delta T_{out}} \quad (4)$$

$$DR_{rh} = \frac{\Delta RH_{in}}{\Delta RH_{out}} \quad (5)$$

where T_{in} and T_{out} are indoor air temperature (°C) and outdoor air temperature (°C), respectively.

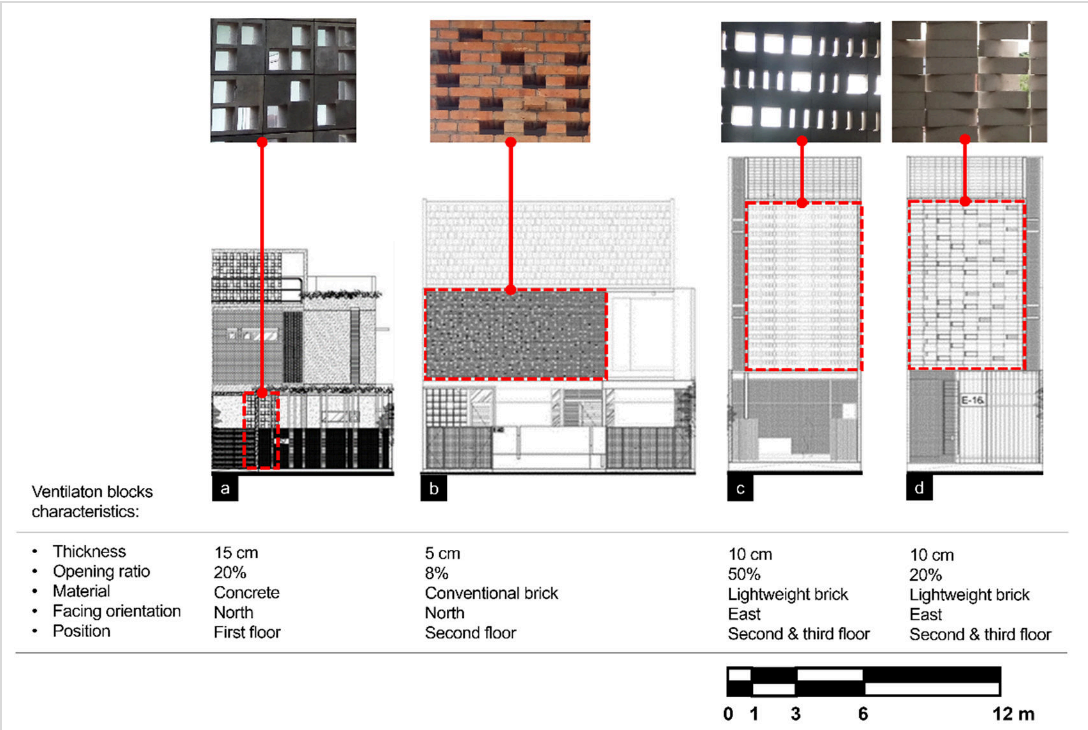


Figure 6. The Ventilation block design characteristics of case studies

Results and discussion

Ventilation Block Design Analysis

In terms of opening ratio, CH 1 and CH 4 (10–20%) demonstrated greater suitability than CH 2 and CH 3. Regarding material characteristics, CH 3 and CH 4 exhibited superior performance because they utilized lightweight bricks with lower thermal conductivity. From the perspective of orientation, CH 3 and CH 4 were considered more advantageous because, in the southern hemisphere, east-facing façades receive lower cumulative solar-radiation exposure compared to north-facing façades. In terms of installation position, the elevated placement implemented in CH 3 and CH 4 enhanced their performance because airflow intensity generally increases with building height. Based on the visual analysis, the most effective ventilation-block design was achieved by CH 4.

Hygrothermal condition and ventilation block contribution in case contemporary tropical housing

A passive-design analysis of the four case studies was conducted to evaluate the suitability of the ventilation-block configurations in reducing indoor air temperature. The assessment criteria included opening ratio, material characteristics, orientation, and installation position, as presented in figure 6.

