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Prediction of natural ventilation performance through a comparative study of interior void and courtyard void designs in two-storey urban row houses

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Abstract. Natural ventilation is an important passive design strategy for improving indoor environmental quality while reducing dependence on energy-intensive mechanical cooling systems. However, in dense urban contexts, two-story row houses often face airflow limitations due to compact layouts, narrow facades, and limited openings. This study aims to predict and compare the performance of two natural ventilation strategies, namely interior void and courtyard void. The research methodology uses three analytical approaches: Convex Space and Computational Fluid Dynamics (CFD) simulations to evaluate airflow circulation patterns, velocity distribution, and indoor temperature. The study was conducted on a two-story row house prototype at Summarecon Residence, Bekasi, with a floor plan area of 6 × 14 m (84 m² per floor). The position and dimensions of the inlet and outlet were made the same in each scenario, while external parameters such as average wind speed and outside temperature in 2024 were used in the simulation. The results show that the courtyard void produces better ventilation performance with an average wind speed of 2.17 m/s and a temperature of 33 °C, compared to the interior void, which only reaches 1.17 m/s with a temperature of 33.43 °C. In addition, the area near the courtyard had a maximum wind speed of 6–7 m/s, while the interior void had 5–6 m/s. These findings provide evidence-based recommendations on the importance of integrating passive ventilation strategies in row house design.

1 Introduction

Natural ventilation is a key passive design strategy that improves indoor air quality, enhances airflow, and reduces reliance on energy-intensive cooling systems, making it vital in tropical and subtropical regions amid rising energy demands and climate change [1, 2]. However, in dense urban row houses, particularly in Southeast Asia, compact layouts, narrow façades, and limited openings hinder effective cross ventilation, often leading to thermal discomfort and poor air quality, underscoring the need for tailored passive ventilation strategies [3].

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The primary objective of this study is to predict and compare the performance of natural ventilation in two distinct design strategies—interior voids and courtyard voids—applied to two-storey urban row houses. Specifically, the study seeks to identify which configuration is more effective in improving cross ventilation, optimizing airflow patterns, and enhancing thermal comfort under the constraints of dense urban environments.

This research is guided by two core questions:

- How do interior voids and courtyard voids influence airflow patterns, velocity distribution, and pressure differentials in two-storey row houses?
- Which void configuration provides superior natural ventilation performance and contributes more effectively to thermal comfort in compact urban housing?

It is hypothesized that courtyard voids, when designed with the same size and position as interior voids, will generate greater pressure differentials and stronger vertical airflow, thereby achieving superior natural ventilation performance compared to interior voids.

This study enriches passive design knowledge by analyzing interior void and courtyard configurations through convex space and CFD simulations, while also offering practical guidance for architects and developers. In tropical row houses, optimized void configurations are proven to enhance airflow, improve thermal comfort, and reduce cooling energy demand. These findings provide evidence-based recommendations for architects and policymakers in designing sustainable housing within dense urban environments [4, 5].

The scope of this study is limited to a two-storey row house prototype with a standardized floor plan measuring 6 × 14 m (84 m^2 per floor). Inlet and outlet dimensions and positions are kept uniform across design variations to ensure comparability. External environmental factors are restricted to prevailing wind velocity and ambient temperature as constant control variables, while other external influences such as vegetation, urban morphology, and urban heat island effects are excluded from the analysis. These limitations ensure a controlled research focus but also suggest directions for future studies that may incorporate more complex environmental conditions.

Research Gap in this research is Façade openings have been widely explored as cross-ventilation strategies, yet recent research emphasizes the significance of voids and courtyards in enhancing natural ventilation. CFD studies show vertical /interior voids improve airflow [6], while courtyard designs reduce indoor temperatures and enhance comfort [2] with morphological variations improving ventilation up to 2.5-time [7].

Despite these findings, most studies investigate Interior voids and courtyards separately, focusing on high-rise. Comparative analyses in two-storey urban row houses remain limited, and methodologies often rely solely on CFD. This research will integrate 2 methods, are CFD method and Convex Space method, These two methods are used comprehensively to analyse the performance of natural ventilation through voids and courtyards in compact housing [3].

