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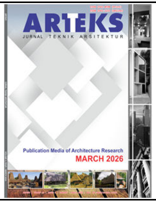

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The influence of staircase geometry and spatial configuration on the enhancement of natural ventilation in urban residential buildings

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ABSTRACT

In densely populated tropical urban contexts, row houses (RD) have increasingly emerged as a prevalent residential solution owing to their efficiency in land utilization and economic affordability. Nevertheless, the compact and contiguous spatial configuration characteristic of this housing typology significantly restricts the availability of natural ventilation openings, impedes effective cross ventilation, and consequently reduces levels of thermal comfort and indoor air quality. Under such conditions, occupants tend to rely more heavily on mechanical ventilation systems, which in turn leads to increased energy consumption and a decline in overall environmental sustainability. This study explores the potential role of staircases as vertical void elements capable of enhancing natural ventilation performance through the application of the stack effect mechanism. An experimental investigation was carried out to analyze the influence of sixteen combinations derived from variations in staircase geometry (I, L, U, Ɔ, and their mirrored configurations), tread construction (solid and perforated), and staircase placement (front, center, and rear) on natural ventilation performance within row house typologies. A quantitative research approach was adopted through the application of Computational Fluid Dynamics (CFD) simulations to evaluate airflow behavior and thermal conditions. The findings indicate that staircases with a massive U-shaped construction geometry demonstrate the most optimal natural ventilation performance, achieving an air velocity of 5 m/s and a temperature of 33.5°C. Specifically, within the U-shaped staircase configuration, airflow velocity increased from stagnant conditions to an active state, reaching 4.62 m/s, accompanied by a temperature reduction of approximately 1°C. These results emphasize the significance of staircases as effective passive design components and underscore their potential contribution to improving energy efficiency and promoting sustainability in tropical urban residential architecture.

Introduction

The dense and contiguous configuration of attached row houses significantly constrains both the number and spatial distribution of building openings, thereby severely limiting the effectiveness of horizontal cross ventilation. This condition results in reduced indoor air velocity, elevated internal temperatures, increased air stagnation, and a consequent decline in overall thermal comfort. As a result, air exchange rates remain suboptimal, potentially posing adverse health implications for occupants. These environmental and physiological challenges highlight the need for more effective and context-specific passive design strategies that are responsive to the climatic conditions of tropical urban environments (Farhana Ahmed and Sarder Mohammad Hafijur Rahman 2024). The reliance on front and rear façades as the sole sources of passive ventilation has proven insufficient in dense row house typologies, often compelling residents to depend heavily on mechanical ventilation systems to achieve acceptable levels of thermal comfort. This dependency, in turn, contributes to increased energy consumption and the deterioration of indoor air quality. An appropriate architectural response lies in the implementation of passive ventilation strategies, including horizontal cross ventilation, vertical ventilation mechanisms such as the stack effect or air wells, wind catchers, and the integration of perforated partitions within interior spatial configurations. Among these strategies, staircase voids demonstrate considerable potential to function as vertical ventilation elements capable of enhancing natural airflow through stack effect and thermal buoyancy mechanisms (Rezadoost Dezfuli et al. 2023; Kajjoba et al. 2025).

Natural ventilation is defined as a passive process of air movement within buildings that operates without mechanical assistance, relying instead on pressure differentials, temperature gradients, and prevailing wind directions. The primary mechanisms of natural ventilation include horizontal cross ventilation and vertical ventilation strategies such as air chimneys, stack effect systems, and vertical voids. Vertical ventilation, in particular, has been shown to substantially enhance the effectiveness of cross ventilation, especially when openings are positioned at higher elevations within the building envelope. The integration of both horizontal and vertical ventilation strategies is especially effective in low- to mid-rise buildings situated on narrow urban plots, where spatial constraints limit façade exposure (Gupta and Khare 2021; Kumar et al. 2022; Pan et al. 2019; Tantasavasdi, Arttamart, and Inprom 2025; Bangalee 2015).

Staircase voids have been identified as highly effective architectural elements for improving thermal comfort in multi-story buildings without necessitating modifications to existing window openings. The performance of natural ventilation facilitated by staircase voids is influenced by several factors, including the void's aspect ratio, building height, and the proportion of void area relative to the total building volume. When designed as open vertical spaces, staircases offer a valuable opportunity to enable inter-floor airflow and enhance vertical air movement. The application of stack effect strategies through vertical ventilation systems, combined with roof ventilation and dynamic horizontal façade ventilation, has been demonstrated to reduce indoor temperatures by up to 4°C and improve ventilation efficiency by as much as seven times compared to single-sided ventilation configurations (Abdulhamid and Tukur 2019; Kumar et al. 2022; Spentzou, Cook, and Emmitt 2019).

