Sainteknol Vol 23, No 2 (2025): December 2025

https://journal.unnes.ac.id/journals/sainteknol

Performance of Natural Ventilation in Residential Buildings under Different Opening Conditions

Fisa Savanti*, Hari Utama, Hanif Ardhiansyah

Universitas Negeri Semarang, Indonesia

*Corresponding Author: fisa.savanti@mail.unnes.ac.id

Abstract

Natural ventilation is widely applied in tropical residential buildings to improve indoor environmental quality and reduce cooling energy demand. However, increasing opening size does not always proportionally enhance ventilation performance. This study aims to experimentally determine the relationship between inlet opening variation and natural ventilation performance in a residential test room (6.0 m × 2.5 m × 3.5 m; 52.5 m^3) oriented along the Southwest–Northeast axis. The investigation was conducted by measuring variations in indoor air velocity, temperature, relative humidity, and estimating the air change rate (ACH) under different inlet opening conditions. The inlet door opening was varied from 20% to 100%, while the outlet door remained fully open. Results indicate a non-linear relationship between opening variation and ventilation performance. Indoor air velocity increased from 0.09 m s^{-1} at 20% opening to a maximum of 0.11 m s^{-1} at 60%, then decreased at larger openings. ACH followed a similar trend, peaking at the intermediate configuration. Temperature differences remained minimal, confirming the dominance of wind-driven airflow, while relative humidity varied with airflow distribution and dilution effects. The findings suggest that moderate inlet openings may provide more efficient ventilation than fully open configurations in tropical residential buildings.

Keywords: natural ventilation; opening variation; air change rate; wind-driven airflow; tropical housing

INTRODUCTION

Natural ventilation remains a primary passive strategy to improve indoor environmental quality and reduce building operational energy, particularly in tropical residential buildings where cooling loads are high. Standards and guidance increasingly acknowledge natural ventilation as a viable design option when climate, building form, and occupant behavior are considered together. The thermal and airflow parameters that determine occupant comfort—air temperature, relative humidity, and air speed are explicitly recognized as interacting factors in international standards and design guides (Ashrae, 2023).

The effectiveness of natural ventilation is controlled by multiple interacting drivers, including wind-induced pressure differences, thermal buoyancy, opening geometry, and the relative positions of inlet and outlet openings. Recent experimental and numerical studies demonstrate that opening size and position do not yield a strictly monotonic improvement in ventilation performance; instead, airflow patterns, jet formation, and flow dispersion yield nonlinear responses to opening configuration. Such non-linear behavior implies that larger openings are not always synonymous with improved volumetric ventilation or local airspeed at occupied locations(Q. Li et al., 2023; Moey et al., 2022).

Although numerous computational studies and wind-tunnel experiments have explored the fluid mechanics of cross-ventilation and opening effects, field-based measurements that capture real environmental variability remain comparatively limited. Field investigations are essential because they integrate environmental variability (wind gustiness, microclimate, and transient thermal conditions) and occupant operation patterns that simplified numerical setups may not reproduce. Recent field and applied studies thus underscore the need for realistic, in-situ evaluation of ventilation strategies, particularly in the tropics, where the relative importance of wind-driven versus buoyancy-driven mechanisms may shift diurnally(Seol et al., 2023).

A common simplification in prior experimental work is simultaneous variation of both inlet and outlet openings or use of idealized boundary conditions, which limits the ability to isolate the aerodynamic role of a single opening. In practical residential operation, occupants frequently adjust only the inlet (e.g., window) while outlets such as vents or eaves remain fixed or fully open. The isolated effect of inlet opening variation on airflow development, velocity distribution, moisture transport, and volumetric exchange, therefore, remains an important but under-examined question. Recent numerical and laboratory studies indicate that paired configurations (e.g., small inlet with large outlet) can sometimes enhance ventilation rates, suggesting that inlet sizing alone may be a practical control variable worth examining under field conditions(Moey et al., 2021).

Furthermore, many studies characterize ventilation using a single metric—commonly local airspeed or simulated flow rate—without concurrently assessing thermal interactions and moisture transport. For design-relevant conclusions in tropical environments, integrated metrics that combine air velocity, indoor/outdoor temperature differentials, relative humidity behavior, and estimated air change rate (ACH) provide a more robust basis for evaluating occupant comfort and latent cooling implications. Recent research and natural-ventilation classification frameworks advocate using ACH and combined comfort indices alongside local airflow measures to inform early design decisions(W. Li et al., 2024).