2 Literature review

A literature review, as an initial research activity, can provide information on the novelty of the topic to be studied and identify appropriate research gaps, both in terms of the field of study and the methodology to be used. The literature review will be tailored to the research title, which is ‘Prediction of Natural Ventilation Performance through a Comparative Study of Interior Void and Courtyard Void Designs in Two-Storey Urban Row Houses.’ Therefore, several relevant research topics will be explored. Relevant topics are as follows:

2.1 Natural ventilation performance in buildings

Natural ventilation, as a passive design strategy, relies on wind and temperature differentials to drive airflow, reducing energy consumption while enhancing thermal comfort and indoor air quality [8]. Its effectiveness in urban row houses depends on building orientation, façade geometry, and opening ratios. Cross-ventilation and stack effects enhance airflow but are limited in dense urban contexts. CFD studies show that optimized voids and courtyard designs can increase airflow up to 2.5 times in compact housing [7]. Recent research emphasizes integrated passive solutions, combining orientation, solar shading, and envelope optimization to enhance comfort and cut cooling energy demand [9-11].

2.2 Urban row house typology

Row houses in tropical climates face challenges related to limited cross-ventilation due to narrow façades and high-density environments. Simulations in Indonesia and Malaysia show that passive strategies such as interior voids and courtyards are essential for improving indoor air quality [12, 13].

2.3 Void design in architecture

Interior voids primarily facilitate horizontal airflow, while courtyards enhance vertical stack effects. Recent studies confirm that courtyard geometry significantly influences thermal and ventilation performance. In Southeast Asia, semi-enclosed courtyards balance natural lighting and airflow [12]. Courtyard voids, combining horizontal and vertical flows, generate stronger ventilation performance, as validated by CFD simulations [7]. Overall, evidence shows courtyards outperform voids in dense tropical housing.

2.4 Ventilation analysis methods

The Convex Space model, rooted in space syntax theory, analyzes spatial connectivity through convex sets to assess how inlets, outlets, and circulation lengths shape airflow dynamics in architectural design [14]. Complementing this, Computational Fluid Dynamics (CFD) provides high-accuracy predictions of velocity, temperature, and pressure distributions, proving essential for passive design optimization. When validated with experimental data, CFD demonstrates strong reliability in enhancing natural ventilation and thermal comfort [15].

CFD and Convex Space analyses show that interior voids enhance horizontal airflow and cross-ventilation but provide limited vertical circulation, consistent with evidence that wider spaces disperse airflow and reduce stack-driven ventilation [4, 16]. CFD remains the primary tool for airflow simulation, especially when validated by wind tunnel tests [17]. Empirical studies demonstrate that voids can increase ventilation efficiency by up to 300%, while courtyards lower indoor temperatures by 2–4 °C [6, 16, 18]. Recent CFD research also shows courtyard morphology improves airflow 2.5 times, underscoring the need for integrated methods combining CFD and spatial analysis [7, 19].

2.5 Previous research on void and ventilation

Empirical evidence shows that the inclusion of voids can enhance ventilation performance by up to 300% compared to buildings without voids [18]. Courtyards have been proven effective in lowering indoor temperatures by 2–4 °C [2]. However, courtyard design may also lead to cross-pollutant transmission, necessitating careful spatial configuration [17].

In addition to the five topics above, we reviewed 30 journals that we considered relevant to examine and use as references in this study.

Thirty relevant journals as references can be seen on Table 1.

Table 1. Literature review.