The configuration and spatial placement of staircases play a critical role in determining indoor airflow performance and the overall effectiveness of building ventilation strategies. Centrally positioned staircases have been shown to enhance vertical airflow distribution while simultaneously contributing to spatial balance and effective thermal zoning within the building core. When designed as open structural elements that function as vertical voids, staircases promote buoyancy-driven airflow through the stack effect, facilitating vertical air movement between floors. This spatial intervention has been shown to improve thermal performance by reducing indoor temperatures by up to 0.5°C and increasing air velocity by approximately 0.03 m/s. Furthermore, perforated stair designs, including open risers or slotted treads, support continuous inter-floor air circulation by minimizing aerodynamic resistance and maintaining airflow continuity within the vertical core (Leopold 2020; Obradović and Grujić 2018).

Staircases that are intentionally integrated as architectural voids to activate the stack effect and strategically positioned at the building core contribute significantly to the overall passive design strategy. Such spatial configurations have been shown to enhance natural ventilation performance, with empirical studies reporting efficiency increases of up to 117% compared to staircases located along the building perimeter. Computational Fluid Dynamics (CFD) simulations further indicate that centrally positioned staircases can increase air exchange rates to as much as 8 ACH (air changes per hour), thereby improving indoor environmental quality and supporting thermal comfort in compact urban housing typologies (Corbett 2019; Charles C.

Munonye 2024; Rajput and Thomas 2023; Shaeri et al. 2023).

The geometric design of staircases in multi-story buildings serves not only structural and circulatory functions but also plays a decisive role in airflow distribution and thermal movement. Staircase geometries such as I-, L-, U-, and spiral-shaped configurations significantly influence vertical airflow behavior through buoyancy-driven mechanisms and stack effect dynamics. Open staircase designs incorporating porous elements such as open risers or perforated railings facilitate pressure differentials that enhance upward airflow. Additionally, staircases designed with open wells create vertical air shafts that function effectively as passive ventilation channels (Angelillo, Olivieri, and DeJong 2021; Bangash and Bangash 1999; Dell'Endice et al. 2022; Olivieri et al. 2022). Spiral or curved staircases facilitate more concentrated and directionally focused airflow paths when compared to linear I-shaped configurations, which generally promote lateral dispersion of airflow. U- and L-shaped staircases are frequently employed to support spatial zoning and the redirection of air movement pathways, with their ventilation effectiveness largely influenced by the orientation and strategic placement of openings. Consequently, staircase geometry, whether I, L, U, spiral, or other hybrid configurations, plays a pivotal role in enhancing the overall natural ventilation performance of buildings (Kojima et al. 2020; Raineri, Monica, and Guarino Lo Bianco 2021; Tseng, Huang, and Huang 2024; Zerlenga et al. 2022).

The placement of staircases within multi-level residential designs, particularly in row house (RH) typologies, extends beyond purely functional or architectural considerations and has a significant influence on indoor airflow behavior. Whether positioned centrally, laterally, or toward the rear of the building, staircases directly govern the direction of the stack effect and the distribution of vertical airflow between floors. Staircase placement is a critical determinant in establishing the neutral pressure plane (NPP) within a building, which subsequently affects air pressure distribution, infiltration rates, and the overall efficiency of vertical ventilation systems. Research has demonstrated that reducing stairwell opening areas from 88% can result in substantial alterations to both temperature distribution and airflow velocity. Furthermore, staircases located in transitional zones between outdoor and indoor environments function as thermal buffers, particularly in mitigating diurnal temperature fluctuations (Hassina and Samıra 2024; Mckeen and Liao 2019).

Positioning staircases at the building core, in conjunction with vertical ventilation openings, represents the most effective configuration for generating positive pressure zones that stabilize indoor thermal comfort conditions (Benkouda, Louafi, and Mebarki 2024; Wang et al. 2024). Interior spatial arrangement, specifically the vertical and horizontal positioning of staircases, is also closely associated with smoke ventilation performance during fire emergencies. Strategic staircase placement can support both gravity-based and mechanically assisted ventilation systems under high-pressure conditions, thereby enhancing occupant safety and improving emergency response performance (Kubicki and Cisek 2019; Uddin et al. 2022).

Row houses (RH) represent a high-density residential typology widely developed in urban environments, particularly as a response to rapid urban expansion. The design of row dwellings (RD) is commonly constrained by limited building orientation options, restricted façade openings, and inadequate cross ventilation, which collectively contribute to an increasing dependence on mechanical ventilation systems. Within the framework of passive architectural design, RH presents a unique challenge due to the restricted application of natural ventilation strategies such as the stack effect and horizontal cross ventilation. Empirical studies indicate that higher height-to-width (H/W) ratios in building block configurations are associated with increased outdoor air temperatures. The narrow and vertically elongated spatial form characteristic of RH further intensifies these thermal inefficiencies, exacerbating both outdoor and indoor microclimatic conditions (Li et al. 2024; Voordeckers et al. 2021).