This study experimentally evaluates natural ventilation in a residential room under controlled variation of inlet opening variation (20–100%) while the outlet was maintained fully open throughout the measurement period. Field measurements of indoor air temperature, relative humidity, and local air velocity were recorded together with representative outdoor climatic parameters. From these measurements, we estimate ACH (using measured indoor velocity and effective inlet area) and analyze the interrelationships among ΔT (outdoor–indoor temperature difference), indoor velocity, humidity transport, and ACH. The measurement protocol and analysis are designed to reflect realistic occupant operation, specifically, the common case of varying inlet opening while leaving the outlet fully open, thus providing practical design insight for tropical residential ventilation.

Our results demonstrate a non-linear relationship between inlet opening variation and ventilation performance metrics: ACH and local indoor velocity increase with opening up to an intermediate variation (observed at ~60% inlet opening), after which further increases in inlet area reduce local airspeed and ACH due to flow dispersion and reduced volumetric efficiency. Investigating optimal inlet opening size and configuration is important because ventilation performance does not necessarily increase with larger openings, and understanding this relationship is critical for improving passive cooling and humidity control in tropical residential buildings. These field-based observations complement recent numerical and experimental work and should inform both designers and occupants when selecting window operation strategies in tropical climates.

METHOD

Experimental Room and Opening Configuration

The study was conducted in a naturally ventilated residential test room with internal dimensions of 2.5 m × 6.0 m × 3.5 m (H), corresponding to a total volume of 52.5 m³ (see Figure 1). The building openings are aligned along the Southwest–Northeast axis, with the inlet door positioned on the Southwest façade and the outlet door on the Northeast façade, and the primary airflow direction is SW–NE. The inlet opening consisted of a rectangular aperture measuring 0.9 m × 2.1 m, resulting in a maximum effective opening area (A_{max}) of 1.89 m². This maximum area was defined as the reference opening from which the tested inlet opening variations (20%, 40%, 60%, 80%, and 100%) were derived. The outlet opening remained fully open (100%) throughout all measurements to isolate the aerodynamic influence of inlet opening variation. Controlling only one opening while keeping the other fixed is recommended to evaluate opening-specific airflow effects and avoid confounding flow interactions (Ashrae, 2023; Etheridge D., 1996).

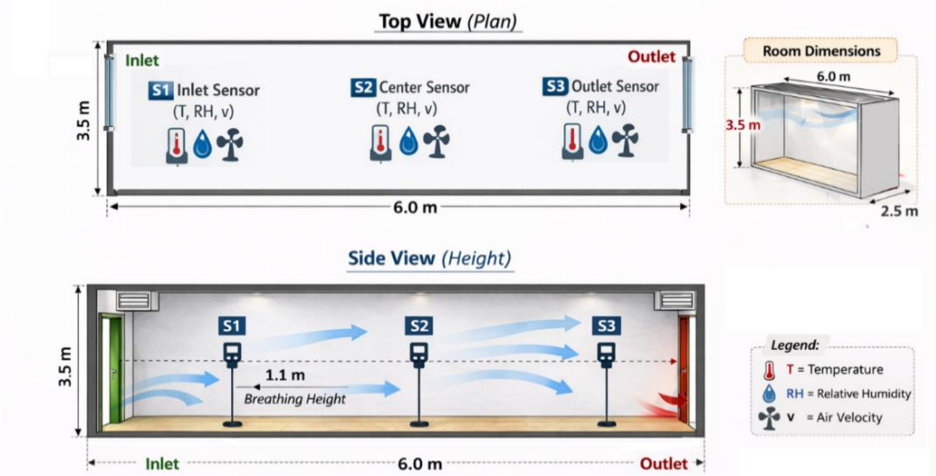

Figure 1. Experimental Setup and Sensor Positioning

Instrumentation

Indoor environmental parameters measured included air temperature (T), relative humidity (RH), and air velocity (v). Measurements were conducted using calibrated environmental monitoring instruments that met international field measurement standards (Hodder & Igor Palella, 2024).