The hygrothermal conditions and the contribution of ventilation blocks across the four contemporary tropical-house case studies reveal a distinct gradient of environmental performance. CH 4 demonstrated the most favorable overall performance, as indicated by the lowest mean indoor air temperature (28.1°C), the longest duration within the thermal comfort range at 16 hours (figure 7d), the smallest daily fluctuations in temperature and relative humidity at 2.7°C and 11%, respectively, and the lowest temperature standard deviation at 0.878°C (table 2). In contrast, CH 2 recorded the lowest mean relative humidity (65.8%); however, it also exhibited the shortest duration within the comfortable relative-humidity range, lasting only 5 hours (figure 7b).

This finding suggests that its configuration possessed limited capability to maintain stable hygrothermal comfort conditions. CH 1 exhibited the highest mean relative humidity (80.4%) and the greatest daily relative-humidity fluctuation (15.2%), although it still provided a relatively favorable thermal comfort duration of 14 hours (figure 7a). In CH 3, increasing the opening ratio to 50% while maintaining the same material and wall thickness improved moisture dissipation performance. Nevertheless, this condition simultaneously intensified temperature fluctuations and reduced the duration of thermal comfort (figure 7c). These findings indicate a clear trade-off between ventilation effectiveness and hygrothermal buffering capacity.

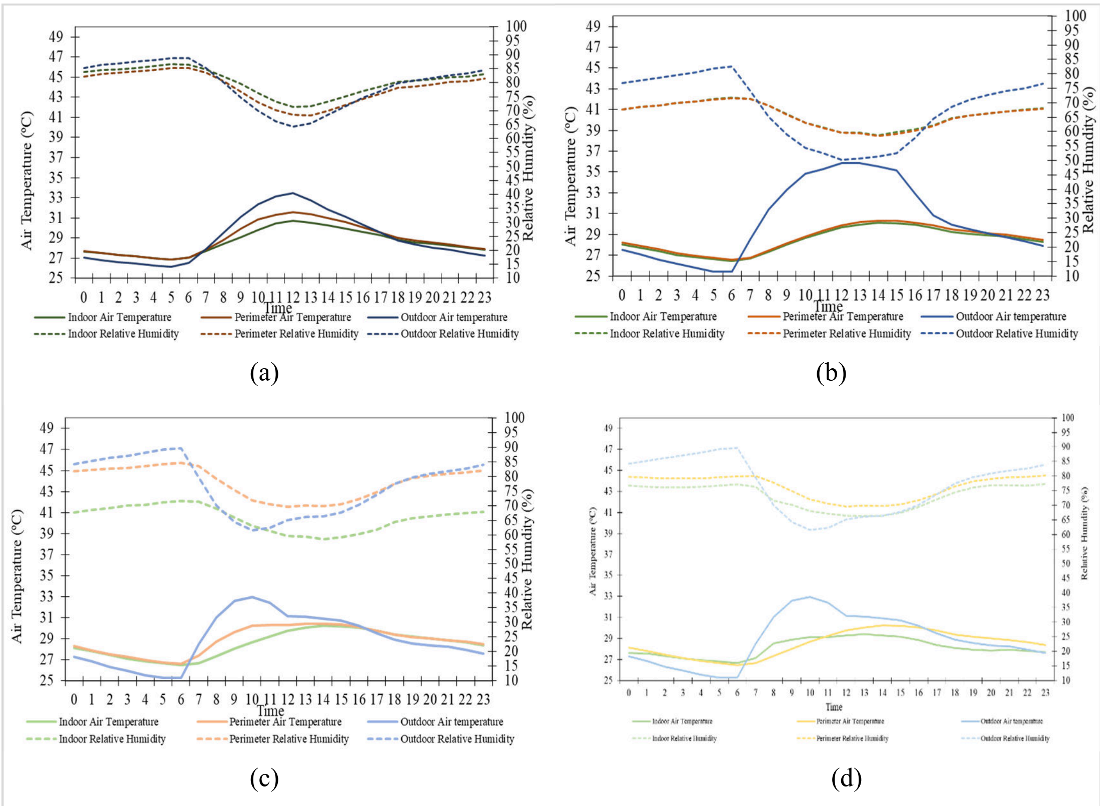


Figure 7. Temporal variations of air temperature and relative humidity in indoor, perimeter and outdoor at 1.5 m above the floor with the corresponding contemporary housing: a) CH 1, b) CH 2, c) CH 3, d) CH 4