This study aims to identify optimal natural ventilation performance arising from various combinations of staircase geometry, spatial positioning, and tread construction types (solid or porous), while maintaining consistent horizontal passive ventilation elements. The principal contribution of this research lies in the formulation of alternative architectural design strategies that utilize staircase geometry and placement as passive vertical ventilation components. This approach has the potential to substantially enhance energy efficiency, thermal comfort, and environmental sustainability in tropical row house developments, while simultaneously reducing reliance on mechanical ventilation systems. The novelty of this research is its proposal of an alternative passive design approach for vertical cross ventilation and stack effect activation through variations in staircase geometry, staircase positioning, stair access configuration, and massive versus porous stair construction, integrated with the limited horizontal ventilation typically available in RH typologies. This strategy aims to achieve maximum cross ventilation performance and improve overall natural ventilation effectiveness in urban row houses characterized by constrained inlet and outlet conditions. The results of this study identify distinct zones of maximum airflow as well as areas prone to air stagnation, providing critical insights into the optimization of staircase-based passive ventilation strategies.

Methods

This study investigates and evaluates the performance of natural ventilation, specifically airflow velocity, temperature distribution, and the proportion of stagnant versus effectively ventilated zones, in row houses through experimental simulations employing Computational Fluid Dynamics (CFD) using ANSYS R2-2024. The analysis focuses on sixteen staircase geometries that function as vertical ventilation elements activated through the stack effect within a standardized interior configuration of row houses measuring 4 meters in width and 10 meters in depth. These sixteen configurations consist of eight base staircase geometries (I, ⅃, U, Ɔ, and their mirrored variants), each examined under two construction conditions: massive construction with open railings and porous construction using permeable components.

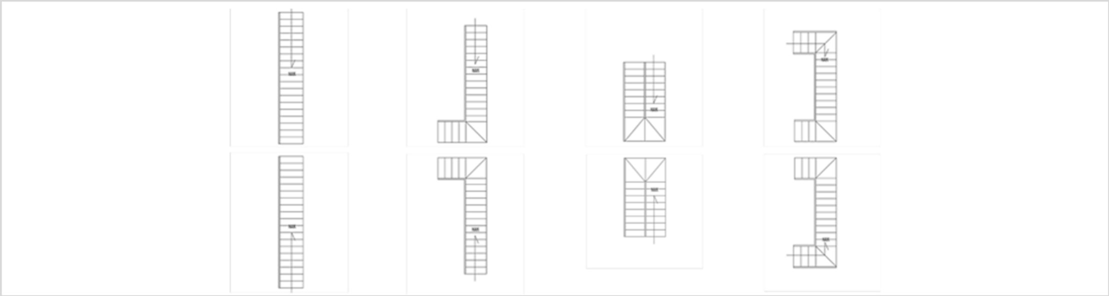


Figure 1. Geometry staircase variables

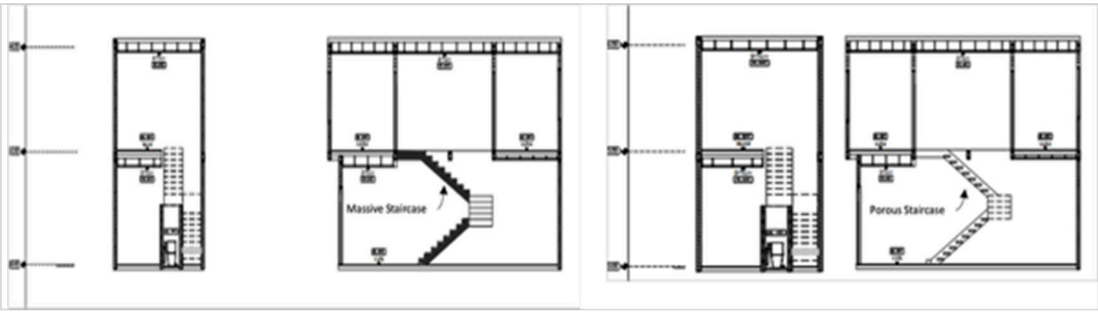


Figure 2. Massive and porous staircase variables

The scope of the study is limited to mid-row house units with no side openings, thereby eliminating the influence of lateral ventilation effects and ensuring controlled airflow conditions. The experimental methodology applies the sixteen staircase configurations as independent variables within a passive design framework that incorporates horizontal ventilation elements, including windows, doors serving as inlet and outlet points, and perforated walls. To ensure consistency across all simulation scenarios, all windows and interior perforated partitions are assumed to be open, while the main entrance door is kept closed. This configuration simulates internal airflow dynamics and enables the assessment of the potential enhancement of ventilation performance generated by vertical airflow movement.