Parameter	Instrument type	Typical accuracy
Temperature	Digital thermo-logger	±0.5 °C
Relative Humidity	Hygrometer sensor	±3% RH
Air velocity	Hot-wire anemometer	±0.01–0.03 m/s

Low-velocity sensors were used because airflow in naturally ventilated indoor environments typically ranges from 0.02 to 0.30 m/s, requiring high-resolution measurement capability. Outdoor environmental parameters (T_out, RH_out, v_out) were simultaneously measured using a portable weather station placed at an unobstructed upwind location. Concurrent outdoor monitoring is necessary because natural ventilation is directly driven by external boundary conditions such as wind speed and temperature gradients.

Sensor Placement

Indoor sensors were installed at breathing height (1.1 m above floor level) at three representative locations: inlet zone, room center, and outlet zone. This height corresponds to the standard occupant exposure level defined in international indoor environmental measurement protocols (Hodder & Igor Palella, 2024). Multi-point measurement is recommended in natural ventilation studies because airflow distribution inside rooms is spatially non-uniform and influenced by jet formation and recirculation patterns (Karava & Stathopoulos, 2011).

Measurement Procedure

Each inlet opening configuration was tested for 120 minutes, with measurements recorded at 0, 30, 60, 90, and 120 minutes. Time-resolved monitoring was adopted because airflow and indoor environmental parameters in naturally ventilated spaces typically undergo transient adjustment before approaching quasi-steady conditions. Data logging from all sensors was synchronized to ensure temporal consistency across variables. Indoor heat and moisture sources were minimized, and occupant activity was restricted to sedentary conditions to maintain a realistic yet controlled residential operation. Maintaining stable internal boundary conditions is recommended in ventilation experiments to isolate the influence of opening configuration on airflow behavior. Measurement uncertainty was estimated using standard error propagation of velocity and opening area measurements, a commonly applied approach in experimental airflow studies.

Calculation of Air Change Rate (ACH)

The volumetric airflow rate entering through the inlet was estimated as:

$$Q = C_d \times Av$$

The air change rate (ACH) was calculated using:

$$ACH = \frac{Q \times 3600}{V}$$

In this study, a discharge coefficient (Cd) of 1.0 was assumed for comparative analysis, as the objective was to evaluate relative performance trends rather than absolute ventilation rate accuracy. This approach is commonly applied in field-based comparative ventilation studies when tracer-gas methods are not feasible. This velocity–area method is widely applied in experimental ventilation studies when tracer-gas techniques are impractical and is considered acceptable for comparative performance analysis.

RESULTS AND DISCUSSION

The field measurement results for different opening scenarios are summarized in Table 1.

Table 1. Indoor environmental parameters under different opening conditions

Inlet Opening Variation (%)	Outdoor condition			Indoor condition		
	T_out (°C)	RH_out (%)	v_out (m/s)	T_in (°C)	RH_in (%)	v_in (m/s)
20%	30.4	83.4	0.21	30.4	81.8	0.09
40%	**30.3**	**84.6**	**0.29**	**30.2**	**84.2**	**0.10**
60%	30.2	85.9	0.37	30.0	86.4	0.11
80%	**30.6**	**82.5**	**0.34**	**30.6**	**82.1**	**0.06**
100%	31.0	76.1	0.31	31.1	78.7	0.03

Overall Environmental Conditions and Temporal Behavior

Tropical daytime boundary conditions in this study (T ≈ 30.2–31.0 °C, RH ≈ 76–86%, wind speed 0.21–0.37 $m \cdot s^{-1}$) are consistent with reported field conditions for humid tropical urban areas and are appropriate for wind-driven ventilative assessments. Field investigations emphasize that when ambient conditions remain quasi-stationary, the influence of architectural variables (e.g., opening variation) on interior airflow can be separated from meteorological noise; conversely, large fluctuations in wind speed or direction can dominate or confuse results, particularly in low-rise residential contexts typical of tropical cities(Handayani et al., 2024).

