

Comparison of Horizontal and Vertical Natural Ventilation Strategies in Urban Townhouses

Chalermwat Tantasavasdi^{1,2,*}, Natthaumporn Inprom^{1,2}

¹ Faculty of Architecture and Planning, Thammasat University, Thailand

² Thammasat University Research Unit in Architecture for Sustainable Living and Environment, Thammasat University, Thailand

* Corresponding e-mail: tchalerm@engr.tu.ac.th

Received 2025-12-21; Revised 2026-04-06; Accepted 2026-05-15

ABSTRACT

This research proposes horizontal and vertical natural ventilation strategies for upper-floor bedrooms of typical townhouse buildings, aiming to solve problems caused by single-sided ventilation and wind obstruction from adjacent buildings in housing development projects. A comparative study of ventilation performance was conducted for various building scenarios using Computational Fluid Dynamics (CFD) simulation under four design-strategy variables, two wind directions, two different street widths, and two townhouse layout types, totaling 32 cases. The results show that the bedrooms of typical townhouses have very low air movement through the average indoor air velocity coefficient ($Cv_i = 0.01\text{--}0.03$) and very low airflow rate through the product of air velocity coefficient at openings and inlet area ($Cv_o \times A = 0.01\text{--}0.04$) values, especially in second-floor bedrooms with single-sided ventilation. Vertical and horizontal ventilation strategies can slightly increase the Cv_i , while significantly improving the $Cv_o \times A$ values, enabling indoor air quality to meet the required ventilation criteria. The one-way wind catcher provides the highest values in $Cv_o \times A$ ($0.08\text{--}0.13$), followed by the two-way wind catcher ($Cv_o \times A = 0.04\text{--}0.13$), and then the horizontal ventilation strategy ($Cv_o \times A = 0.04\text{--}0.11$). From comparing the influence of the four variables on the ventilation performance of townhouses, the design-strategy variable has the greatest impact on increasing Cv_i and $Cv_o \times A$ values, followed by wind direction, and then street width and layout type, which have similar levels of influence. The findings ultimately give a comprehensive set of guidelines for townhouse design in urban conditions.

Keywords: cross ventilation, wind catcher, wind direction, street width, CFD simulation

INTRODUCTION

According to United Nations projections, by 2050 an estimated 68% of the world's population is expected to live in urban areas, an increase of more than 13% compared with data from 2018 (United Nations, Department of Economic and Social Affairs, Population Division [UN DESA], 2019). The rapid urban expansion driven by growing population demand is particularly evident in developing countries in Asia, especially in Southeast Asia (Shankar & Lo, 2019). Residential building projects have become increasingly dense to maximize economic efficiency while keeping housing affordable for the general public. This trend aligns with current housing conditions in Bangkok and its metropolitan area, where the proportion of high-density housing types on small plots, such as townhouses, continues to rise (Tochaiwat & Pultawee, 2024).

Townhouses today share common characteristics: elongated floor plans, shared side walls, openings located only at the front and back, and a first-floor layout typically consisting of an open-plan living area connected to a kitchen. The upper floors are divided into front and rear bedrooms (Takkanon, 2006; Palaiologou & Vaughan, 2012). Most upstairs bedrooms have only one exterior opening due to the limited placement of windows at the front and back. This results in poor ventilation and negatively impacts indoor air quality, an issue that has become increasingly important to living quality, especially after the COVID-19 pandemic. Due to the airborne transmission characteristics of COVID-19, numerous previous studies have found that buildings with poor ventilation are associated with a higher risk of disease transmission (Cheung et al., 2022; Tantasavadi et al., 2024; Zhu et al., 2020). Consequently, increasing the ventilation rate within buildings has become an important mitigation strategy widely recognized by many organizations, which can be achieved through both mechanical ventilation systems and natural ventilation, such as by opening windows (Centers for Disease Control and Prevention [U.S. CDC], 2024a; World Health Organization [WHO], 2021).

Studies on improving ventilation performance in buildings with limited exterior openings, such as townhouses, have identified two main natural

ventilation strategies: horizontal and vertical. Horizontal natural ventilation refers to design approaches that support cross ventilation using elements such as courtyards (Toe & Kubota, 2015; Zakaria et al., 2015) or voids between rooms to create openings at the center of the building (Ibiyeye et al., 2016). These methods, commonly applied in townhouses in Vietnam and Malaysia, can enhance ventilation rates and reduce indoor temperatures. Vertical natural ventilation refers to the use of roof-mounted wind catchers. This technique originates from traditional architecture in desert regions, where fresh air above the building is drawn inside. Modern adaptations of this technology have been studied for contemporary buildings in various countries (Jomehzadeh et al., 2020; Sangdeh & Nasrollahi, 2020). Wind catcher systems can significantly improve ventilation performance compared with typical single-sided townhouses (Drach, 2009) and have been shown to create comfortable indoor conditions even in hot-humid climates (Sadeghi et al., 2020). Previous research also shows that combining wind catchers with windows increases ventilation rates, with performance influenced by shaft size and height (Calautit et al., 2013), shaft configuration (Montazeri & Montazeri, 2018), and window dimensions (Mohamed & El-Amin, 2022; Tantasavasdi et al., 2025).

Most of the existing studies examine only scenarios in which wind enters directly through the wind catchers on flat roofs, which have little limitation. Very few have studied wind catchers on sloped roofs, which pose greater limitations from their configuration as one wind catcher can block the wind to another. Furthermore, no research has yet investigated ventilation performance in townhouses whose airflow is constrained by the typical master-planning conditions of housing development projects. Building upon the horizontal and vertical natural ventilation strategies discussed above, this study fills the research gap by developing design guidelines tailored for improving ventilation in upper-floor bedrooms of a representative three-story townhouse, selected from current market surveys as a model of units commonly affected by single-sided ventilation and wind obstruction from adjacent buildings. These considerations lead to the following research questions:

1. How do horizontal and vertical ventilation configurations differ in their ability to enhance cross-ventilation performance in townhouse buildings within the urban context of housing development projects?

2. How do design variables that include wind direction, street width, and townhouse layout type influence indoor ventilation performance?

In answering the research questions, ventilation performance across multiple scenarios was evaluated using CFD simulation under varying design strategies, wind directions, street widths, and townhouse layout types. The resulting findings are synthesized into a set of natural ventilation design recommendations appropriate for townhouses located in dense urban environments where neighboring buildings impede airflow.

METHODOLOGY

Selecting a Base Case

This study collected data on various layouts of three-story townhouse-type row houses currently available on the market in Bangkok and its metropolitan area, covering 16 brands from 9 real estate developers. Most townhouses have a plot or building width between 5.5 and 5.8 meters, which is sufficient to accommodate two parking spaces, with plot sizes ranging from 72 to 92 square meters. The first floor of a typical townhouse is commonly organized as a continuous open-plan living, dining, and kitchen area. The second and third floors generally contain between two and four bedrooms. The location of the master bedroom varies across designs, being situated on either the second or

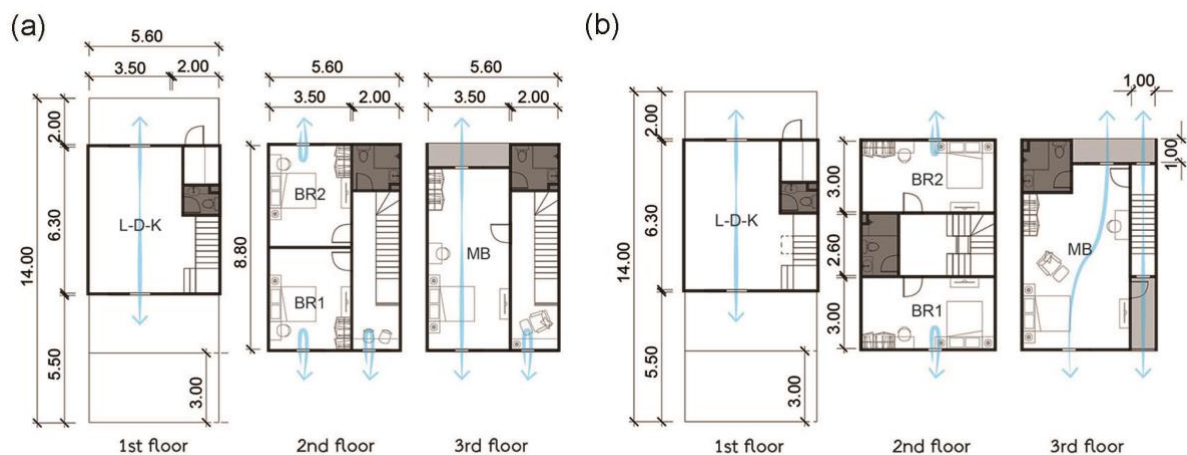
the third floor, and each floor typically contains one to two bathrooms.

The surveyed townhouses can be categorized into six layout types (Types a to e), distinguished by the arrangement of four main functional zones: (1) living spaces, consisting of the living area (L), dining area (D), kitchen (K), master bedroom (MB), and secondary bedrooms (BR); (2) bathrooms (WC); (3) stair hall; and (4) balconies (bal.), as shown in Figure 1. All types share a common characteristic—an open-plan first floor—yet differ in the placement of the stair hall, which may be located at either the front or the rear of the building. For this research, Type a, which is the most frequently occurring layout, and a combined Type bc, representing designs where the second and third floors share characteristics of Types b and c, were selected to ensure that the case-study townhouse models adequately represent the layouts most commonly found on the market.

These two layout types were further refined into standardized case-study townhouse models, referred to as Townhouse Type A and Type B. Both models were adjusted to have identical dimensions, proportions, and numbers of rooms: three bedrooms and three bathrooms; an interior width of 5.6 meters; and a plot depth of 14.0 meters. This configuration allows for a continuous row of seven units without exceeding the 40-meter maximum length permitted under the Thai Building Control Act. The interior floor-to-ceiling height is 2.6 meters. All openings were specified to have a uniform size of 0.6 meters in width and 1.0 meter in height, corresponding to the minimum dimensions commonly found in standard sliding windows available on the market. A summary of the layout configurations and window locations for the two Base Case townhouse models is presented in Figure 2.