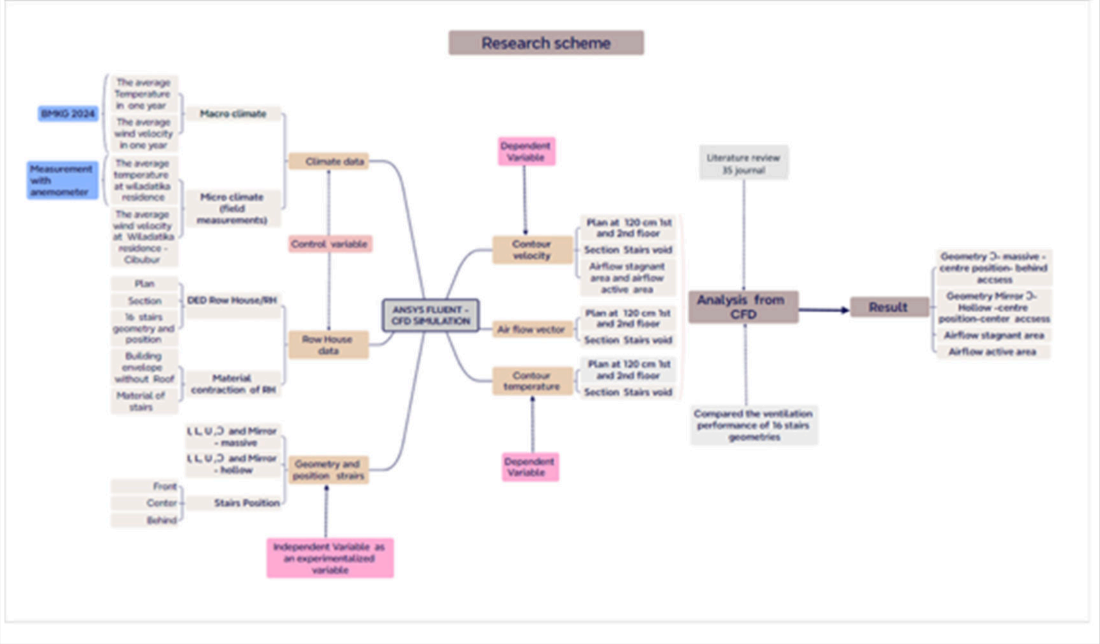


Figure 3. Research scheme

This study employs Computational Fluid Dynamics (CFD) simulations conducted using ANSYS Fluent to evaluate airflow behavior and thermal performance within row houses (RH). The primary objective is to generate comprehensive data visualizations, including airflow vectors, wind velocity contours (WV), and temperature distribution contours (T), by analyzing the combined influence of horizontal and vertical ventilation strategies. Horizontal ventilation, implemented through fixed architectural elements such as windows and doors, functions as passive inlet and outlet components and remains constant across all simulation cases. The use of CFD simulations to derive accurate thermal correlations has been demonstrated to significantly improve the predictive reliability of thermal performance models in naturally ventilated buildings (Chew, Chen, and Gorlé 2022).

The simulated object consists of a row house (RH) characterized by the following parameters: (a) the building comprises two stories, each with a floor area of 4 × 10 meters; (b) the RH is positioned at the center of a continuous row housing block, with adjacent units directly attached on both sides, resulting in the absence of side openings; (c) passive ventilation is limited to openings located on the front and rear façades, which function as inlet and outlet points for horizontal airflow; (d) the spatial layout incorporates horizontal ventilation elements, including doors and windows on the façades as well as within internal rooms; (e) interior openings, such as operable partitions, internal doors, and windows, serve as supplementary horizontal ventilation components; (f) vertical ventilation is facilitated through staircase voids with varying geometric configurations; and (g) although the shape and spatial position of each staircase geometry differ, the total void area is maintained consistently across all configurations.

According to Dahlblom et al. (2019); Maivel, Ferrantelli, and Kurnitski (2018), the recommended h eight for measuring air velocity and temperature in support of thermal comfort assessment ranges between 60 and 150 cm. In this study, the measurement height for both velocity and temperature in the CFD simulation was set at 120 cm, representing typical activity levels within the row house (RH) and corresponding to the position of inlets, outlets, and staircases as both horizontal and vertical ventilation elements.

The row house (RH) is located within the residential neighborhood of Wiladatika, Cibubur, Depok, West Java. Local climatic data for

Cibubur were obtained from the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG), covering a full year, including both dry and wet seasons. Additional microclimate data were collected through field measurements conducted on site in the Cibubur area. The climate variables used in the simulation include wind velocity (WV) and temperature (T), both treated as normalized variables representing the annual average conditions for the respective year. Primary climatic data were collected through direct microclimate measurements conducted in the Wiladatika residential area, Cibubur, East Jakarta, using an anemometer to record ambient temperature and wind velocity. Measurements were taken over one week during both the dry season (July 2024) and the rainy season (March 2025), between 08:00 and 15:00 local time (WIB). The recorded average values ranged from 31–33°C during the dry season and 28–31°C during the rainy season, with wind velocities ranging from 2.2 to 2.5 m/s. The row house (RH) design located in the Cibubur, Depok area was redrawn in plan and sectional views using CAD software to ensure accurate modeling of the spatial and architectural layout for CFD simulation. Building material data were collected to determine thermal properties, which inform temperature contour mapping in both plan and sectional analyses.

Operational definitions of key variables in this study are as follows: Controlled variables (normalized) include wind velocity (WV) and outdoor temperature (T), based on microclimate conditions in the Wiladatika Cibubur area of West Java. Independent variables consist of 16 variations of staircase geometry, position, and access configuration simulated within the RH layout. Dependent variables include indoor wind velocity (WV) and indoor air temperature (T), which are evaluated as indicators of ventilation performance. Constant variables refer to the fixed design of all horizontal ventilation elements (windows and doors) in the RH model, which remain unchanged throughout the simulations.