The observed transient adjustment—larger variability during the first ~60 minutes followed by gradual stabilization—is consistent with tracer-gas and field monitoring studies that document the time required for a room to undergo multiple air exchanges and reach a new quasi-steady state after a change in boundary conditions. Tracer-decay experiments and recent methodological reviews demonstrate that equilibration time depends on room volume, ventilation rate (ACH), and internal mixing; therefore, allowing sufficient stabilization time or averaging over several exchange cycles is necessary to obtain representative ventilation metrics(Remion et al., 2019).

For comparative evaluation of opening configurations, time-averaged metrics (e.g., 30-minute or longer block means) are recommended because they filter out high-frequency turbulence and gust-induced variability that do not represent the sustained ventilation regime. Practical field protocols and recent methodological studies provide guidance on averaging windows and on the use of complementary methods (e.g., tracer-gas decay vs. velocity×area estimates) to cross-validate ACH estimates under quasi-steady conditions. Adopting such standardized averaging and cross-validation approaches increases the robustness and reproducibility of in-situ natural ventilation assessments(Choi & Song, 2020).

Effect of Inlet Opening Variation on Indoor Air Velocity

Indoor air velocity exhibited a non-linear relationship with inlet opening variation, rising from 0.09 $m\ s^{-1}$ at 20 % opening to a peak of 0.11 $m\ s^{-1}$ at 60 %, then decreasing at 80 % and 100 % despite increased opening area. This pattern reflects the competing effects of flow concentration and pressure redistribution in naturally ventilated spaces; when the inlet is moderately sized, incoming airflow accelerates due to contraction effects, generating a focused jet that penetrates deeply and enhances local airflow rates. Such behavior has been observed in experimental and numerical studies showing that moderately sized openings can induce higher localized velocities than very large openings, due to stronger momentum concentration and favorable pressure gradients at the opening(Demir & Aktepe, 2025a). To account for external wind variability, the ratio between indoor and outdoor velocity (v_in/v_out) was evaluated. The ratio showed a decreasing trend beyond the 60% opening variation, supporting the interpretation that the observed optimum was not solely due to higher outdoor wind speed but to aerodynamic effects associated with the inlet geometry.

When the inlet opening becomes excessively large, the aerodynamic advantage of contraction is lost, and the airflow tends to disperse over a wider cross-section, leading to lower local velocity readings within the occupied zone. Computational investigations of opening size effects also demonstrate that increasing the inlet beyond an optimal range can raise indoor pressure and reduce flow acceleration, thereby weakening the velocity field within the space. This phenomenon is consistent with Bernoulli's principle, where pressure and velocity are inversely related in a flow field; a larger opening reduces contraction, raises static pressure near the inlet, and diminishes the driving pressure difference for accelerated flow. Therefore, opening size alone does not determine airflow intensity; the distribution of pressure and the resulting momentum transfer are critical.

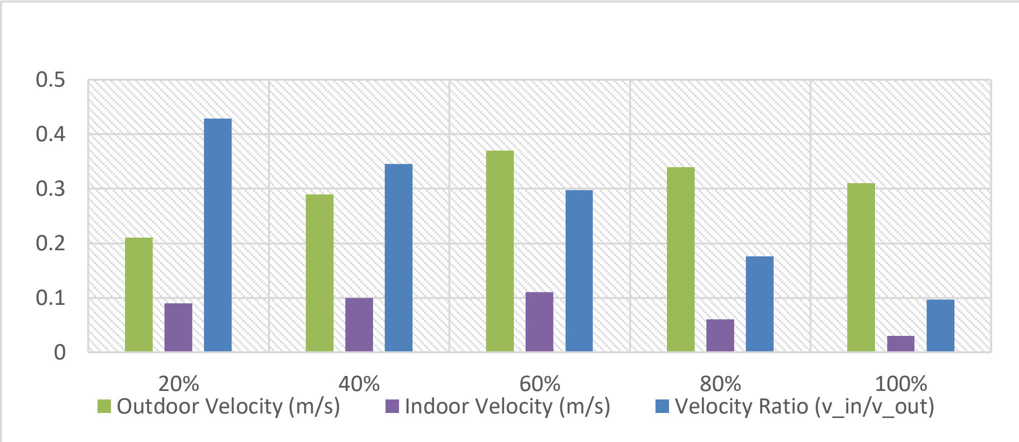

Figure 2. Non-linear response of indoor air velocity and velocity ratio (v_in/v_out) to inlet opening variation