Table 2. Hygrothermal condition of the corresponding contemporary housing

	CH 1 (20%; Concrete;15cm)	CH 2 (8%; brick; 5cm)	CH 3 (50%; light brick;10cm)	CH 4 (50%; light brick;10cm)
Mean T	28.6	28.4	28.5	28.1
Mean RH	80.4	65.8	65.7	73.2
Duration of comfortable T	14	12	12	16
Duration of comfortable RH	9	5	9	9
Daily range T	3.9	3.7	3.8	2.7
Daily range RH	15.2	12.9	13.1	11
Attenuation T	1.233	1.2	1.232	0.878
Attenuation RH	4.841	4.206	4.3	4.258

Overall, these patterns demonstrate that the most effective ventilation-block configuration is not simply characterized by high thermal mass or a large opening ratio, but rather by its capacity to achieve equilibrium between heat control, moisture dissipation, and the attenuation of daily environmental fluctuations. Studies by Ding, Rasmussen, and Qin (2024) and Larcher et al. (2025) similarly indicate that the ability of materials to reduce indoor humidity fluctuations is strongly influenced by material thickness and moisture absorption–desorption capacity. Accordingly, the most effective ventilation block is one that operates simultaneously as both a thermal buffer and a moisture buffer, rather than merely functioning as a passive ventilation component. The incorporation of ventilation blocks into breathing architectural systems contributes to improved energy efficiency and enhanced thermal comfort, as emphasized in studies concerning indoor environmental quality (Antczak-Jarząbska and Niedostatkiewicz 2018; Fauzi, Al-Athas, and Rini 2024; Park, Kim, and Yoon 2016).

Ventilation block moderation effect in case contemporary tropical houses

The influence of ventilation blocks on hygrothermal comfort in Indonesian contemporary tropical houses demonstrates the presence of an adaptive climate-buffer mechanism operating through a balance between sensible-heat moderation and water-vapor regulation, as illustrated in table 3 and figure 8. Empirical findings from the four case-study houses indicate that optimum cooling moderation was achieved through a small-opening configuration combined with relatively thin material layers, as observed in CH 2. This configuration produced the highest mean cooling effect of 1.87°C, maintained cooling for 14 hours, and generated the lowest temperature damping ratio of 0.327. In contrast, optimum moisture moderation occurred in the large-opening configuration utilizing thicker and more hygroscopic materials, as observed in CH 3, which recorded a mean moisture effect of 11.16% with a duration of 22 hours. Meanwhile, the intermediate configuration implemented in CH 4 demonstrated the most balanced overall performance, particularly in terms of spatial propagation effect at 0.39°C and the longest cooling duration at 16 hours. The influence of opening ratio indicates that increasing the opening ratio from 20% to 50% strengthened the coupling between indoor and outdoor environments, thereby accelerating water-vapor exchange, as reflected in the increase in moisture effect from 3.66% to 11.16%. However, this condition simultaneously reduced the temperature-damping capability, as indicated by the decline in cooling effect from 0.77°C to 0.38°C and the increase in temperature damping ratio from 0.37 to 0.52.