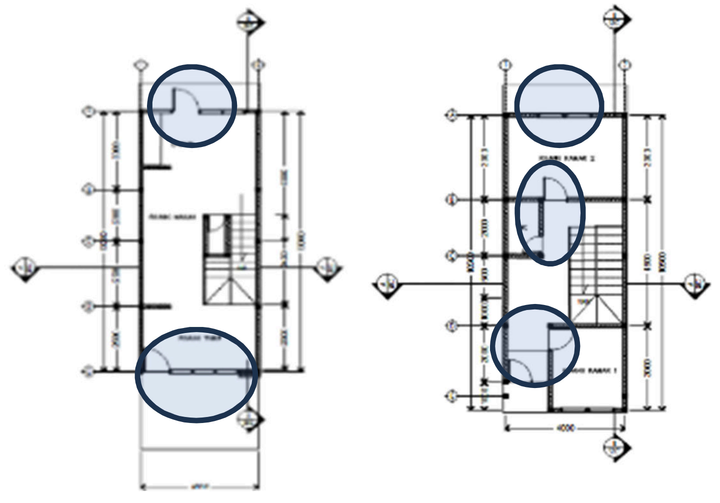


Figure 4. Floor Plans (1st – 2nd) – The same design inlet and out for CFD simulation and the deference are design SC with 16 variable designs

Throughout the simulations, the geometry of the staircase functioned as the independent variable, while the passive horizontal ventilation elements of the RH design such as window and door openings were held constant to reflect existing architectural conditions. It can be illustrated in the floor plan using a fixed horizontal ventilation layout. The resulting airflow behavior was analyzed through vector plots, velocity contours, and temperature distributions to evaluate the effectiveness of the stack effect generated by each staircase configuration. Throughout the simulations, the geometry of the staircase functioned as the independent variable, while the passive horizontal ventilation elements of the RH design such as window and door openings were held constant to reflect existing architectural conditions.

The row house (RH) examined in this study is located within the residential neighborhood of Wiladatika, Cibubur, Depok, West Java, Indonesia. Local climatic data for the Cibubur area were obtained from the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG) and cover a full annual cycle, including both dry and wet seasons. To complement these secondary data, additional microclimate information was collected through on-site field measurements conducted within the Wiladatika residential area. The climatic variables applied in the CFD simulations include wind velocity (WV) and ambient temperature (T), both of which were treated as normalized variables representing annual average conditions for the study period. Primary climatic data were obtained through direct microclimate measurements carried out in the Wiladatika residential area, Cibubur, using an anemometer to record ambient air temperature and wind velocity. Measurements were conducted over a one-week period during the dry season (July 2024) and repeated during the rainy season (March 2025), between 08:00 and 15:00 local time (WIB). The recorded average ambient temperatures ranged from 31°C to 33°C during the dry season and from 28°C to 31°C during the rainy season, while measured wind velocities varied between 2.2 m/s and 2.5 m/s. To ensure accurate representation of spatial and architectural conditions in the CFD simulations, the row house (RH) design located in the Cibubur, Depok area was redrawn in both plan and sectional views using computer-aided design (CAD) software. Building material data were collected to determine relevant thermal properties, which were subsequently used to inform temperature contour analyses in both plan and sectional simulation outputs.

The operational definitions of key variables in this study are as follows. Controlled (normalized) variables include outdoor wind velocity (WV) and outdoor air temperature (T), derived from the microclimatic conditions of the Wiladatika Cibubur area in West Java. Independent variables consist of sixteen variations of staircase geometry, spatial position, and access configuration simulated within the RH layout. Dependent variables include indoor wind velocity (WV) and indoor air temperature (T), which serve as primary indicators of natural ventilation performance. Constant variables refer to the fixed configuration of all horizontal ventilation elements, specifically windows and doors, within the RH model, which remain unchanged throughout all simulation scenarios.

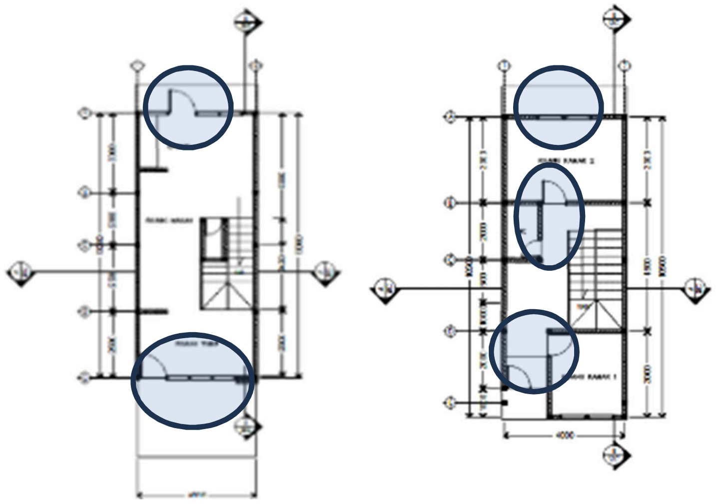


Figure 5. Floor plans (1st–2nd floors): identical inlet and outlet design for cfd simulations, with variations applied only to staircase configurations across 16 design alternatives

Throughout the simulation process, staircase geometry functioned as the sole independent variable, while all passive horizontal ventilation elements of the RH design, including window and door openings, were maintained as constant to reflect existing architectural conditions. This fixed horizontal ventilation layout is illustrated in the floor plan configurations. Airflow behavior resulting from each staircase configuration was analyzed using airflow vector plots, wind velocity contours, and temperature distribution maps to evaluate the effectiveness of stack effect–driven ventilation generated by the respective staircase geometries.