The observed non-linear trend in velocity is also supported by field and CFD studies of natural ventilation, which show that airflow patterns in naturally ventilated rooms are highly sensitive to the ratio of inlet to outlet sizes and to the specific geometry of the openings. When the opening becomes too large relative to other architectural features, flow separation and internal recirculation can occur, leading to stagnation zones and uneven velocity fields despite the high theoretical capacity for airflow (Tajuddeen & Grygierek, 2026). Together, these mechanisms explain why moderate inlet openings yielded the highest indoor velocities, whereas further enlarging the opening produced diminishing returns in ventilation performance.

Air Change Rate Response to Opening Variation

The calculated air change rate (ACH) exhibited a non-linear trend similar to indoor air velocity, increasing from low values at 20% opening to a maximum at 60%, and then decreasing as the opening approached 100%. This pattern indicates that volumetric ventilation efficiency is not maximized by the largest opening area. Field and simulation studies have shown that airflow through building openings depends not only on opening size but also on pressure differentials, discharge coefficients, and flow organization. When openings are moderately sized, pressure gradients are more effectively converted into directional airflow, resulting in higher effective ventilation rates. In contrast, excessively large openings may reduce pressure differentials and weaken airflow acceleration, thereby limiting volumetric exchange despite increased geometric area(Hirose et al., 2021).

The decline in ACH at large openings can be explained by aerodynamic dispersion and reduced momentum concentration. At intermediate openings, incoming air forms a coherent jet that maintains directional momentum and enhances air penetration into the room. However, when the opening becomes too large, flow separation and spreading occur near the opening plane, causing the air to distribute over a wider region and lose kinetic energy. Experimental and computational investigations of cross-ventilated spaces confirm that overly large openings can generate recirculation zones and stagnant regions, which reduce effective ventilation performance even when theoretical opening capacity is high(Demir & Aktepe, 2025b). This demonstrates that airflow effectiveness is governed by flow structure rather than opening area alone.

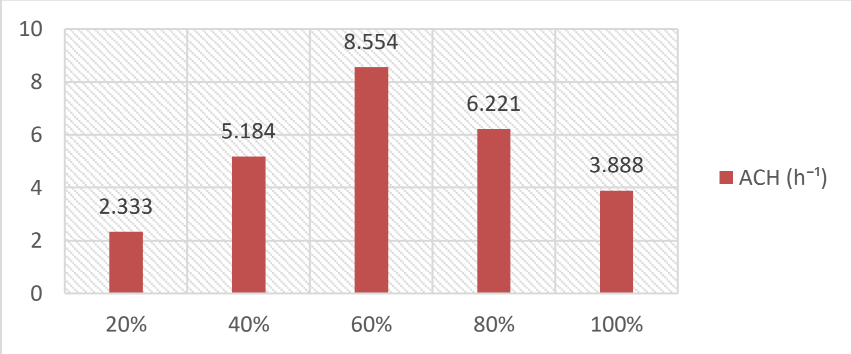

Figure 3. Variation of Air Change Rate (ACH) with Inlet Opening Variation

These results reinforce a key principle of natural ventilation physics: airflow rate is controlled by coupled interactions among opening geometry, pressure distribution, and turbulence characteristics. Modern ventilation research emphasizes that the relationship between opening size and ventilation performance is inherently non-linear, particularly in wind-driven systems where pressure coefficients vary across façade surfaces. Consequently, design strategies based solely on maximizing opening area may lead to suboptimal performance. Instead, optimizing opening proportions and configurations is necessary to achieve efficient air exchange and uniform airflow distribution, as highlighted in recent multi-parameter ventilation optimization studies (Chu, 2023).

Indoor Temperature Response and Relative Humidity Behavior

Indoor air temperature exhibited only minor variation across opening configurations, with differences generally below 1 °C. The small indoor–outdoor temperature difference indicates that thermal buoyancy forces were weak during the experiment, meaning ventilation was primarily wind-driven rather than buoyancy-driven. This observation is consistent with typical daytime tropical conditions, in which indoor and outdoor temperatures are similar, and wind pressure is the dominant driver of airflow. The relatively small temperature gradients also confirm that changes in ACH and air velocity observed across opening variations cannot be attributed to thermal effects, reinforcing that opening geometry was the principal controlling variable in this experiment(Jiang et al., 2023).