No.	First author	Year	Research Location	Methodology	Findings	Relevance to the research topic
1	Bardhan	2020	Mumbai, India	CFD + Simulation	Void improves cross-ventilation	Shows void relevance in dense housing
2	Bardhan	2020	Mumbai, India	CFD + Energy modeling	Interior design saves cooling energy	Highlights interior design role for NV
3	Baydoun	2022	Malaysia	CFD simulation	Perforated windows improve airflow	Supports passive façade ventilation
4	Callegaro	2023	Italy	Simulation (Energy+)	Passive design improves comfort	Confirms passive cooling benefits
5	Chohan	2024	Middle East	CFD + Case study	Courtyard design resilient in arid zones	Applies courtyard in hot-arid contexts
6	Gunasagaran	2022	Penang, Malaysia	CFD + Daylight simulation	Semi-enclosed courtyard optimizes airflow and light	Applicable for tropical terrace houses
7	Hakim	2025	Indonesia	Systematic review	Vertical void enhances passive ventilation	Key for high-density housing
8	Khan	2022	Middle East	CFD simulation	Courtyard improves passive cooling	Relevant to courtyard cooling studies
9	Kumar	2021	Japan	CFD + Wind tunnel	Vertical void enhances airflow	Supports CFD reliability
10	Laloui	2021	Malaysia	Field + CFD	Horizontal voids improve ventilation up to 4×	Highlights void effects on ventilation
11	Loo	2021	Global Review	Systematic review	Building voids key in passive design	Summarizes passive design features
12	Moscoso-García	2023	Ecuador	Simulation + Field monitoring	Courtyard reduces indoor temperature	Supports courtyard in tropical housing
13	Obeidat	2021	Jordan	CFD simulation	Wind towers improve natural ventilation	Validates wind tower strategy
14	Phattanawasin	2022	Thailand	CFD + Space syntax	Compact courtyard houses save energy	Supports compact tropical housing
15	Rodríguez-de-Ita	2024	Mexico/LatAm	CFD + Morphological evolution	Evolutionary courtyard design improves airflow 2.5×	Validates CFD in courtyard optimization
16	Sarkar	2020	India	CFD + Energy modeling	Interior layout saves cooling energy	Links design to energy savings
17	Stasi	2023	Italy	CFD + Simulation	Natural ventilation reduces energy poverty	Supports NV in low-income housing
18	Sun	2023	China	CFD simulation	Courtyard config affects strip houses thermal comfort	Highlights courtyard geometry effects
19	Sun	2024	UK	CFD + Wind tunnel	Courtyards may transmit pollutants	Warns about courtyard pollutant risk
20	Sun	2025	China	CFD simulation	Courtyard roof shape affects passive cooling	Roof shape influences NV
21	Yao	2020	China	Passive cooling simulation	Courtyard improves rural housing comfort	Supports courtyard in rural housing
22	Zoure	2022	Burkina Faso	EnergyPlus simulation	Passive design reduces office energy	Validates passive office cooling
23	Medouki	2022	Algeria	Daylighting + Simulation	Courtyard daylight-ventilation synergy	Courtyard daylight synergy
24	Molina-Botero	2022	Colombia	CFD simulation	Height influences ventilation distribution	Height influences airflow in housing
25	Mendoza	2025	Philippines	CFD + Solar analysis	Integrated strategies improve airflow 250%	Links ventilation & solar strategies
26	Hakim	2025	Indonesia	Systematic review	Vertical void effective in tropics	Validates voids in tropical housing
27	Khan	2023	Oman	CFD simulation	Urban form influences ventilation	Urban layout impacts NV
28	Stasi	2023	Italy	CFD + Simulation	Ventilation reduces energy demand	Supports NV in energy poverty
29	Rodríguez-de-Ita	2024	Mexico	CFD simulation	CFD courtyard optimization enhances NV	Supports CFD optimization for courtyard
30	Bardhan	2020	Indonesia	CFD + Simulation	Void relevance confirmed in dense urban housing	Reinforces void role in urban row housing

A review of the literature shows that most ventilation studies use the CFD simulation method. The unique feature of this study is the integration of the Convex Vpace (CV) method and geometry as variables in CFD simulation. The research innovation scheme is as Figure 1 below.

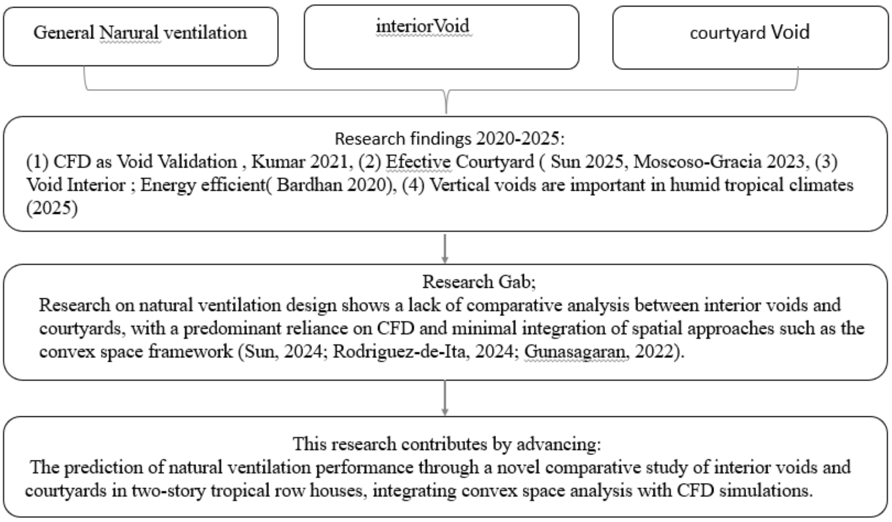


Fig. 1. Research innovation scheme.