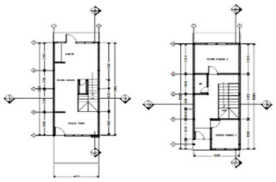
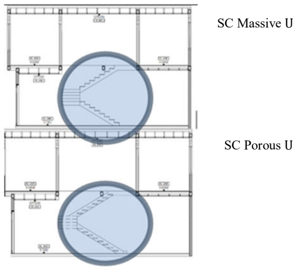
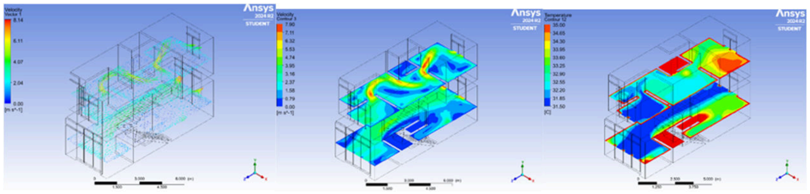
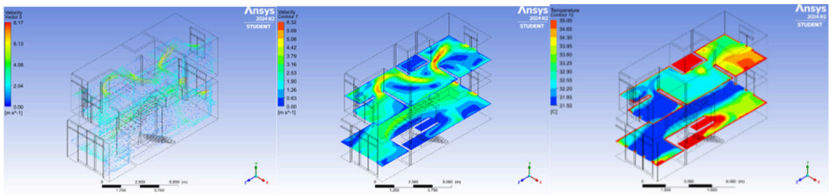
Results and discussion

The local climatic conditions of the Cibubur area, Depok, West Java, are characterized by an average wind speed of approximately 2.5 m/s and ambient temperatures ranging between 31°C and 35°C, as reported by the Indonesian Meteorological, Climatological, and Geophysical Agency (BMKG 2024). To ensure site-specific accuracy, climatic data for the research location were obtained through direct field measurements using an anemometer to record wind speed and ambient air temperature. These measurements were conducted over one consecutive week in March, representing the rainy season, and repeated over one week in July, representing the dry season. The observed climatic conditions during these periods are consistent with BMKG records, confirming average wind speeds of approximately 2.5 m/s and temperature ranges between 31°C and 35°C in Cibubur and its surrounding areas.

Field measurement results indicate that the average ambient temperature (T) during the dry season is 31.8°C, while during the rainy season it decreases to 29.5°C, resulting in a seasonal mean temperature (T_avg) of 30.6°C. When these values are considered alongside long-term climatic data for Cibubur over a one-year period, which indicate an annual average temperature of approximately 31.35°C, a representative ambient temperature of 31.5°C was selected for the CFD simulations. The wind velocity (WV) applied in the simulations was similarly derived from seasonal averages, measured at 2.6 m/s during the dry season and 2.5 m/s during the rainy season. Based on these values, an average wind velocity of 2.5 m/s was adopted as the representative boundary condition for the CFD analysis.

Within the simulation framework, the control variables represent the environmental conditions, specifically outdoor wind velocity and ambient temperature. Accordingly, a wind velocity of 2.5 m/s and an ambient temperature of 31.5°C were applied as fixed input parameters in the CFD simulations. The simulations were conducted using ANSYS Fluent 2024 R2 and were performed at two elevation levels corresponding to the first and second floors of the row house (RH). Measurements of airflow velocity and temperature were taken at a height of 120 cm above floor level, consistent with the established measurement height for thermal comfort assessment. These elevations were represented in both two-dimensional floor plans and sectional views, with particular emphasis on the spatial relationship between airflow patterns and staircase locations. The CFD simulations generated a series of graphical outputs used to evaluate airflow behavior and thermal distribution within the RH. These outputs include airflow vector diagrams for both the first and second floor plans, as well as vertical airflow vectors through the staircase void illustrated in sectional views to demonstrate stack effect behavior. Wind velocity contours were produced for each floor, accompanied by vertical velocity contours within the staircase void to assess the magnitude and continuity of upward air movement. In addition, temperature distribution contours were generated for each floor plan, while vertical temperature gradients along the staircase void were visualized in sectional views to evaluate the effectiveness of thermal buoyancy mechanisms. Using the sixteen staircase geometries as independent variables within an identical floor plan configuration, the CFD simulations produced airflow vectors, wind velocity contours, and temperature contours that reflect the combined influence of horizontal and vertical ventilation strategies in the row house. These results provide a comparative assessment of ventilation performance across all staircase configurations and are summarized in the following table 1.