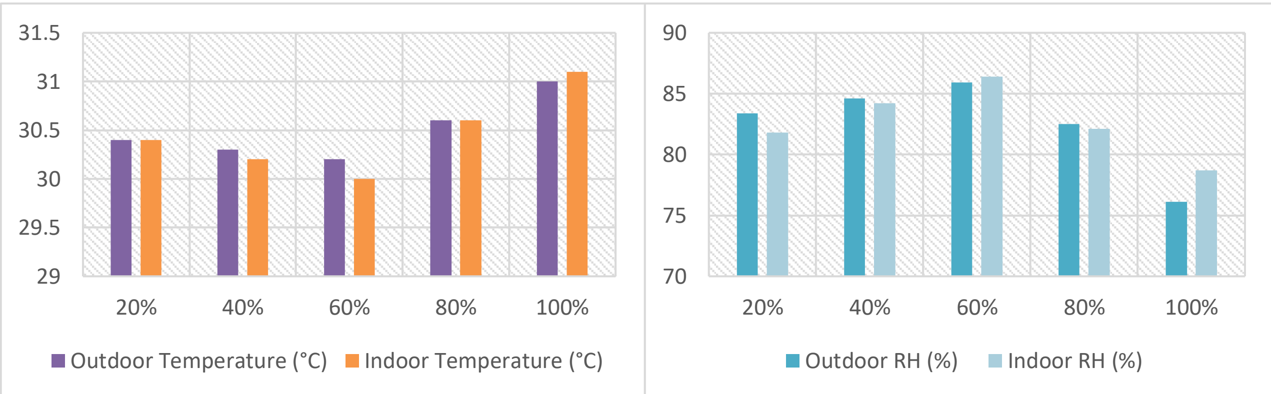

Figure 4. a) Indoor Air Temperature as a Function of Inlet Opening Variation (left);
b) Indoor Relative Humidity Response to Inlet Opening Variation (right)

Indoor relative humidity showed a non-linear pattern similar to that of airflow variables. Indoor relative humidity increased from 20% to 60% opening, reaching a maximum at the intermediate configuration, and decreased at 100% opening, suggesting enhanced dilution at full opening. This trend suggests that moisture transport into the room depends on both airflow rate and mixing efficiency. Moderate openings allow efficient transport of outdoor moist air into the indoor space, whereas very large openings promote dilution through increased air exchange, thereby reducing indoor humidity levels. This result highlights that ventilation performance cannot be evaluated using a single parameter; airflow, temperature, and humidity represent different physical processes and must be interpreted collectively(Conzatti et al., 2025).

Ventilation Performance

Analysis of the temperature difference between outdoor and indoor air (ΔT) showed no strong correlation with ACH. The narrow ΔT range (approximately −0.1 to 0.2 °C) indicates negligible buoyancy effects. Consequently, airflow was dominated by wind-driven forces, confirming theoretical predictions that buoyancy becomes secondary when temperature gradients are small. This finding is particularly relevant for tropical climates, where daytime temperature differences between indoor and outdoor environments are often minimal. Under such conditions, ventilation design strategies should prioritize aerodynamic factors such as opening placement and geometry rather than relying on stack-driven airflow(Hu et al., 2023; Iqbal et al., 2022).

The observed non-linear ventilation performance aligns with previous findings showing that ventilation rates are influenced not only by opening size but also by airflow organization and pressure distribution. For example, studies have demonstrated that specific opening ratios and configurations produce higher ventilation rates than simply maximizing aperture areas, and that excessively large openings may reduce effective ventilation due to flow dispersion and reduced aerodynamic efficiency(Yin et al., 2024; X. Zhang et al., 2023).

Implications for Natural Ventilation Design

From a practical perspective, these findings suggest that partial opening of windows or inlets may provide more effective ventilation than fully opening them. This has important implications for passive cooling strategies, energy efficiency, and indoor comfort in tropical residential buildings. Designers should therefore consider optimizing opening ratios and configurations rather than assuming that maximum opening always yields the best ventilation performance. The results provide experimental evidence supporting the concept of an optimal opening variation for natural ventilation, offering guidance for both architectural design and occupant-operating strategies (Iqbal et al., 2024; M. Zhang et al., 2024).