Figure 1*Townhouse Types Identified in the Survey*

Note. Floor plan layouts (a-e); and bar chart showing the number of brands corresponding to each of the six layout types (f)

Figure 2*Floor Plans and Opening Locations on Each Floor of the Case-Study Townhouses*

Note. Type A (a); and Type B (b)

Design Solutions and Scenarios

This study focuses primarily on improving ventilation performance in upper-floor bedrooms, as these rooms typically rely on single-sided ventilation, which is inherently inefficient. Based on a review of relevant theories and contemporary design strategies that enhance cross ventilation in townhouses, three improvement approaches appropriate for the constraints of existing townhouse layouts and plot sizes were identified, as illustrated in Figure 3 and described below.

1. Horizontal Ventilation Strategy (Figure 3a–3b): This modification utilizes the stair hall as part of the ventilation pathway, combined with a ventilation opening installed above the doorway. The opening measures 1.5 meters in width and 0.4 meters in height, providing an area of 0.6 m², which is equivalent to the size of the exterior wall openings in the various rooms.

2. Vertical Ventilation Strategy 1 (Figure 3c–3d): This approach incorporates a one-sided wind catcher with a cross-sectional area of 0.6 m². The shaft acts both as an inlet and an outlet, depending on the wind direction, enabling airflow even when wind approaches the building from opposite directions.

3. Vertical Ventilation Strategy 2 (Figure 3e–3f): This approach employs a two-sided wind catcher with a total cross-sectional area of 1.2 m², consisting of 0.6 m² inlet–outlet openings on each side. The system captures high-velocity wind from above the building on two opposite sides and channels it into the interior, allowing air to exit through the existing exterior wall openings.

4. Both vertical ventilation strategies offer the advantage of drawing in high-velocity air from above the building, which is not obstructed by adjacent structures, thereby enhancing indoor airflow. However, this improvement comes at the cost of reduced usable interior space due to the additional shaft area required. In addition to the townhouse layout (Types A and B) and ventilation strategies (Base Case, Horizontal, Vertical 1 and Vertical 2), this study also examines the influence of wind direction (windward-front and windward-rear conditions) and street width (9 m and 16 m) on ventilation performance. In total, 32 simulation cases were conducted, as summarized in Table 1.

CFD Simulation Setups and Validation

This study employed CFD simulation using Phoenix version 2022, which solves the Reynolds-averaged Navier–Stokes (RANS) equations and uses a structured grid to analyze air velocity. The simulations adopted a coupled approach in which indoor and outdoor airflow is computed simultaneously—an approach well suited for natural ventilation studies influenced by building morphology (Tong et al., 2016). The Standard k – ϵ turbulence model was applied, and the minimum grid size within the building was set to 0.2 m, following Tantasavasdi et al. (2025), who validated the accuracy of the software against the study by Montazeri and Montazeri (2018), whose model incorporated a wind catcher and window configuration comparable to that used in the present research. As this study focuses on cross ventilation generated by openings on opposite façades, the influence of the buoyancy effect is expected to be minimal. Therefore, the energy equation was not activated in the simulation, allowing the analysis to focus primarily on wind-driven airflow.

For each case, the CFD domain extended five times the building height upstream, above, and laterally (61.0 m), and ten times the building height downstream (122.0 m), as recommended by Tominaga et al. (2008). The domain boundaries and townhouse locations for the windward-front and windward-rear conditions are shown in Figure 4a and Figure 4b, respectively. Boundary conditions for all scenarios used an external wind profile as demonstrated in Figure 4c. The inlet wind speed at any height level was calculated using the following relationship: $U_h = U_{met} (\delta_{met}/H_{met})^{a_{met}} (H/\delta)^a$ where U_h represents the wind speed at the inlet at a given height (m/s). U_{met} is the reference wind speed, taken as 2 m/s. H_{met} denotes the reference measurement height from the meteorological station (m), which is assumed to be 10 m. H represents the height of the inlet level (m). The parameter a is the terrain roughness exponent for the surrounding area of the building, taken as 0.22, while a_{met} is the terrain roughness exponent corresponding to the surroundings of the meteorological measurement station, also taken as 0.22.

Figure 3*Floor Plans and Opening Locations on Each Floor of the Improved Townhouse Cases*

Note. A–Horizontal (a); B–Horizontal (b); A–Vertical 1 (c); B–Vertical 1 (d); A–Vertical 2 (e); and B–Vertical 2 (f)

Table 1*Input Variables for Each CFD Simulation Scenario*

Case	Layout type	Ventilation strategy	Wind direction		Street width	
			Front	Rear	9 m	16 m
1	A	Base case	o		o	
2			o			o
3				o	o	
4				o		o
5		Horizontal	o		o	
6			o			o
7				o	o	
8				o		o
9		Vertical 1	o		o	
10			o			o
11				o	o	
12				o		o
13		Vertical 2	o		o	
14			o			o
15				o	o	
16				o		o
17	B	Base case	o		o	
18			o			o
19				o	o	
20				o		o
21		Horizontal	o		o	
22			o			o
23				o	o	
24				o		o
25		Vertical 1	o		o	
26			o			o
27				o	o	
28				o		o
29		Vertical 2	o		o	
30			o			o
31				o	o	
32				o		o

Furthermore, δ represents the atmospheric boundary layer thickness associated with the terrain surrounding the building, assumed to be 370 m, and δ_{met} represents the atmospheric boundary layer thickness corresponding to the terrain surrounding the meteorological station, also taken as 370 m.

Adjacent buildings were modeled to replicate the obstruction effects commonly found in typical

townhouse developments, consisting of perpendicular rows of units forming two upwind blocks and one downwind block. This configuration represents the influence region, defined as the surrounding building context that affects airflow patterns and pressure distribution around the target building, in accordance with established urban CFD guidelines (Tominaga et al., 2008). These surrounding buildings were modeled as solid volumes without openings or

façade details. For the case-study buildings, the first floor was modeled as a solid block, while upper floors were represented using zero-thickness plates. No interior furniture or occupants were included in the simulations. In calculations, convergence criteria for all simulations required residuals of mass to be below 0.1% (Srebric & Chen, 2002).

Air velocity data were extracted for each CFD case in two ways: (1) at the occupant level, measured on a 0.5×0.5 m grid across each bedroom at a height of 1.1 m—representing the breathing zone (Srivastava et al., 2021); and (2) at all opening surfaces, measured on a 0.2×0.2 m grid (Figure 4d). The air velocities measured at various locations in each townhouse case were used to calculate the average velocity coefficient (C_v). The C_v value is appropriate for this study because it is a dimensionless parameter calculated as the ratio between the actual air velocity observed in a case and the reference wind speed. Consequently, it can be readily applied to estimate indoor air velocities at different locations under other reference wind conditions. The indoor velocity coefficient (C_{v_i})

was derived from the velocities measured at the breathing zone height, while the velocity coefficient at the openings (C_{v_o}) was calculated from the velocities measured at the openings. The C_{v_i} value reflects the air velocity within a room and is therefore suitable for analyzing thermal comfort. When C_{v_o} is multiplied by the inlet opening area (A), the result implies the ventilation rate of the room. The calculation is shown in Equation (1) below for comparing ventilation performance among the improvement strategies.

$$C_v = \frac{1}{n} \times \sum_{i=1}^n (v_i / v_h) \quad (1)$$

where

C_v = average velocity coefficient

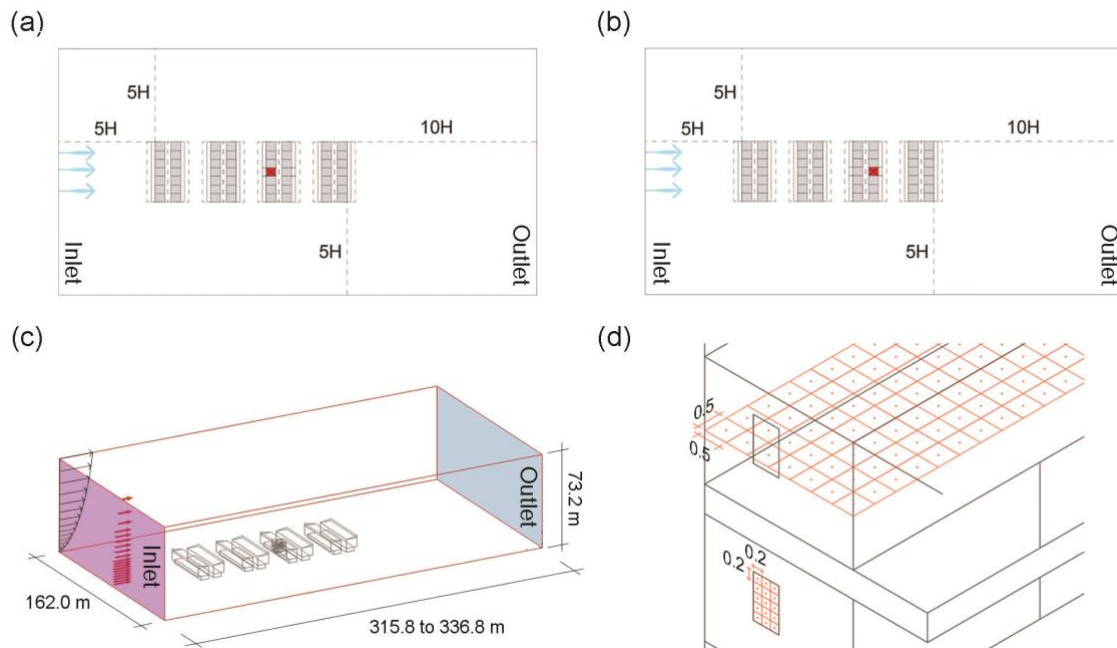
v_i = mean velocity at location i at breathing zone height or at opening (m/s)

v_h = mean outdoor reference freestream velocity at breathing zone height (m/s)

n = number of measurement locations in the model

Figure 4

Components of the CFD Simulation



Note. Setback distances and townhouse configuration for the windward-front condition (a); setback distances and configuration for the windward-rear condition (b); domain size and boundary conditions (c); and measurement points for air velocity evaluation in the model (d)

Subsequently, indoor air quality for each scenario was evaluated by calculating air changes per hour (ACH) using Equation (2), combining the $Cv_o \times A$ values with a 10-year dataset of hourly mean wind speeds in Bangkok (Tantasavasdi & Inprom, 2023), which reports outdoor wind speeds at breathing zone height ranging from 1.8 to 3.8 m/s. These results will demonstrate the study's application to an actual climatic condition. In addition, the appropriate range of Cv values depends on the external reference wind speed. If the reference wind speed (V_h) is 2 m/s, $Cv_o \times A$ should be at least 0.03–0.06 for rooms with an area of 16–32 m² in residential buildings in order to achieve an adequate ventilation rate of approximately 5 ACH (U.S. CDC, 2024b). On the other hand, a suitable Cv_i should be at least 0.1, which would correspond to an indoor air velocity of approximately 0.2 m/s—the threshold at which occupants begin to perceive airflow (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2023).