Table 1. Result example of CFD simulation with ansys fluent analysis

Stair Case/SC	1st – 2nd Floorplan	1st – 2nd Section
SC Massive U and Porous U	 Floor Plans (1st – 2nd) – Cross Section A-A (Independent Variable Constant) Staircase U	 Independent variable staircase geometry
SC Massive U	 (a) Airflow Vectors (b) Velocity Contours (c) Wind Temperature Distribution	
SC Porous U	 (a) Airflow Vectors (b) Velocity Contours (c) Wind Temperature Distribution	

The CFD simulations of sixteen distinct staircase geometries within the interior of the row house (RH), encompassing both velocity and temperature distributions, are systematically summarized in the table 2 below.

Table 2. Performance of staircase geometry and spatial configuration

No	Staircase geometry	Staircase position	Staircase access	Floor	Airflow (area)	Massive		Porous	
						WV m/s average	T °C average	WV m/s average	T °C average
1	Shape I	Center	Behind	1st Floor	Stagnant	0,35	34	0,59	34,2
					Active	1,6	34,1	2,3	32,2
				2nd Floor	Stagnant	0,33	34	0,59	34,5
					Active	2,3	33,2	4,1	32,6
2	Shape ┘	Center	Behind	1st Floor	Stagnant	0,33	34,8	0,6	34,3
					Active	1,6	32,5	2,4	32,5
				2nd Floor	Stagnant	0,49	34,1	0,6	34,5
					Active	4	33,5	3,6	33
3	Shape U	Center	Center		Stagnant	0,79	34,1	0,63	34,1

No	Staircase geometry	Staircase position	Staircase access	Floor	Airflow (area)	Massive		Porous	
						WV m/s average	T °C average	WV m/s average	T °C average
				1st Floor	Active	2,46	32,5	3,8	32,2
				2nd Floor	Stagnant	0,38	34,5	0,63	34,5
					Active	5	33,5	4,3	33
4	Shape Ɔ	Center	Behind	1st Floor	Stagnant	0,42	34,5	0,62	34
					Active	2,3	32,2	1,9	34
				2nd Floor	Stagnant	0,42	33,8	0,62	34,5
					Active	4,8	33,5	3,7	33
5	Mirror Shape l	Center	Front	1st Floor	Stagnant	0,33	33,5	0,7	34
					Active	2,3	32	2,5	32,2
				2nd Floor	Stagnant	0,33	34	0,35	34,5
					Active	3,19	32,5	4,5	33
6	Mirror Shape ˥	Center	Front	1st Floor	Stagnant	0,33	34,8	0,7	34
					Active	2,2	32	2,6	32
				2nd Floor	Stagnant	0,33	34,5	0,7	34,5
					Active	3,84	32,5	4,3	33
7	Mirror Shape ∩	Center	Center	1st Floor	Stagnant	0,7	34,1	0,7	34,5
					Active	2,8	32,5	2,7	32,2
				2nd Floor	Stagnant	0,7	34,5	0,7	34,5
					Active	5	32,2	4,2	32,5
8	Mirror Shape Ɔ	Center	Front	1st Floor	Stagnant	0,7	34	0,7	34,5
					Active	2,7	32	2,8	32,2
				2nd Floor	Stagnant	0,7	34,5	0,7	33,6
					Active	4,7	32,2	4,25	33

The CFD simulation results presented above identified the staircase geometry that achieves the most optimal natural ventilation performance, based on wind velocity and temperature characteristics. This evaluation considered both stagnant rooms, spaces that do not receive adequate airflow, typically located far from inlets and outlets in both the vertical/stair and horizontal/opening directions, and active rooms, which are spaces that experience optimal airflow due to their proximity to inlets and outlets, both vertically and horizontally. The findings of this study indicate that staircases with a robust U-shaped configuration exhibit the highest natural ventilation efficiency, achieving a wind velocity of 5 m/s and a temperature of 33.5°C. Within the U-shaped staircase geometry, the velocity increases from stagnant to active spaces by 4.62 m/s (from 0.38 to 5 m/s), while the temperature decreases by 1°C (from 34.5°C to 33.5°C).