This study is limited to short-term daytime measurements under quasi-stationary tropical conditions. External wind speed was not mechanically controlled, potentially introducing variability in absolute ACH values. In addition, the velocity–area method provides an estimated ventilation rate and does not replace tracer-gas validation. Future studies may incorporate tracer-gas decay methods and longer monitoring periods to strengthen quantitative validation.

CONCLUSION

The results show that natural ventilation performance is not linearly related to opening size. The highest indoor air velocity was observed at the 60% opening condition, indicating an optimal opening configuration that promotes more focused airflow. At full opening, the air velocity decreased due to a more evenly distributed airflow pattern. This confirms that air velocity is a local flow parameter and does not directly represent overall ventilation effectiveness. Indoor air temperature increased slightly with larger openings, indicating that natural ventilation served as a thermal equalization mechanism between indoor and outdoor environments rather than as a cooling system. Relative humidity showed a non-linear trend, with the lowest value observed at the fully open condition, suggesting more effective moisture dilution through uniform air exchange. Although energy consumption was not directly measured, improved airflow and moisture dilution may reduce reliance on mechanical cooling under certain operating conditions.

REFERENCES

Ashrae. (2023). *ANSI/ASHRAE Addendum j to ANSI/ASHRAE Standard 55-2020*. www.ashrae.org/continuous-maintenance

Choi, Y., & Song, D. (2020). How to quantify natural ventilation rate of single-sided ventilation with trickle ventilator? *Building and Environment*, *181*, 107119. https://api.semanticscholar.org/CorpusID:225400783

Chu, C.-R. (2023). Assessment of year-round wind-driven ventilation by an integrated ventilation model. *Building and Environment*, *243*, 110710. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110710

Conzatti, A., FOSAS DE PANDO, D., Chater, B., & Coley, D. (2025). Are simple models for natural ventilation suitable for shelter design? *Buildings and Cities*, *6*(1), 158–181. https://doi.org/10.5334/bc.497

Demir, H., & Aktepe, B. (2025a). Investigation on the Effect of Opening Size and Position on Wind-Driven Cross-Ventilation in an Isolated Gable Roof Building. *Applied Sciences (Switzerland)*, *15*(11). https://doi.org/10.3390/app15116190

Demir, H., & Aktepe, B. (2025b). Investigation on the Effect of Opening Size and Position on Wind-Driven Cross-Ventilation in an Isolated Gable Roof Building. *Applied Sciences (Switzerland)*, *15*(11). https://doi.org/10.3390/app15116190