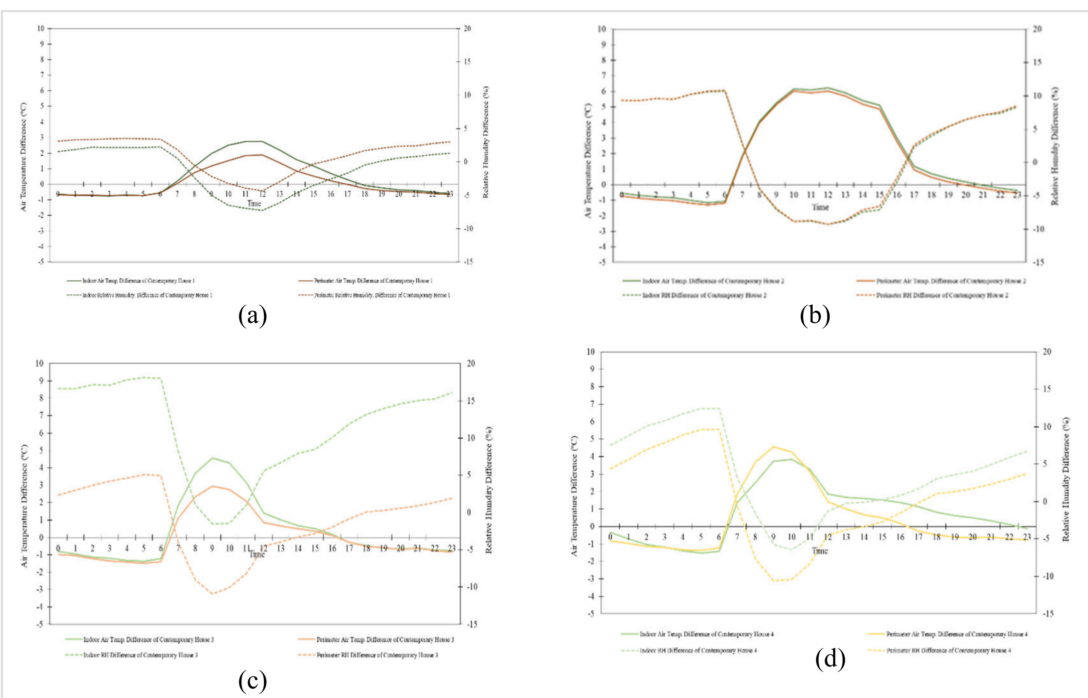


Figure 8. Temporal variations of air temperature and relative humidity reduction in indoor and perimeter at 1.5 m above the floor with the corresponding contemporary housing: a) CH 1, b) CH 2, c) CH 3, d) CH 4

Table 3. Hygrothermal moderation effect of the corresponding contemporary housing

	CH 1 (20%; Concrete;15cm)	CH 2 (8%; brick; 5cm)	CH 3 (50%; light brick;10cm)	CH 4 (50%; light brick;10cm)
Mean Cooling effect (CE)	0,43°C	1,87°C	0,38°C	0,77°C
Duration CE (hours)	11	14	10	16
Mean Moisture Effect (ME)	1,16%	2,04%	11,16%	3,66%
Duration ME (jam)	11	15	22	17
Mean Spatial propagation effect (SPE)	0,33°C	0,18°C	0,36°C	0,39°C
Duration SPE (jam)	19	24	23	18
Damping ratio temperature (DRT)	0,51	0,327	0,52	0,37
Damping ratio Relative Humidity (DRRH)	0,60	0,371	0,46	0,45
Effectiveness of Cooling moderation	2,21-2,75°C	5,1–6,2°C	4,00°C	2,82–3,62 °C
Effectiveness of Moisture moderation	2,15-2,27%	10,2–10,7%	17,99%	12,6-13,7%.

Furthermore, the influence of ventilation-block thickness indicates that thinner wall elements measuring 5 cm were more responsive in attenuating temperature fluctuations, whereas intermediate thicknesses of 10 cm were more effective in extending both the duration and propagation of the moderation effect. Conversely, greater thicknesses, represented by the 15 cm concrete configuration, did not automatically improve performance due to the limited hygroscopic properties of the material.