$$ACH = \frac{3600}{V} \times (Cv_o \times A) \times v_h \quad (2)$$

where

ACH = air changes per hour

V = room volume (m³)

RESULTS

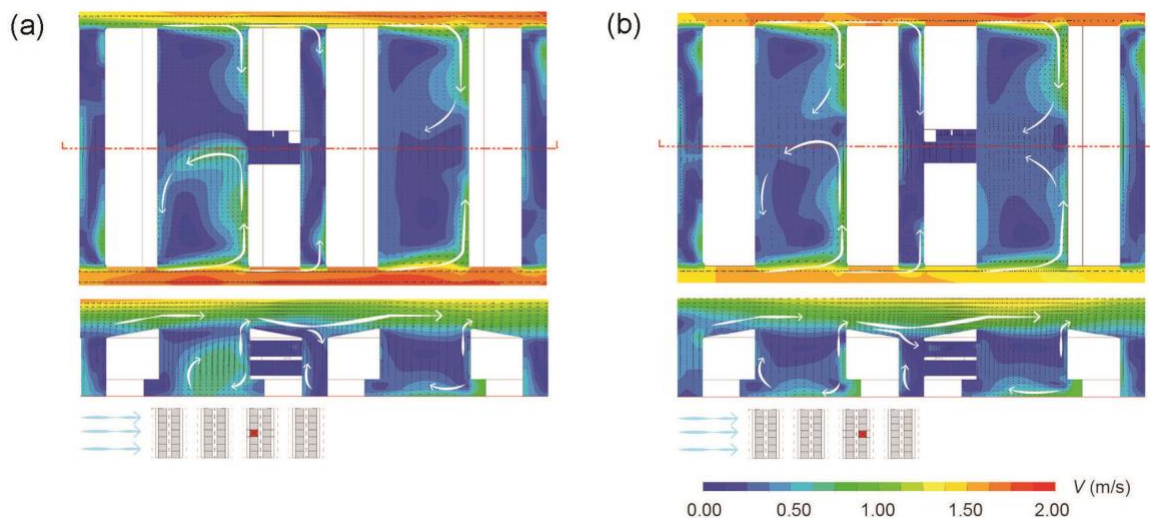
Airflow Around the Buildings

The results of the ventilation analysis around the buildings at the master-plan level across all 32 cases indicate that airflow patterns around the various areas of the housing project are similar for both Townhouse Type A and Type B, regardless of whether the street width is 9 m or 16 m, as illustrated in Figure 5. The linear grid arrangement of the townhouse blocks results in wind obstruction caused by the upwind buildings. Consequently, airflow entering the case-study units originates from two primary sources: (1) wind approaching from open spaces located at the sides of the townhouse blocks, which first impinges on the building façades and then deflects into the street canyons between buildings, and (2) wind flowing over the top of the upwind buildings and descending into the leeward areas behind them.

The behavior of wind entering the openings of the case-study townhouses differs between windward-front and windward-rear conditions. In the scenario where wind acts on the front façade (Figure 5a), most of the airflow entering the

Figure 5

Example of CFD Results at the Master-Plan Scale



Note. Showing the second-floor plans and sections of Townhouse Type A with a 9-m street width under windward-front conditions (a); and windward-rear conditions (b)

building comes through the openings on the rear wall (the leeward side). This occurs because the roof forms of the upwind townhouse blocks are upward-tilted, causing the incoming wind to rise, pass over the study block, and descend along the sloped roof toward the rear of the building. Under this master-plan-level airflow condition, when wind acts on the rear façade (Figure 5b), the airflow enters primarily through the windward openings located on the rear wall of the building.

Indoor Airflow Under Windward-Front Conditions

The airflow behavior inside the buildings under windward-front conditions with a 9-m street width is similar to that observed with a 16-m street width. In nearly all scenarios, wind enters the rooms primarily through the openings on the rear façade (the leeward side) due to similar master-plan-level influences. For Townhouse Type A, shown in Figure 6, the Base Case and Horizontal configurations exhibit airflow patterns consistent with the predictions (Figure 6a). In contrast, the Vertical 1 and Vertical 2 configurations display different airflow characteristics on the second floor. On the third floor, a portion of the airflow diverts through the wind catcher shaft before reaching the occupied zones located deeper inside the rooms.

Each cross ventilation strategy improves air velocity at various indoor locations to a modest extent in nearly all scenarios ($Cv_i = 0.02$ – 0.03 and $Cv_o \times A = 0.04$ – 0.09), compared with the Base Case ($Cv_i = 0.01$ and $Cv_o \times A = 0.03$ – 0.04) (Figure 6b). The improvements are particularly notable in the master bedroom and Bedroom 2, both located on the rear side of the building. For the 9-m street-width cases, the Horizontal and Vertical 2 strategies provide the greatest improvement in average Cv_i at the breathing zone level ($Cv_i = 0.03$), whereas Vertical 1 achieves the highest increase in $Cv_o \times A$ at the openings ($Cv_o \times A = 0.08$). For the 16-m street-width cases, Vertical 1 performs best overall, yielding the highest average values of both Cv_i (0.03) and $Cv_o \times A$ (0.09).

For Townhouse Type B, shown in Figure 7, the CFD results indicate that the Base Case and Horizontal configurations exhibit airflow patterns

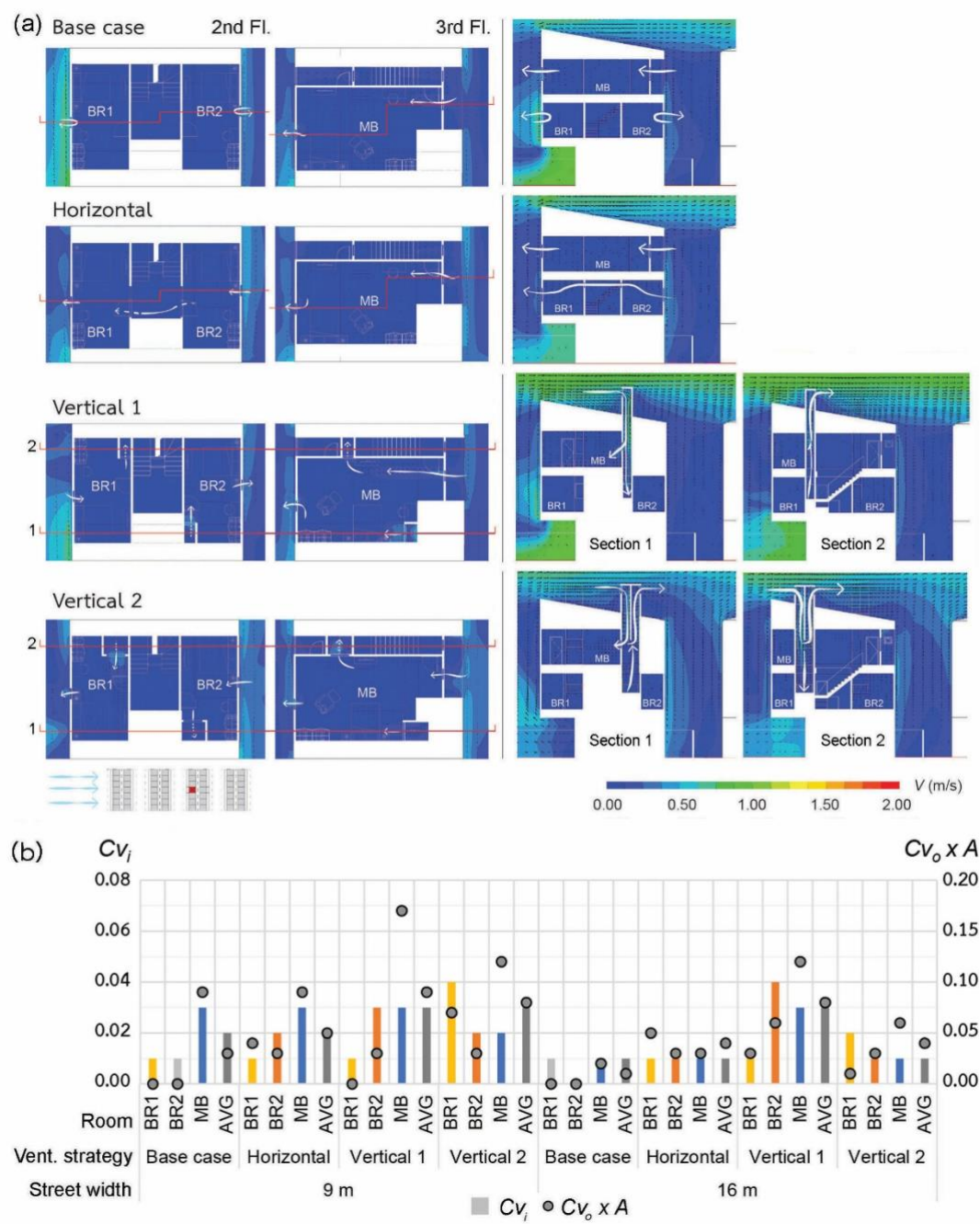
consistent with the expected design predictions (Figure 7a). In contrast, the Vertical 1 and Vertical 2 cases show differing airflow directions in the second-floor bedrooms: the direction of inflow and outflow in Vertical 1 is opposite to that of Vertical 2. This phenomenon is attributable to the differing degrees of airflow obstruction above the roof. The wind catcher shaft in Vertical 2 is larger, resulting in higher wind speeds at the rear of the building compared with Vertical 1. Consequently, wind enters through the rear openings in Vertical 2, whereas in Vertical 1, wind enters from the front openings.

The cross ventilation strategy in the Horizontal configuration does not significantly affect Cv_i but increases the average value of $Cv_o \times A$ (Figure 7b). In contrast, both Vertical strategies (Vertical 1 and Vertical 2) increase average Cv_i and $Cv_o \times A$, consistent across both street widths (9 m and 16 m). Among the configurations, Vertical 1 yields the greatest improvement in both Cv_i and $Cv_o \times A$ compared with the Base case ($Cv_i = 0.01$ – 0.02 , $Cv_o \times A = 0.01$ – 0.03). For Vertical 1, the values reach 0.03 and 0.09, respectively, when the street width is 9 m, and 0.03 and 0.08, respectively, when the street width is 16 m.