Etheridge D., S. M. (1996). *Building Ventilation: Theory and Measurement*. John Wiley & Sons.
Handayani, K. N., Murtyas, S., Wijayanta, A. T., & Hagishima, A. (2024). Thermal Comfort Challenges in Home-Based Enterprises: A Field Study from Surakarta's Urban Low-Cost Housing in a Tropical Climate. *Sustainability (Switzerland)*, *16*(16). https://doi.org/10.3390/su16166838
Hirose, C., Ikegaya, N., Hagishima, A., & Tanimoto, J. (2021). Indoor airflow and thermal comfort in a cross-ventilated building within an urban-like block array using large-eddy simulations. *Building and Environment*, *196*. https://doi.org/10.1016/j.buildenv.2021.107811
Hodder, S., & Igor Palella, B. (2024). Measurement and Quantification of Thermal Environments; ISO 7726-Ergonomics of the Thermal Environment-Instruments and methods for measuring and monitoring physical quantities ARTICLES. *The REHVA European HVAC Journal*.
Hu, M., Zhang, K., Nguyen, Q., & Tasdizen, T. (2023). The effects of passive design on indoor thermal comfort and energy savings for residential buildings in hot climates: A systematic review. *Urban Climate*, *49*, 101466. https://doi.org/10.1016/j.uclim.2023.101466
Iqbal, M., Atthaillah, A., Safyan, A., Indriani, L., & Sina, A. M. (2024). Kenyamanan Termal pada Bangunan Berventilasi Alami di Iklim Tropis. *Nature: National Academic Journal of Architecture*, *11*(2), 152–163. https://doi.org/10.24252/nature.v11i2a3
Iqbal, M., Dastur, M., & Fikry, M. (2022). Indoor Thermal Comfort Improvement of the Naturally Ventilated House in Tropical Climate, Indonesia. *Proceedings of Malikussaleh International Conference on Multidisciplinary Studies (MICoMS)*, *3*, 00007. https://doi.org/10.29103/micoms.v3i.48
Jiang, Z., Kobayashi, T., Yamanaka, T., & Sandberg, M. (2023). A literature review of cross ventilation in buildings. *Energy and Buildings*, *291*, 113143. https://doi.org/https://doi.org/10.1016/j.enbuild.2023.113143
Karava, P., & Stathopoulos, T. (2011). Airflow assessment in cross-ventilated buildings with operable façade elements. *Building and Environment*, *46*, 266–279. https://doi.org/10.1016/j.buildenv.2010.07.022
Li, Q., Tai, V. C., Moey, L. K., Go, T. F., Safehian, J., & Yazdi, M. H. (2023). Impact of planar area ratio and opening positions on natural cross ventilation performance in sheltered high-rise buildings: A simulation study. *Building and Environment*, *245*, 110889. https://doi.org/https://doi.org/10.1016/j.buildenv.2023.110889
Li, W., Xu, X., Yao, J., Chen, Q., Sun, Z., Makvandi, M., & Yuan, P. F. (2024). Natural ventilation cooling effectiveness classification for building design addressing climate characteristics. *Scientific Reports*, *14*(1). https://doi.org/10.1038/s41598-024-66684-9
Moey, L. K., Sing, Y. H., Tai, V. C., Go, T. F., & Ng, J. Y. (2022). Numerical investigation of inlet opening size on wind-driven cross ventilation. *Journal of Mechanical Engineering and Sciences*, *16*(1), 8662–8672. https://doi.org/10.15282/jmes.16.1.2022.02.0685
Moey, L. K., Sing, Y. H., Tai, V. C., Go, T. F., & Sia, Y. Y. (2021). Effect Of Opening Size On Wind-Driven Cross Ventilation. *International Journal of Integrated Engineering*, *13*(6), 99–108. https://doi.org/10.30880/ijie.2020.13.06.009
Remion, G., Moujalled, B., & El Mankibi, M. (2019). Review of tracer gas-based methods for the characterization of natural ventilation performance: Comparative analysis of their accuracy. *Building and Environment*, *160*, 106180. https://doi.org/https://doi.org/10.1016/j.buildenv.2019.106180
Seol, H., Arztmann, D., Kim, N., & Balderrama, A. (2023). Estimation of Natural Ventilation Rates in an Office Room with 145 mm-Diameter Circular Openings Using the Occupant-Generated Tracer-Gas Method. *Sustainability (Switzerland)*, *15*(13). https://doi.org/10.3390/su15139892
Tajuddeen, I., & Grygierek, K. (2026). Distribution of air in naturally ventilated spaces: An integration of pre-trained ANN & transfer learning models for deep interpolations. *Building and Environment*, *288*, 114019. https://doi.org/https://doi.org/10.1016/j.buildenv.2025.114019
Yin, X., Muhieldeen, M. W., Razman, R., Ee, J. Y. C., & Chiong, M. C. (2024). The potential effects of window configuration and interior layout on natural ventilation buildings: A comprehensive review. *Cleaner Engineering and Technology*, *23*, 100830. https://doi.org/https://doi.org/10.1016/j.clet.2024.100830
Zhang, M., Han, W., He, Y., Xiong, J., & Zhang, Y. (2024). Natural Ventilation for Cooling Energy Saving: Typical Case of Public Building Design Optimization in Guangzhou, China. *Applied Sciences (Switzerland)*, *14*(2). https://doi.org/10.3390/app14020610
Zhang, X., Yao, H., & Xu, M. (2023). Study on the Influence of Window Type on Natural Ventilation Effect Based on CFD Simulation. *E3S Web of Conferences*, *439*. https://doi.org/10.1051/e3sconf/202343902001