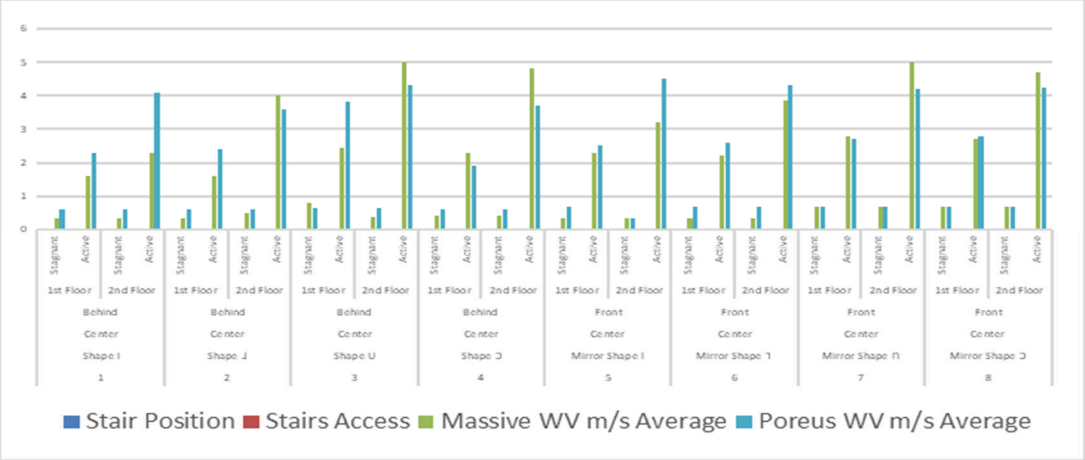


Figure 5. Result comparation wind velocity of staircase geometry with massive and porous construction

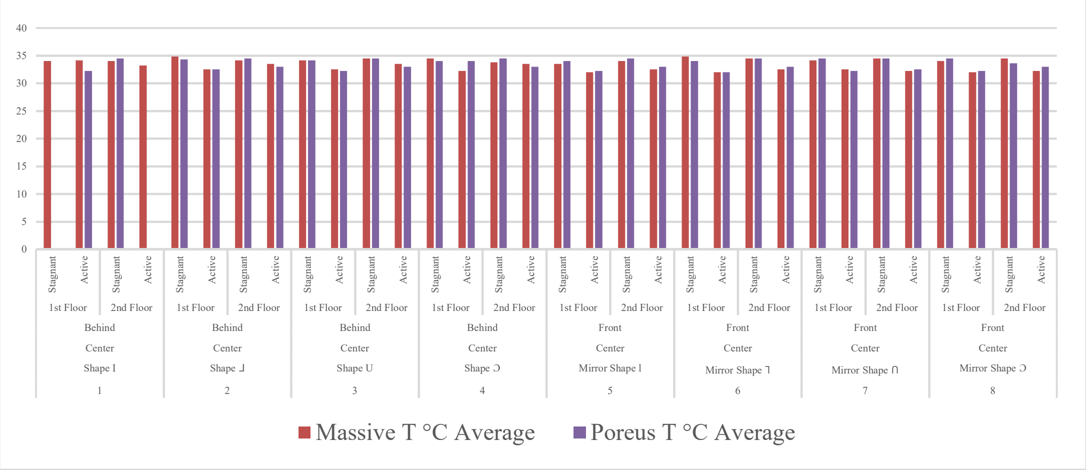


Figure 6. Result comparation temperature of staircase geometry with massive and porous construction

These results indicate that the synergy between horizontal ventilation and vertical ventilation through the stack effect, specifically achieved using a U-shaped staircase geometry with massive and porous treads, centrally located and oriented toward the front façade inlet, can substantially enhance overall ventilation performance (Kumar et al. 2022; Tantasavasdi, Arttamart, and Inprom 2025; Bangalee 2015). This enhancement is primarily attributed to the interaction between horizontal airflow and the vertical stack effect generated by the centrally positioned staircase with front access. The effectiveness of this configuration is further corroborated by previous studies conducted by Obradović and Grujić (2018).

Based on the two graphs above, which illustrate the percentages of stagnant versus ventilated areas, it can be concluded that the combination of horizontal ventilation (through inlet and outlet openings on the façades) and a massive U-shaped construction with central access aligned with the inlet produces the largest ventilated area, reaching 76% on the first floor and 78% on the second floor. Similarly, a U-shaped porous construction with central access aligned with the inlet yields the largest ventilated areas, achieving 76% on the first floor and 84% on the second floor.

Conclusions

This study underscores the critical role of staircase geometry, positioning, and construction type in enhancing natural ventilation within compact urban row houses (RH). The integration of vertical and horizontal passive ventilation systems, particularly via stack-effect stair voids, has been shown to exert a significant influence on airflow distribution and indoor thermal performance. The simulation-based approach further highlights the architectural importance of spatial design strategies that promote energy efficiency and occupant comfort.

Several recommendations are proposed to optimize vertical airflow using U-shaped staircase geometries. Regardless of whether the treads are massive or porous, the staircase should remain centrally positioned, with access facing the front façade (inlet side), and should incorporate open railing designs. Relocating the toilet commonly situated beneath the staircase to the rear of the building is also advised to improve upward buoyant airflow, as heat emitted from the tread materials can accelerate vertical air movement through the stair void. In compact row houses, effective natural ventilation both horizontal and vertical can be achieved by employing perforated interior partitions and ensuring that the staircase design incorporates open elements, such as railings and step components. Additionally, CFD simulation outputs, presented as velocity and temperature contours at the 120 cm elevation level, can guide optimal furniture placement within the RH layout. Such investigations enhance understanding of microclimate potential and its positive contribution to ventilation performance in compact urban housing. By bridging empirical simulation with architectural design strategies, this research advances passive ventilation practices and provides a foundation for future studies exploring spatial–microclimate interactions in high-density housing contexts.

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Khotijah Lahji contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

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