Indoor Airflow Under Windward-Rear Conditions

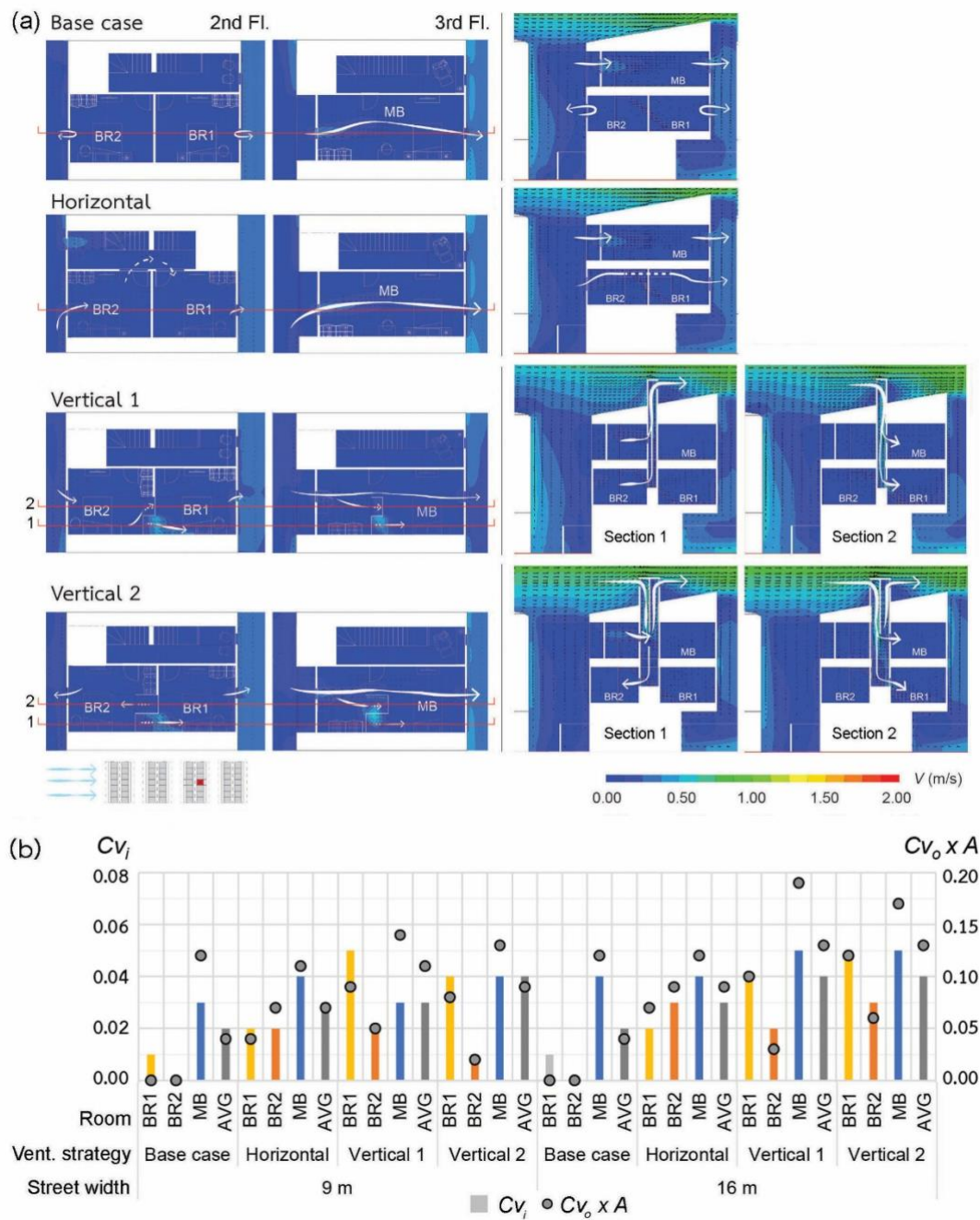
The airflow patterns inside the building under windward-rear conditions differ markedly from those under windward-front conditions due to the influence of the master plan. The cases with a 9-m street width exhibit airflow characteristics similar to those with a 16-m street width. In almost all scenarios, wind enters the rooms through the rear openings of the building (the windward side). For Townhouse Type A, as shown in Figure 8, the general directions of inflow and outflow behave as expected in all configurations, except in the Vertical 1 and Vertical 2 cases (Figure 8a). In these cases, some of the wind entering the master bedroom (MB) from the rear-wall windows shortcuts through the wind catcher shaft before distributing to other parts of the room. This short-circuiting is especially prominent in Vertical 2, which has a larger wind catcher area located near the center of the room.

Figure 7
Results of Townhouse Type B Under Windward-Front Conditions and 9-M Street Width



Note. CFD results at the second- and third-floor levels and sections (a); and Cv_i and $Cv_o \times A$ values for each case (b)

Figure 8
Results of Townhouse Type A Under Windward-Rear Conditions and 9-M Street Width



Note. CFD results at the second- and third-floor levels and sections (a); and Cv_i and $Cv_o \times A$ values for each case (b)

Each cross ventilation strategy improves the average indoor air velocity at various points, particularly the Vertical 1 and Vertical 2 configurations, which enhance airflow in the second-floor bedrooms (Figure 8b). The Base Case exhibits the lowest average Cv_i and $Cv_o \times A$ values, which remain unchanged regardless of

street width ($Cv_i = 0.02$, $Cv_o \times A = 0.04$). When the street width is 9 m, the Vertical 2 configuration provides the greatest improvement in Cv_i (0.04), while the Vertical 1 configuration yields the highest average $Cv_o \times A$ (0.11). When the street width increases to 16 m, both Vertical 1 and Vertical 2 deliver the highest values of Cv_i

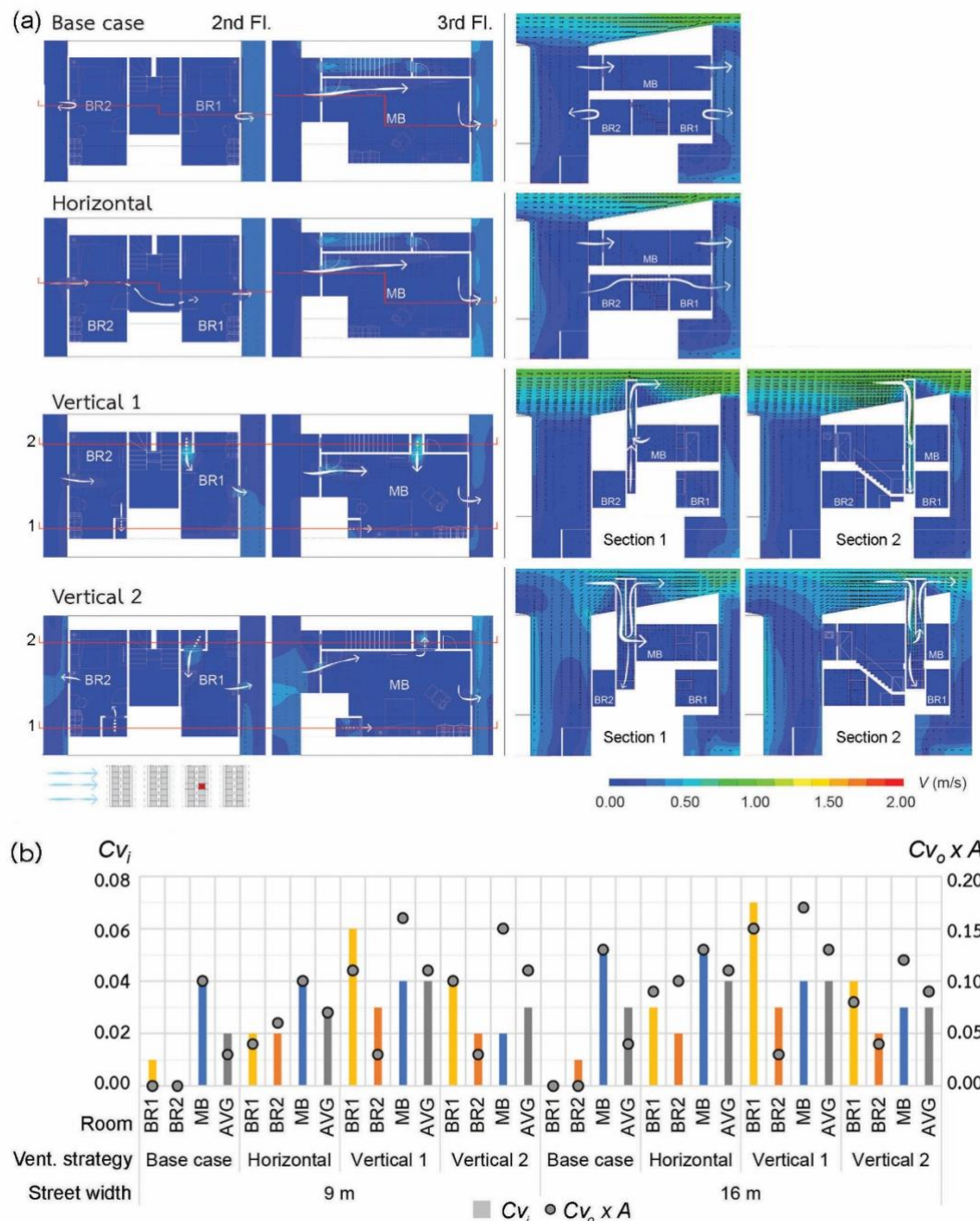
and $Cv_o \times A$, with identical results of 0.04 and 0.13, respectively.

For Townhouse Type B, shown in Figure 9, most of the wind entering the building continues to flow through the rear openings, and the overall inflow–outflow patterns behave as expected in nearly all scenarios (Figure 9a). In the Vertical 2

configuration, which features a larger wind catcher shaft, short-circuiting within the master bedroom is less pronounced compared with Townhouse Type A. This difference arises from the layout of the wind catcher shaft in Type B, which is more spatially distributed and positioned closer to the exterior walls than in Type A.