Based on the mean Cooling Effect and its duration, ventilation blocks exhibit greater effectiveness when the opening ratio is maintained at a moderate level rather than excessively enlarged. Moderate openings are sufficient to facilitate airflow and dissipate heat while still maintaining resistance against excessive heat gain. Simultaneously, the mean Moisture Effect and its duration are more strongly influenced by material porosity and opening dimensions. The results obtained from CH 3 demonstrate that a 50% opening ratio combined with 10 cm lightweight brick is highly effective in enhancing moisture exchange. Meanwhile, the highest mean Spatial Propagation Effect was observed in CH 4 (0.39°C), whereas the longest duration of Spatial Propagation Effect was recorded in CH 2 (24 hours). These findings indicate that the distribution of the moderation effect is not determined solely by opening size, but rather by the interaction among opening ratio, material characteristics, and wall thickness. Larger openings accelerate environmental exchange within the perimeter zone, although they do not necessarily extend stable cooling distribution into the deeper indoor zone.

Discussions

Visual observations indicate that CH 4 possesses the most favorable design parameters in terms of wall thickness, opening ratio, material selection, orientation, and installation position. These findings are consistent with previous studies demonstrating that the effectiveness of airflow transmission through porous materials depends on thermal conductivity, panel dimensions, and suction pressure (Craig and Grinham 2017). Another study reported that insulated air-duct systems could reduce total daily heat gain by 84.7%, with optimal thermal performance achieved through larger porous layers (J. Wang et al. 2018). This suggests that ventilation-block thickness may significantly influence the building’s capacity to retain and moderate heat. The field-measurement results and visual observations were subsequently compared to verify the effect of ventilation blocks on temperature reduction.

The evaluation of the four contemporary tropical houses indicates that the performance of ventilation blocks as adaptive climate buffers depends on the combined interaction among opening ratio, material characteristics, and wall thickness rather than on a single design parameter. Moderate openings are more effective as climatic buffers because they balance ventilation performance with thermal protection (Tong et al. (2021); Tong et al. (2019), while porous wall systems are capable of reducing indoor air temperatures by up to 5.6°C(Ascione et al. 2015; ElDin, Abdou, and ElGawad 2016).

Lightweight brick demonstrated the most effective performance because its lower thermal conductivity reduced heat transfer while maintaining more stable environmental fluctuations. This differs from thick concrete materials which, despite possessing high thermal inertia, were not automatically effective in controlling humidity conditions. High thermal mass effectively attenuates temperature fluctuations; however, it is less optimal for regulating moisture within humid tropical climates. This finding is consistent with (F. Li et al. 2021), who emphasized that moisture transfer significantly influences the thermal performance of wall systems. Alongi et al. further noted that reducing thermal capacity can improve the performance of low-thermal-conductivity porous walls (Alongi, Angelotti, and Mazzarella 2017). Similar findings were identified in studies employing hollow-wall systems, which also demonstrated improved performance associated with low thermal conductivity (Yu et al. 2018).

Meanwhile, the wall-thickness analysis indicates that optimum performance was not achieved by the thickest wall configuration, but rather through an intermediate thickness appropriately matched to the material characteristics. This finding supports Neya et al. (2021) and Cascione et al. (2021), who emphasized that the ability of materials to absorb and release water vapor, commonly referred to as moisture buffering, together with thermal delay response, constitutes a critical factor in controlling hygrothermal conditions. Furthermore, the coupled interaction between heat and moisture transfer has also been emphasized by Y. Wang et al. (2022). Therefore, an effective ventilation block functioning as an adaptive climate buffer is one capable of balancing thermal mass, moisture buffering, and ventilation control rather than merely maximizing a single performance parameter. This finding aligns with Gupta and Deb (2023), who emphasized the importance of combining insulating materials with appropriate opening ratios to improve thermal-envelope performance within tropical climates. Comparatively, solid walls incorporating openings may contribute to airflow and passive cooling performance; however, their effectiveness strongly depends on opening design and window-to-wall ratio (J. Li et al. 2021; H. Wang, Zhou, and Tang 2025).