3 Methodology

This study employs a mixed-method computational approach to evaluate the natural ventilation performance of two design strategies: interior voids and courtyard voids. The methodology integrates Convex Space analysis and Computational Fluid Dynamics (CFD) simulations with, applied to a standardized two-storey row house prototype.

The simulation model was based on a two-storey row house prototype with a floor area of 6 × 14 m (84 m^2) per floor. The inlet and outlet dimensions and positions were kept identical across both void design scenarios to ensure comparability. Two configurations were tested: (1) an interior void located at the center of the house, and (2) a courtyard void positioned along the rear boundary. External conditions such as prevailing wind velocity and ambient temperature were applied based on typical tropical urban climate data. Other external factors, including vegetation, adjacent building effects, and urban heat island phenomena, were excluded to maintain focus on the comparative performance of the two void strategies [7].

Integrating convex space analysis and CFD simulation, this study provides fluid dynamics precision and spatial design insights, enabling systematic comparisons between interior empty spaces and courtyard empty spaces to improve natural ventilation performance in compact urban housing. The analysis and synthesis process in this study is as follows: (1) Redrawing the research object layout plan, (2). Measuring the climate at the research location in Sumarecon Residen, specifically the cherry area as a 6x14m row house, (3). Simulating Convex Space (CS) and creating a flowchart diagram, (4). Measuring the wind flow path in the row houses, both in width and length, (5). The air flow path is as follows.

The CS simulation results are (figure 2 and 3):

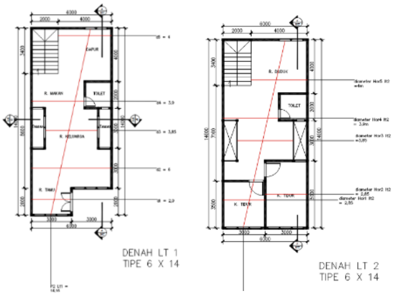


Fig. 2. Results of measurements of the length and width of the airflow path in a row house with a void interior.

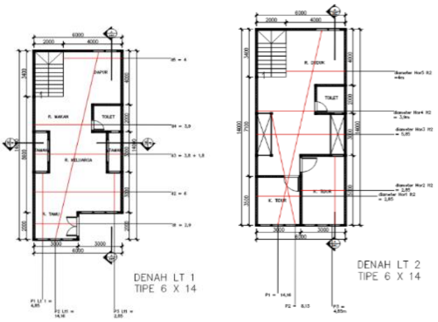
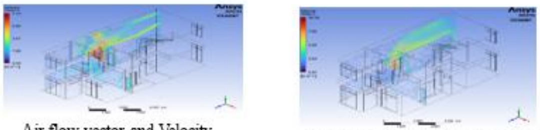


Fig. 3. Results of measurements of the length and width of the airflow path in a row house with a Courtyard void.

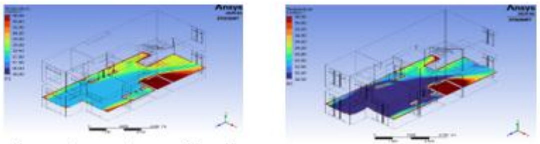
CFD simulation results in the form of air flow vectors and wind velocity and temperature measurements in the interior of the Row House Results of CFD simulation comparison between Rowhouse with Interior void design and Courtyard void (figure 4).

Interior void Coutyard void



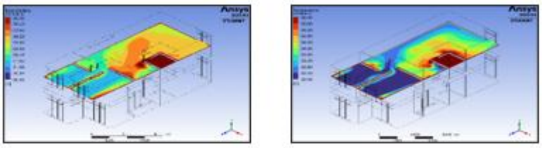
Air flow vector and Velocity value Interior void

Air flow vector and Velocity value Courtyad void



Temperature contours on floor plan 1-1.2m

Temperature contours on floor Plan



Temperature contours on floor plan 2-1.2m

Temperature contours on floor plan 2-1.2m

Fig. 4. CFD analysis.