Figure 9

Results of Townhouse Type B Under Windward-Rear Conditions and 9-M Street Width



Note. CFD results at the second- and third-floor levels and sections (a); and Cv_i and $Cv_o \times A$ values for each case (b)

All cross ventilation strategies improve the average air velocity at various indoor positions, with Vertical 1 and Vertical 2 particularly enhancing airflow in the second-floor bedrooms (Figure 12b). The Base Case exhibits the lowest values of Cv_i (0.02–0.03) and $Cv_o \times A$ (0.03–0.04). Each cross ventilation approach yields better airflow performance ($Cv_i = 0.04$). When the street width is 9 m, Vertical 1 provides the greatest improvement in Cv_i . For the 16-m street condition, the Horizontal and Vertical 1 strategies produce the highest Cv_i . With respect to $Cv_o \times A$, when the street width is 9 m, both Vertical 1 and Vertical 2 yield the highest and equal average values (0.11). When the street width increases to 16 m, the Vertical 1 configuration provides the highest $Cv_o \times A$ value of 0.13.

DISCUSSION

Influence of Key Variables on Ventilation Performance

The findings were analyzed according to the independent variables in this study—ventilation strategy, wind direction, street width, and townhouse layout—to determine the relative importance of each factor affecting indoor airflow behavior. Regarding ventilation strategy, all three cross ventilation improvement approaches yielded higher values of Cv_i and $Cv_o \times A$ compared with the Base Case, which had single-sided ventilation, as shown in Figure 10. The improvement in $Cv_o \times A$ was particularly pronounced. The vertical ventilation strategies (Vertical 1 and Vertical 2) consistently enhanced ventilation performance more than the Horizontal strategy, which was limited by obstruction from adjacent buildings, resulting in lower pressure area at the front of the buildings. As expected, the Base Case with single-sided ventilation exhibited the lowest performance across all scenarios.

The Vertical 1 strategy produced higher average $Cv_o \times A$ values than Vertical 2 in nearly all cases, ranging from 1.1 to 2.0 times greater. This was

because, in most scenarios, airflow entered the building primarily through the wind catcher. In contrast, the Vertical 2 strategy experienced short-circuiting of airflow, where part of the incoming air exited before reaching the lower bedroom, resulting in lower efficiency than Vertical 1. This outcome is consistent with previous studies (Montazeri & Montazeri, 2018). Vertical 1 provided the highest increase in average $Cv_o \times A$ relative to the Base Case, yielding improvements of 2.8 times for Townhouse Type A and 3.7 times for Townhouse Type B. The results for Cv_i varied by townhouse layout type. In Townhouse Type A, Vertical 2 produced the highest average Cv_i , increasing 2.2 times over the Base Case. On the other hand, in Townhouse Type B, Vertical 1 yielded the greatest improvement in Cv_i , increasing 1.8 times relative to the Base Case.

When comparing the influence of wind direction on the building, it was found that windward-rear cases produced higher values of Cv_i and $Cv_o \times A$ than windward-front cases. This trend was consistent across all 32 scenarios, as shown in Figure 11. For Townhouse Type A, wind approaching from the rear resulted in average Cv_i and $Cv_o \times A$ values that were approximately 1.5 times higher than those observed when the wind approached from the front. For Townhouse Type B, wind approaching from the rear produced average Cv_i and $Cv_o \times A$ values that were approximately 1.7 and 1.6 times higher, respectively, compared to wind approaching from the front.

This phenomenon is attributed to the influence of the roof geometry of the townhouses, consistent with previous studies on the effects of sloped roofs (Tominaga et al., 2024). The buildings in the present study feature roofs sloping from the front toward the rear (Figure 12). As a result, wind flowing above the building is directed downward along the roof slope and into the open space behind the building, creating a higher air pressure area. Therefore, the air can enter the building openings more effectively in cases where the building is located in the windward-rear position (Figure 12a) than in cases where the building is in the windward-front position (Figure 12b).

Figure 10
Bar Chart Illustrating the Values of Cv_i and $Cv_o \times A$ Categorized by Ventilation Strategy

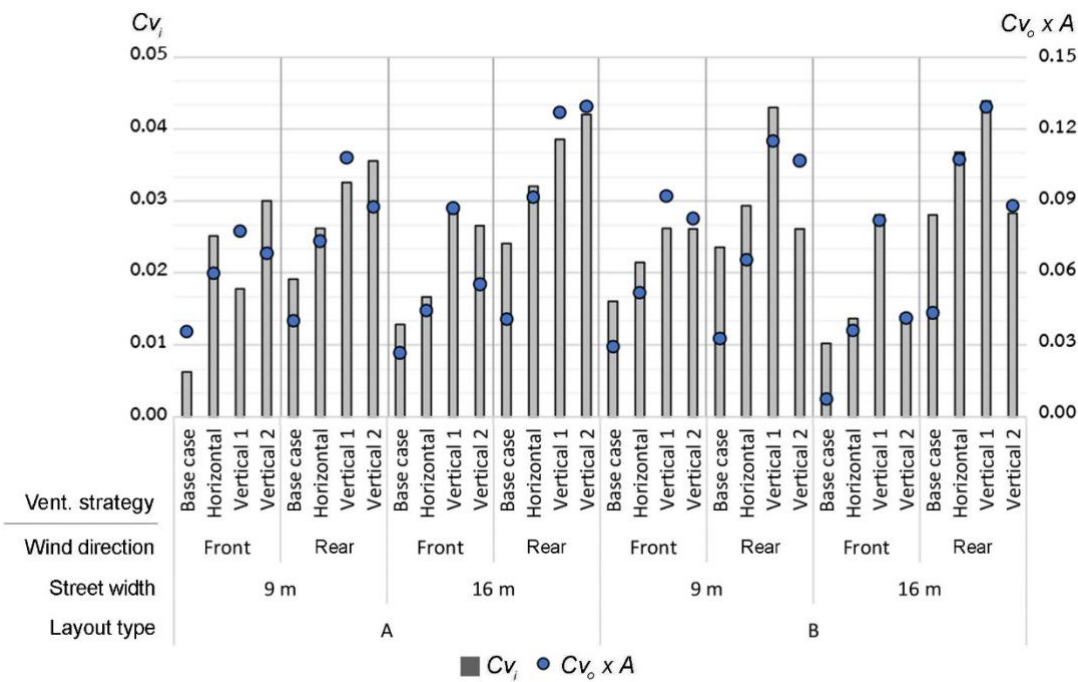


Figure 11
Bar Chart Illustrating the Values of Cv_i and $Cv_o \times A$ Categorized by Wind Direction

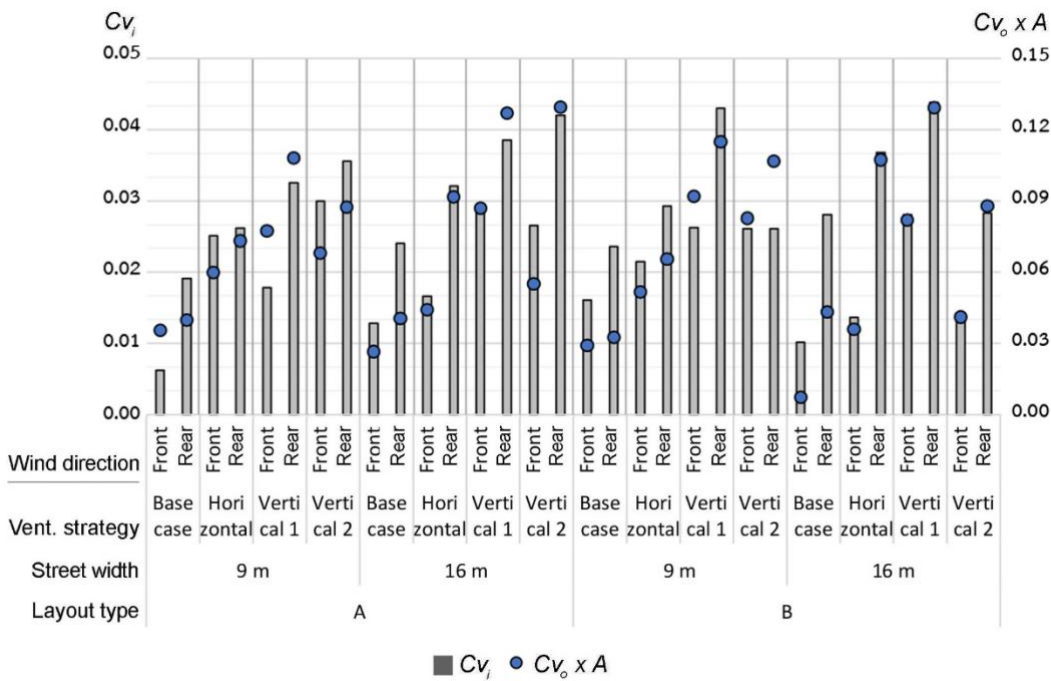
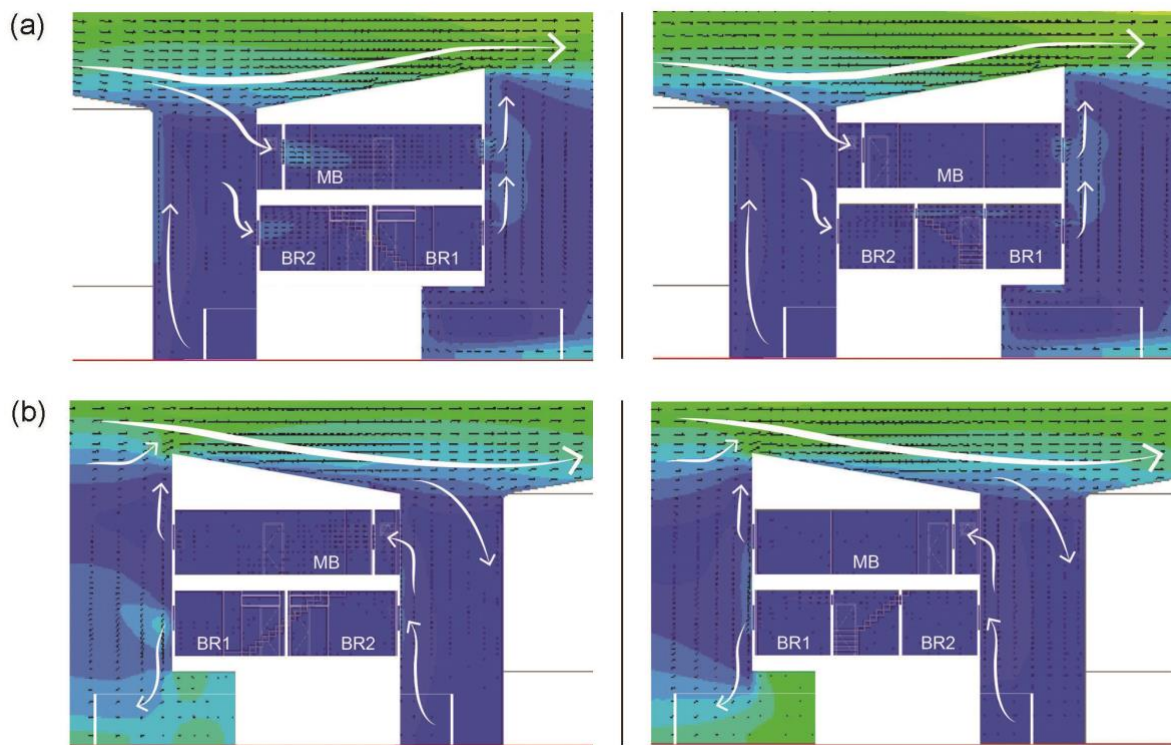