Based on the Temperature Damping Ratio (DRT) and Relative Humidity Damping Ratio (DRRH), CH 2 exhibited the most stable configuration in both thermal and hygrometric performance. This finding reinforces the notion that hygrothermal comfort is determined not solely by mean temperature and relative-humidity values, but also by the ability of building elements to attenuate the amplitude of daily environmental fluctuations. This observation is consistent with Ding, Rasmussen, and Qin (2024), who demonstrated that moisture-buffering capacity is strongly influenced by the effective thickness of materials. The damping-ratio values (DRT 0.32–0.52; DRRH 0.37–0.60) indicate significant attenuation of fluctuation amplitudes, while the observed time lag, ranging from nearly zero to 3–4 hours, suggests that material configuration and thermal mass particularly thick concrete govern phase-shift behavior, as similarly reported in studies concerning thermal mass and phase-shift performance in tropical climates (Ascione et al. 2015). The positive spatial-propagation effect observed across all case studies confirms the existence of a heat-retention mechanism within the perimeter zone before heat reaches the core indoor space, which is consistent with the concept of a transitional thermal layer (Zhang et al. 2019).

Ventilation blocks may therefore be optimized within two principal performance modes. First, they may function as sensible thermal buffers to reduce daytime heat gain and peak indoor temperatures through the use of smaller openings combined with brick materials. Second, they may operate as latent moisture buffers to reduce excessive humidity through larger openings combined with hygroscopic lightweight-brick materials. Overall, the most balanced configuration for achieving hygrothermal comfort appears to consist of a moderate opening ratio of approximately 20%, lightweight hygroscopic materials, and an intermediate thickness of approximately 10 cm. Accordingly, ventilation blocks should be understood not merely as passive ventilation components, but rather as adaptive climatic buffers whose performance emerges through the optimization of material properties, opening ratio, and wall thickness.

Conclusions

This study addresses the research questions concerning diurnal hygrothermal behavior, the influence of ventilation blocks on hygrothermal comfort, and the hygrothermal performance index of ventilation blocks functioning as adaptive climate buffers in contemporary tropical housing in Indonesia. The findings confirm that the primary role of ventilation blocks is to function as moderating buffer elements that create integrated buffered zones, particularly within indoor environments. The hygrothermal conditions observed in contemporary tropical houses demonstrated significant variations in performance. CH 4 achieved the best overall performance, characterized by the lowest mean temperature of 28.1°C, the longest thermal-comfort duration of 16 hours, and the smallest temperature and humidity fluctuations at 2.7°C and 11%, respectively. The contribution of ventilation blocks was not determined by a single design variable, but rather through the interaction among opening ratio, material characteristics, and wall thickness. A lightweight-brick configuration with a thickness of 10 cm and an opening ratio of 20% produced the most optimal hygrothermal stability.

Ventilation systems improve hygrothermal comfort by achieving a balanced interaction between sensible heat moderation and moisture regulation. Optimal cooling performance is attained through configurations with smaller openings and thinner material assemblies, which generate a cooling effect of 1.87°C, sustain a duration of 14 hours, and yield a temperature damping ratio of 0.327. In contrast, optimal moisture regulation is achieved through configurations with larger openings and hygroscopic materials, resulting in a moisture effect of 11.16% over a 22-hour duration. A moderate configuration, approximately a 20% opening ratio combined with 10 cm lightweight brick, exhibits the most balanced overall performance, producing a spatial propagation effect of 0.39°C and maintaining a cooling duration of 16 hours. An increase in the opening ratio from 20% to 50% enhances moisture regulation capacity, as reflected in the rise of the moisture effect from 3.66% to 11.16%; however, this adjustment simultaneously reduces cooling performance, with the cooling effect decreasing from 0.77°C to 0.38°C, while also increasing the temperature damping ratio from 0.37 to 0.52. Consequently, the most effective ventilation-block configuration is not defined by maximizing a single parameter, but rather by achieving an optimal equilibrium between cooling performance, humidity stability, and the spatial distribution of hygrothermal moderation effects.

Acknowledgments

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