From the series of research methodology activities above, mapping of independent variables (vi) will be carried out: (x1, x2, ... x13) consisting of the CS model and the CFD model, for independent variables x1-5 which are variables representing the Convex Space model, independent variables x6-x13 represent independent variables from CFD. Both models will be analysed using Linear Regression-SPSS to test the effect of independent variables on dependent variables (Y). The magnitude of the effect will be determined by the Rsquare value in the regression analysis. Therefore, the following research scheme is proposed (figure 5):

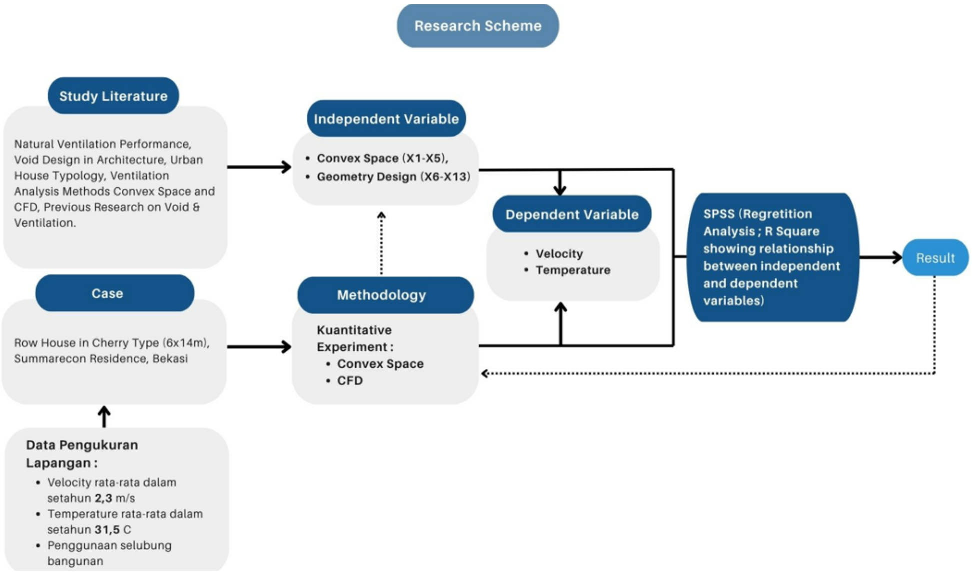


Fig. 5. Research scheme.

4 Result and discussion

4.1 Climate data for the Summarecon Bekasi

Primary data was obtained from field measurements and secondary data from BMKG 2024. Both data sets were analysed to produce the climate data, illustrated climate in Sumarecon Residence (figure 6):

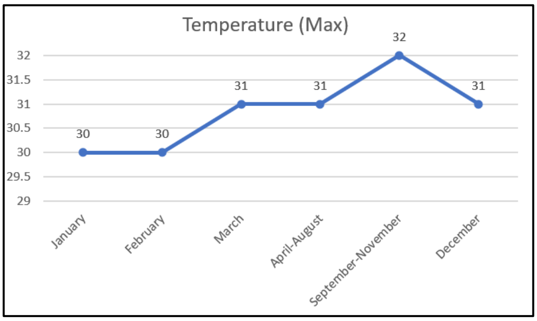


Fig. 6. The climate data in Sumarecon – Bekasi.

Average monthly temperature in Bekasi in 2024 is 31,5°C and the average wind velocity is 2.3 m/s. (BMKG 2024).

4.2 Research object

The object of this study is a two-storey row house in Summarecon, specifically in the Mulberry Residen - Sumarecon housing complex, type Cherry no. 30, with a building size of 6 x 14 and two voids in the middle (figure 7 and 8). The configuration is located on the left and right sides.

Fig. 7. Site plan and Illustration of rowhouse.