Figure 12*CFD Results for Sectional Views of Townhouse Type A and Type B*

Note. Windward-rear conditions (a); and windward-front conditions (b)

Regarding street width, previous research has shown that wind speed around buildings is influenced by the height-to-street-width ratio (H/W). Wind speeds along the street tend to be higher when the H/W ratio is low than when it is high (Jareemit & Srivanit, 2019). This is consistent with the findings of the present study when considering wind speeds in comparable ground-level areas surrounding the buildings. However, when examining the Cv_i and $Cv_o \times A$ values of the buildings, the patterns vary depending on the combined effects of wind direction and building position, as shown in Figure 13.

In windward-front cases, increasing the street width results in reduced ventilation performance: In 5 out of 8 cases, Cv_i decreased, and in 6 out of 8 cases, $Cv_o \times A$ decreased. This may be because most of the incoming air enters from the rear of the building, where the air pressure is low and recirculating airflows with lower wind speeds dominate, making the overall trend less predictable. In contrast, in windward-rear cases,

increasing street width from 9 m to 16 m generally enhances ventilation performance. In all 8 cases, Cv_i increased by an average factor of 1.2, and in 7 out of 8 cases, $Cv_o \times A$ increased by an average factor of 1.3.

Regarding the building layout variables of the townhouse configurations, the trends in wind speed vary depending on the combined influence of ventilation strategies and wind direction, as demonstrated in Figure 14. Although Townhouse Type A has a slightly higher opening-to-floor-area ratio ($OFR = 4.0\text{--}10.0\%$) for the bedrooms compared with Townhouse Type B ($OFR = 3.6\text{--}7.8\%$), the ventilation performance differs by wind direction. In windward-front cases, Townhouse Type A generally exhibits higher Cv_i and $Cv_o \times A$ values than Townhouse Type B, with both metrics averaging 1.1 times greater. In contrast, in windward-rear cases, Townhouse Type B tends to achieve higher Cv_i and $Cv_o \times A$ values than Townhouse Type A, averaging 1.2 times higher for both metrics.

Figure 13

Bar Chart Illustrating the Values of Cv_i and $Cv_o \times A$ Categorized by Street Width

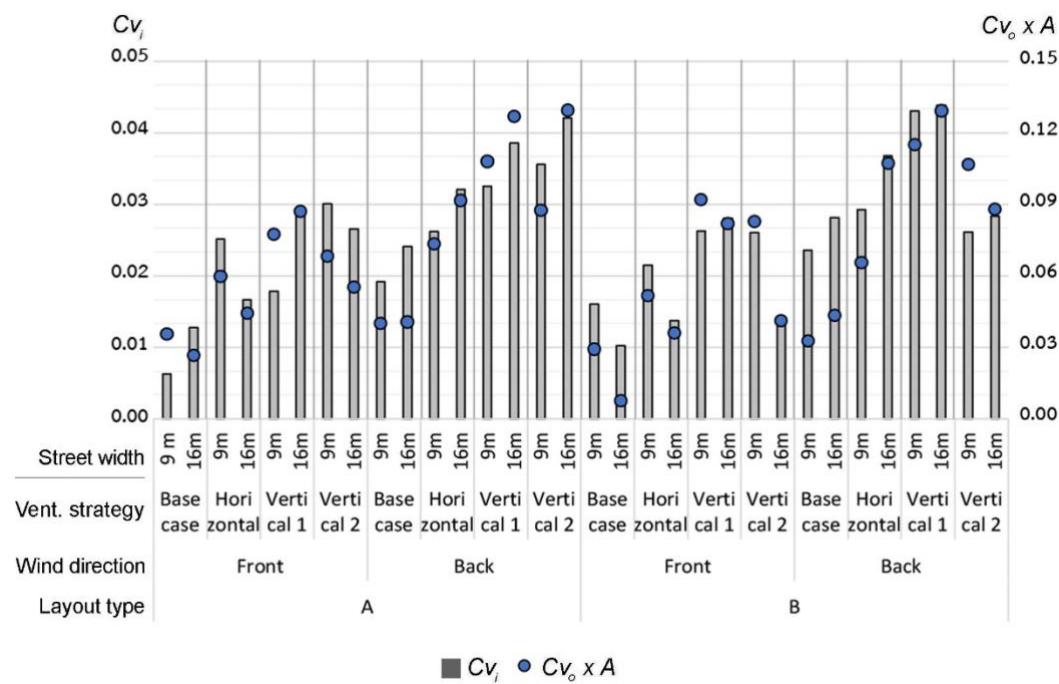
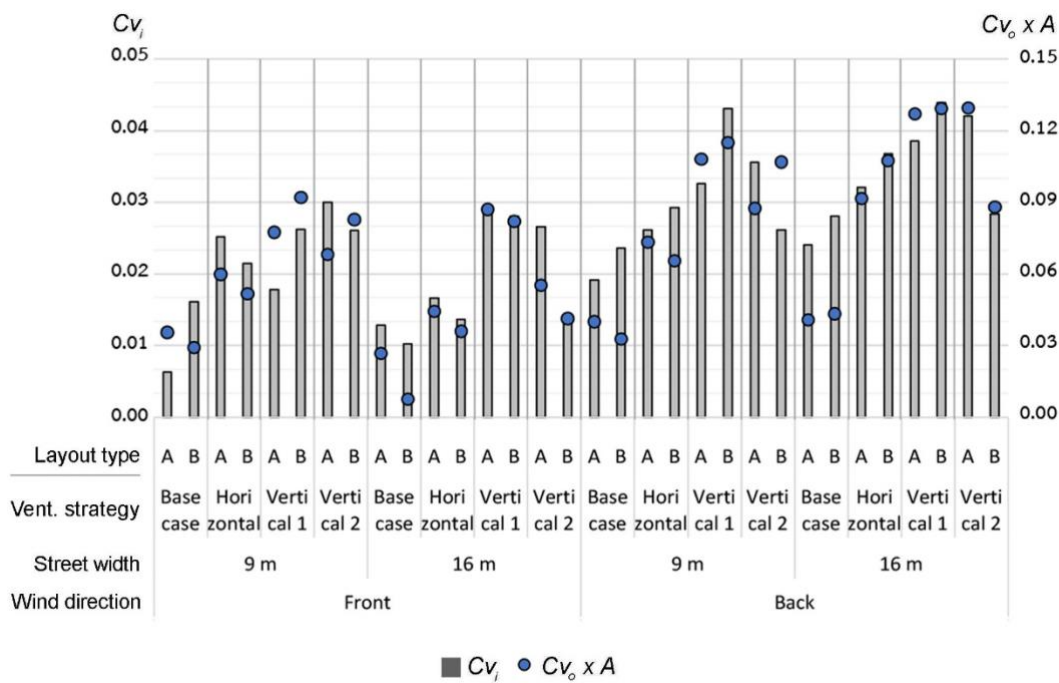


Figure 14

Bar Chart Illustrating the Values of Cv_i and $Cv_o \times A$ Categorized by Layout Type



When the individually analyzed variables are examined collectively, the trends in Cv_i and $Cv_o \times A$ become clearer, as illustrated in Figure 15. Among the four key design-related variables, ventilation strategy has the greatest influence on changes in Cv_i and $Cv_o \times A$, followed by wind direction, while the effects of street width and townhouse layout type exhibit the trends relatively similar to one another. The Vertical 1 ventilation strategy yields the largest improvement, expanding the range of Cv_i to 0.02–0.04 and $Cv_o \times A$ to 0.08–0.13, compared with the base case, which shows Cv_i values of 0.01–0.03 and $Cv_o \times A$ values of 0.01–0.04. In windward-rear cases, the ranges of Cv_i (0.02–0.04) and $Cv_o \times A$ (0.03–0.13) are greater than the windward-front cases, which produces Cv_i values of 0.01–0.03 and $Cv_o \times A$ values of 0.01–0.09. For street width, the 16-meter street displays Cv_i (0.01–0.04) and $Cv_o \times A$ (0.01–0.13) ranges similar to the 9-meter street, which has Cv_i values of 0.01–0.04 and $Cv_o \times A$ values of 0.03–0.11. Likewise, Townhouse Type A exhibits

Cv_i (0.01–0.04) and $Cv_o \times A$ (0.03–0.13) ranges comparable to Townhouse Type B, which shows Cv_i values of 0.01–0.04 and $Cv_o \times A$ values of 0.01–0.13.

Comparison With Previous Studies

This study employed openings comparable in size to those typically found in commercially available townhouses, which are relatively small. To compare the results with a previous study by Tantasavasdi et al. (2025), additional simulations of townhouse cases were conducted, as shown in Figure 16. Townhouse Type B with the Vertical 1 ventilation strategy was selected because its spatial layout and ventilation approach closely resemble those of the previous work, with the main differences being the absence of obstructing neighboring buildings and a smaller number of floors in the earlier study.

Figure 15

Box Plot Presenting the Distribution of Cv_i and $Cv_o \times A$ Across all 32 Cases

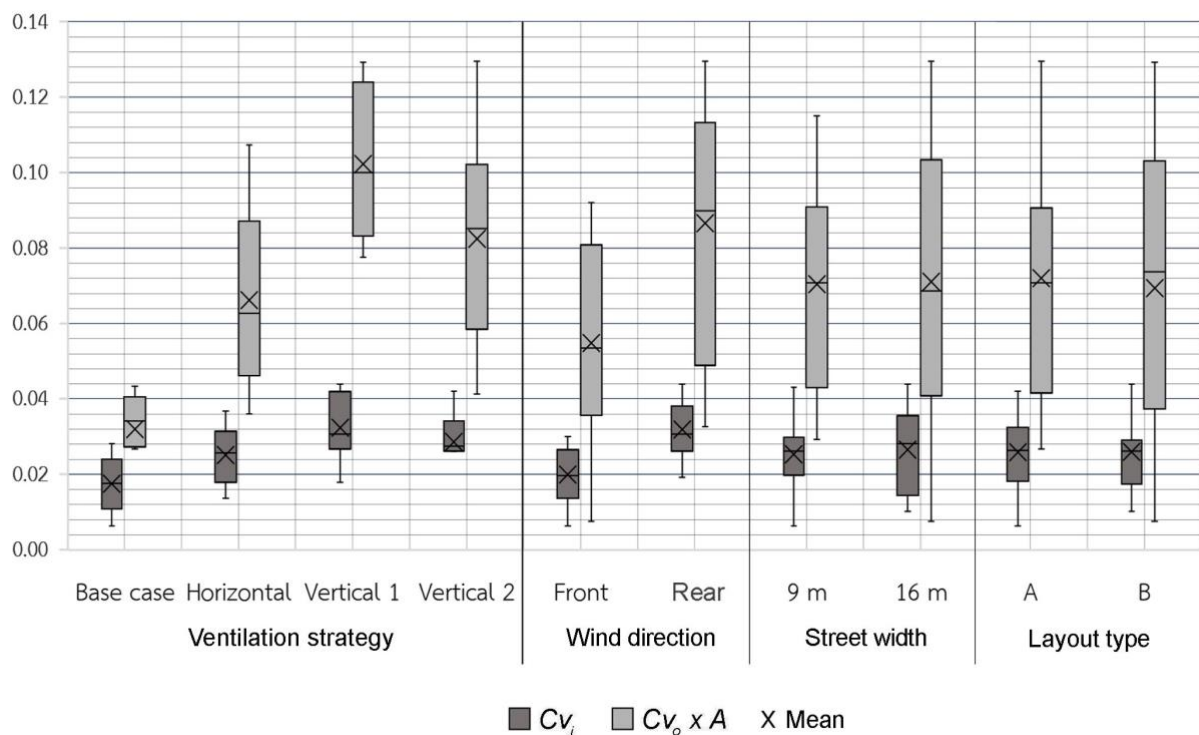
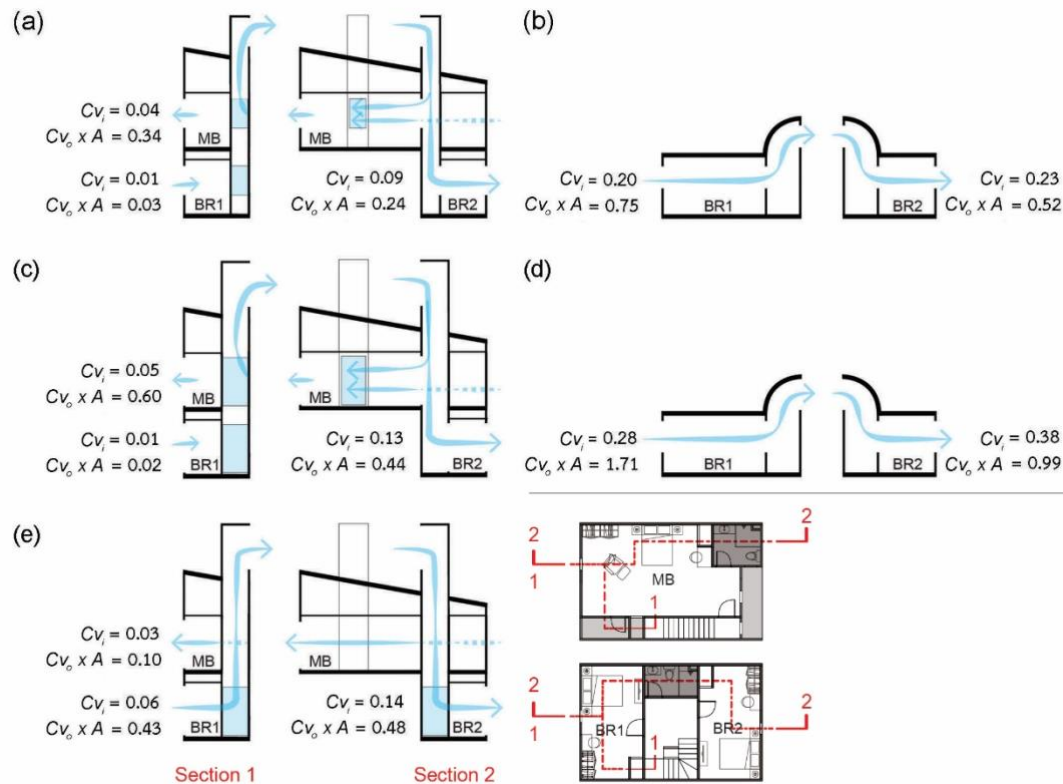


Figure 16*Comparison of Cv_i and $Cv_o \times A$* 

Note. Vertical 1 townhouses in this study (a) and townhouses in previous research with equivalent OFR of 20% (b); Vertical 1 townhouses in this study (c) and townhouses in previous research with equivalent OFR of 50% (d); and the townhouse model with wind catcher openings provided only on the second floor and floor plans (e)

The simulation results indicate that when each bedroom has an OFR of 20%, the Cv_i and $Cv_o \times A$ values of BR1 and BR2 in this study (Figure 16a) are at least two times lower than those in the previous study (Figure 16b), particularly for BR1 located at the front of the building. When the OFR of each bedroom increases to 50%, Cv_i and $Cv_o \times A$ also increase in all bedrooms, except for BR1, in this study (Figure 16c), but both bedrooms still exhibit lower Cv_i and $Cv_o \times A$ values than those reported by the previous study (Figure 16d). These comparisons demonstrate that when a townhouse has more floors and neighboring buildings that obstruct airflow, increasing the OFR does not necessarily enhance indoor ventilation performance. This is evident from BR1 (Figure 16a and 16c), which shows no significant change in Cv_i or $Cv_o \times A$.

Furthermore, the upper-level internal openings of the wind catcher located at the front of the townhouse in this study cause most incoming airflow to exit through the openings before reaching other interior spaces. To examine this effect, an additional simulation was conducted (Figure 16e), in which all upper-level internal openings of the wind catcher were closed, leaving only the wall openings for cross ventilation. The results show that closing the upper-level internal openings of the wind catcher improves ventilation in the lower rooms, increasing the ventilation rates in the front and rear bedrooms to comparable levels ($Cv_o \times A = 0.43$ and 0.48). However, the values remain lower than those in the previous study, where the building had no surrounding obstructions.

In summary, the presence of adjacent buildings that obstruct airflow can significantly reduce

ventilation rates in bedrooms by several-fold, especially in those located at the front of the building. Additionally, the findings suggest that designing separate wind catchers for each floor enhances ventilation in lower rooms more effectively than using a single shared wind catcher that disperses airflow across multiple outlets.

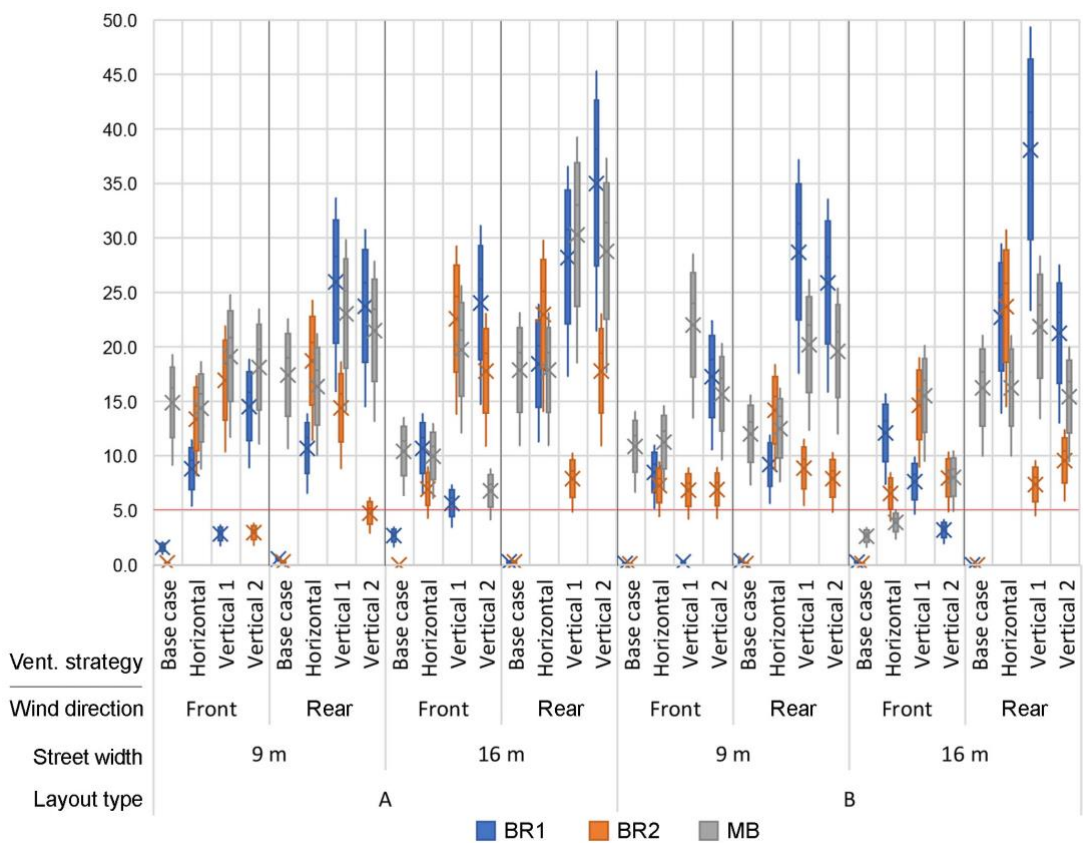
Application for Indoor Air Quality Assessment

This section demonstrates how the findings of this study can be applied to actual climatic conditions, using Bangkok as an example. The assessment was performed by calculating the air changes per hour (ACH) using Equation (2), based on the $Cv_o \times A$ values obtained from each case in this study, together with the hourly average wind speed for February over a 10-year period. The data from 2009 to 2019 was retrieved from WMO 455601/48456 (Don Mueang

International Airport). During this month, the prevailing winds originate from the south, with outdoor wind speeds at breathing zone height ranging from 1.8 to 3.8 m/s. The calculations also incorporate the volume of each bedroom and provide the results shown in Figure 17.