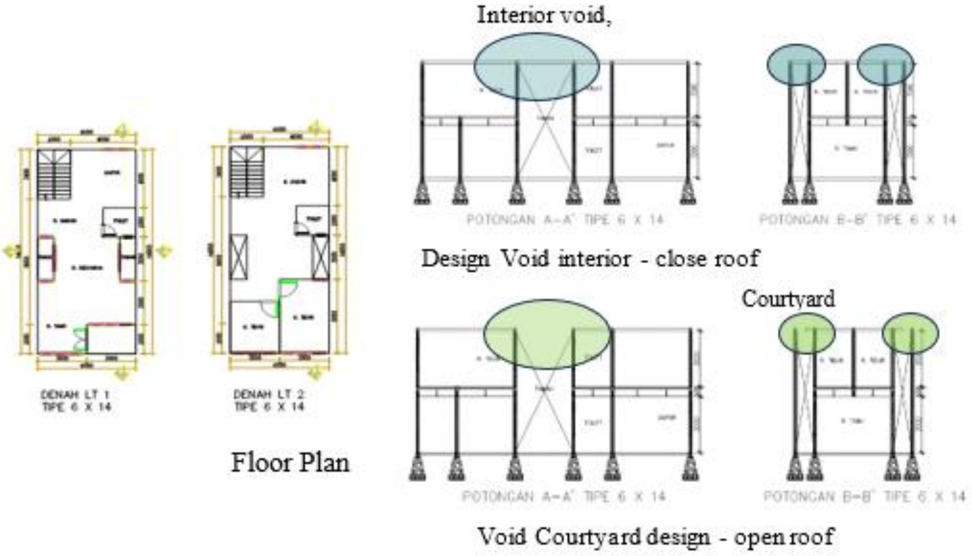


Fig. 8. Floor plan and section row house.

4.3 Analysis and discussion

The CFD and Convex Space analyses indicate that the interior void configuration enhances horizontal airflow across adjacent spaces, providing relatively uniform cross ventilation but with limited vertical circulation. This finding is consistent with studies showing that increased room width reduces airflow velocity due to flow dispersion, limiting stack-driven ventilation [6, 16].

In contrast, the courtyard void generates stronger ventilation performance by combining horizontal inflow with vertical upward airflow, creating higher pressure differentials and facilitating thermal extraction. Similar results have been reported by Rodríguez-de-Ita and Sosa-Compeán [7] and Sun [17], who emphasized the role of courtyard geometry in enhancing airflow efficiency. Overall, courtyard voids outperform interior voids in promoting natural ventilation in dense urban housing, validating the hypothesis of this study [19, 20].

Simulation results show that the dependent variables (y1-y5), which are functions of the independent variables, and the independent variables (y6-y13), which are the average velocity and average temperature values, Y=f(x), The results of the regression analysis show that not all 13 independent variables have an effect on the dependent variables (velocity and temperature). This can be seen in the regression analysis table (table 2):

Table 2. The relationship between independent and dependent variables (R2).

Linear Regression Analysis						
Linear Regression Analysis: the relationship between independent variables and dependent variables through R Square values						
Case Row House 2 story Type Cherry 6×14, Summarecon Bekasi		**Y1_Velocity–Temperature Average_Volume Lt 1**	**Y2_Velocity–Temperature Average_Volume Lt 2**	**Y3_Velocity Average_Volume Lt 1 dan 2**	**Y4_Velocity Average_Potongan Horizontal 120 cm Lt 1**	**Y5_Velocity Average_Potongan Horizontal 120 cm Lt 2**
Methodology Model Convex Space (CS)	X1 = (Floor plan width) Convex Space_first floor (average = avg)	1	1	1	1	1
	X2 = (Length of Floor Plan) Convex Space_first floor_avg	1	1	1	1	1
	X3 = (Floor plan width) Convex Space_second floor_avg	1	1	1	1	1
	X4 = (Length of Floor Plan) Convex Space_second floor_avg	1	1	1	1	1
	X5 = Height vertical as opening ventilation_Convex Space_avg	1	1	1	1	1
Model Metodologi CFD (Geometry Design)	X6 = Luas Void_m²	–	–	–	–	–
	X7 = Tinggi Void_m	1	1	1	1	1
	X8 = Luas Inlet Lt 1	–	–	–	–	–
	X9 = Luas Inlet Lt 2	1	1	1	1	1
	X10 = Luas Outlet Lt 1	–	–	–	–	–
	X11 = Luas Outlet Lt 2	1	1	1	1	1
	X12 = Jarak antar Inlet dan Outlet Lt 1	1	1	1	1	1
	X13 = Jarak antar Inlet dan Outlet Lt 2	1	1	1	1	1

Linear regression analysis show that several independent variables, namely X6, X8, and X10, have no effect on the average velocity in the row house space. These variables are square of void area, inlet area, and outlet area. The results of the analysis of the Convek space and CFD models, which consist of 13 independent variables assumed to affect ventilation performance [dependent variable/(y) in the form of average velocity and temperature values], as well as thermal performance in row houses, show that the results of the comparison of the thermal performance of the interior void and courtyard void ventilation designs are as follows (table 3):

Table 3. Comparison interior void VS courtyard.

No.	Dependent Variable	Interior void	Courtyard	Unit	Difference	Standard ASHRAE 55-2013 dan Lechner 2015
1	Y1_Velocity Average_Volume Lt 1	1.95	2.19	m/s	0.24	> 0.25 m/s – 1 m/s in temperature 29–31°C
2	Y2_Velocity Average_Volume Lt 2	1.80	2.01	m/s	0.21	> 0.25 m/s – 1 m/s in temperature 29–31°C
3	Y3_Velocity Average_Volume Lt 1 dan 2	1.87	2.10	m/s	0.23	> 0.25 m/s – 1 m/s in temperature 29–31°C
4	Y4_Velocity Average_Section Floor plan 1 Horizontal 120 cm	1.84	2.42	m/s	0.58	> 0.25 m/s – 1 m/s in temperature 29–31°C
5	Y5_Velocity Average_Section Floor plan 2 Horizontal 120 cm	1.74	2.11	m/s	0.37	> 0.25 m/s – 1 m/s in temperature 29–31°C
6	Y6_AverageTemperature_Volume Lt 1	32.98	32.83	°C	0.15	23.0°C – 26.0°C
7	Y7_AverageTemperature_Volume Lt 2	34.05	33.37	°C	0.68	23.0°C – 26.0°C
8	Y8_AverageTemperature_Volume Lt 2	33.59	33.11	°C	0.48	23.0°C – 26.0°C
9	Y9_AverageTemperature_Horizontal Section Floor plan-1 120 cm	32.85	32.66	°C	0.19	23.0°C – 26.0°C
10	Y10_AverageTemperature_Horizontal Section Floor plan-2 120 cm	33.68	33.07	°C	0.61	23.0°C – 26.0°C
Note: Higher air velocity helps improve thermal comfort when room temperatures are high (27–31°C).						

The results of the ventilation performance analysis show that the average velocity values for the volume of floor 1, the volume of floor 2, and the total volume of floors 1 and 2, as well as on the floor plans of floors 1 and 2 at an elevation of 120 cm from the floor, (120 cm is the standard comfortable height for residential activities), shows that the void courtyard has higher performance, with an average velocity of 2.17 m/s in certain zones, especially in the space around the courtyard. The average velocity value in the floor space of floors 1 and 2 in row houses that use interior voids is 1.84 m/s, so the difference in ventilation performance between the two void designs is 0.33 m/s. According to the standards of ASHRAE Standard 55 - 2013 and Lechner (2015), this difference will improve ventilation performance in other spaces, particularly on the second floor.

5 Conclusions and recommendations

5.1 Conclusions

This study confirms the superior performance of courtyard-based natural ventilation design, particularly when utilizing the stack effect principle, in comparison to conventional interior void configurations. The findings highlight several critical insights:

- Courtyard design demonstrates enhanced ventilation efficiency, showing higher airflow velocity compared to interior void systems. This supports its validity as a passive ventilation strategy in tropical residential architecture.
- In this case study, the average airflow velocity within the courtyard-based design reached 2.18 m/s, closely approaching the microclimatic ambient velocity of 2.3 m/s. Notably, certain zones within the building recorded even higher velocities, further emphasizing the courtyard's role in promoting effective air movement.
- For row house typologies, which typically face limitations in façade exposure and opening configurations (both inlet and outlet), the integration of a central courtyard has proven to significantly enhance natural ventilation performance. This solution not only supports thermal comfort but also offers a sustainable alternative to mechanical ventilation, contributing to energy reduction in residential buildings.
- The use of courtyards as a natural ventilation system contributes to indoor air quality improvement through increased air exchange rates (ACH – air changes per hour). Therefore, this design element aligns with sustainable building principles and occupant health considerations.

5.2 Recommendations

Based on the findings, the following recommendations are proposed for architectural design and further research:

- It is strongly advised to position the courtyard at the center of the building layout, particularly for row houses, to promote a more uniform distribution of airflow and increased air velocity throughout interior spaces.
- The precise positioning of the courtyard significantly influences the thermal performance of the building. Strategically placed courtyards can effectively reduce indoor air temperature, enhancing passive cooling potential.
- While the current research provides promising results, it is recommended that future studies explore variations in courtyard dimensions, positions, and geometric configurations to determine the most effective design parameters for optimizing natural ventilation performance in different building typologies and climatic conditions.

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