The evaluation follows the ACH criteria recommended by the Centers for Disease Control and Prevention Centers for Disease Control and Prevention [U.S. CDC] (2024b) for adequate ventilation in residential settings under the “new normal”—a minimum of 5 ACH. Analysis of the 24-hour average ACH for each bedroom across all 32 townhouse cases shows that second-floor bedrooms in the Base Case (both Type A and Type B) did not meet the recommended threshold in any scenario. In contrast, the master bedroom (MB), which features an original cross ventilation configuration, met the criteria in nearly all cases, with one exception: Type B with windward-front conditions and a street width of 16 m.

Figure 17
Box Plot Illustrating Sample ACH Calculations for the Three Bedrooms in Each Townhouse Case



Across all three improved ventilation strategies, the ACH of second-floor bedrooms increased substantially, enabling a greater number of cases to meet the recommended threshold. This outcome is consistent with previous findings demonstrating the effectiveness of cross-ventilation strategies in improving indoor air quality (Tantasavasdi & Inprom, 2023). In windward-rear cases, the ACH of all three bedrooms met the recommended threshold for nearly every hour, with the exception of Type A–Vertical 2 with a 9-m street width.

For windward-front cases, the optimal performance varied across ventilation strategies and was influenced by both street width and building type. In the Horizontal strategy, Type A achieved acceptable ACH levels in all three bedrooms across all scenarios, whereas Type B met the recommended threshold during most hours only when the street width was 9 m. Under the Vertical 1 strategy, both Type A and Type B achieved acceptable ACH levels for nearly every hour when the street width was 16 m. For the Vertical 2 strategy, Type A met the criteria for nearly every hour when the street width was 16 m, whereas Type B achieved acceptable ACH levels for nearly every hour only when the street width was 9 m.

CONCLUSION

This study investigates strategies for enhancing natural ventilation performance in second- and third-floor bedrooms of townhouses commonly found in contemporary housing projects. Three design approaches for introducing cross ventilation were proposed: (1) horizontal cross ventilation, (2) vertical ventilation using a one-sided wind catcher, and (3) vertical ventilation using a two-sided wind catcher. Ventilation performance in all three bedrooms of each townhouse configuration was evaluated through CFD simulations across 32 scenarios, comprising four design strategies, two wind directions, two street-width conditions, and two townhouse layout types. The results were assessed using the average indoor air velocity coefficient at the breathing zone (C_{vi}) for thermal comfort and the product of the air velocity coefficient at openings and inlet area ($C_{vo} \times A$) for indoor air quality.

The findings indicate that both Base Case townhouse types (A and B) exhibit very low average C_{vi} and $C_{vo} \times A$ values (0.01–0.03 and 0.01–0.04, respectively), particularly in second-floor bedrooms due to single-sided ventilation. The proposed cross-ventilation strategies improved $C_{vo} \times A$ substantially, especially the Vertical 1 approach, which effectively directed airflow downward from the upper wind catcher into the bedrooms. This strategy consistently yielded the highest average $C_{vo} \times A$ values (0.08–0.13) for both townhouse types. However, improvements in C_{vi} at the occupied zone were modest (0.02–0.04) and remained insufficient to achieve perceptible thermal comfort.

Among the four design variables examined, the ventilation strategy had the greatest impact on the variation of C_{vi} and $C_{vo} \times A$. Transitioning from the Base Case to cross-ventilation configurations increased C_{vi} by 100.9%–400.5% and $C_{vo} \times A$ by 166.3%–1,092.3%. The next most influential factor was wind direction, followed by street width, while differences between townhouse layout types were minimal.

An hourly assessment of indoor air quality under Bangkok's climatic conditions showed that, in the Base Case, the third-floor master bedroom (MB), which already adopts cross ventilation, generally met the recommended threshold of 5 ACH, whereas the smaller second-floor bedrooms consistently failed. Implementing cross ventilation improvements increased ACH values in second-floor bedrooms, enabling more cases to meet the recommended airflow rate. The C_{vi} and $C_{vo} \times A$ values generated in this study can therefore be applied for preliminary ventilation assessments under different climatic inputs and can assist in design decision-making to enhance natural ventilation in similar townhouse developments particularly under conditions where wind-driven effects dominate and buoyancy effects are negligible.

Beyond the four primary variables, the study also found that the relationship between wind direction and roof geometry influences ventilation performance, as airflow frequently entered the townhouses from the rear due to downward flow along the sloped roof surface. Additional simulation cases comparing this study with previous findings further revealed that the wind catcher internal openings directly affect ventilation rates. Consequently, roof geometry,

rear façade openings, and the internal openings of wind catcher shafts represent important variables for future investigation along with other urban conditions such as wind direction from various angles.

This study found that, within the context of housing developments where airflow is obstructed by adjacent buildings at the master-planning scale, increasing the area of openings intended for cross ventilation does not always improve the ventilation performance of townhouse buildings as predicted by theory. Based on these findings, several important design guidelines for natural ventilation in townhouses can be summarized as follows:

1. Designing openings on opposite façades provides better ventilation performance than single-sided openings, even in dense urban environments.
2. Under conditions where neighboring buildings obstruct airflow, vertical ventilation strategies perform better than horizontal strategies.
3. A one-sided wind catcher configuration performs better than a two-sided configuration while requiring less usable space.
4. Designing the roof form with a slope descending toward the leeward side of the building helps increase air velocity and reduces stagnant air zones behind the building.
5. The placement of openings within rooms, both on external and internal walls, should be arranged as far apart as possible to allow air to distribute more evenly and to minimize short-circuit airflow.

DISCLOSURES AND ACKNOWLEDGEMENTS

This study was supported by Faculty of Architecture and Planning, Thammasat University Research Fund, Contract No. TDS 2/2024. The authors thank Thammasat Research Unit in Architecture for Sustainable Living and Environment for their support. The authors report there are no competing interests to declare. An AI tool has been used to improve the readability of the texts but all contents are the creation of the authors.

REFERENCES

- American Society of Heating, Refrigerating and Air-Conditioning Engineers. (2023). *ANSI/ASHRAE standard 55: Thermal environmental conditions for human occupancy*. <https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy>
- Calautit, J. K., Hughes, B. R., & Ghani, S. A. (2013). A numerical investigation into the feasibility of integrating green building technologies into row houses in the Middle East. *Architectural Science Review*, 56(4), 279–296. <https://doi.org/10.1080/00038628.2012.686433>
- Centers for Disease Control and Prevention. (2024a) *About ventilation and respiratory viruses*. <https://www.cdc.gov/niosh/ventilation/about/index.html>
- Centers for Disease Control and Prevention. (2024b). *How much ventilation is enough?* <https://www.cdc.gov/niosh/ventilation/prevention/Aim-for-5.html>
- Cheung, T., Li, J., Goh, J., Sekhar, C., Cheong, D., & Tham, K. W. (2022). Evaluation of aerosol transmission risk during home quarantine under different operating scenarios: A pilot study. *Building and Environment*, 225, Article 109640. <https://doi.org/10.1016/j.buildenv.2022.109640>
- Drach, P. R. C. (2009). A study on air circulation: The case of house VI of “Vila” 37 with the application of wind-catch. *Building Simulation*, 2, 307–316. <https://doi.org/10.1007/s12273-009-9415-6>
- Ibiyeye, A. I., Shari, Z., & Jaafar, M. F. Z. (2016). Evaluating natural ventilation provisions and occupants’ ventilation behaviour in five terrace housing types in Putrajaya, Malaysia. *Archnet-IJAR International Journal of Architectural Research*, 10(2), 130–152. <https://www.archnet.org/publications/10698>

- Jareemit, D. & Srivanit, M. (2019). Effect of street canyon configurations and orientations on urban wind velocity in Bangkok suburb areas. *IOP Conf. Series: Materials Science and Engineering*, 690, Article 012006. <https://doi.org/10.1088/1757-899X/690/1/012006>
- Jomehzadeh, F., Nejat, P., Calautit, J. K., Yusof, M. B. M., Zaki, S. A., Hughes, B.R., & Yazid, M. N. (2016). A review on windcatcher for passive cooling and natural ventilation in buildings, Part 1: Indoor air quality and thermal comfort assessment. *Renewable and Sustainable Energy Reviews*, 70, 736–756. <https://doi.org/10.1016/j.rser.2016.11.254>
- Mohamed, M. A. A., & El-Amin, M. F. (2022). Inward and outward opening properties of one-sided windcatchers: Experimental and analytical evaluation. *Sustainability*, 14(7), Article 4048. <https://doi.org/10.3390/su14074048>
- Montazeri, H., & Montazeri, F. (2018). CFD simulation of cross-ventilation in buildings using rooftop wind-catchers: Impact of outlet openings. *Renewable Energy*, 118, 502–520. <https://doi.org/10.1016/j.renene.2017.11.032>
- Palaiologou, G., & Vaughan, L. (2012). *The Manhattan row house as an exemplar of urban adaptability: 1874-2011*. In Conference: New Urban Configurations EAAE/ISUF International Conference, TU Delft, Netherlands. https://repository.lboro.ac.uk/articles/conference_contribution/The_Manhattan_row_house_as_an_exemplar_of_urban_adaptability_1874-2011/23592252?file=41386596
- Sadeghi, M., Samali, B., Wood, G., & de Dear, R. (2020). Comfort cooling by wind towers in the Australian residential context – Experimental wind tunnel study of comfort. *Journal of Wind Engineering & Industrial Aerodynamics*, 196, Article 104014. <https://doi.org/10.1016/j.jweia.2019.104014>
- Sangdeh, P. K., & Nasrollahi, N. (2020). Windcatchers and their applications in contemporary architecture. *Energy and Built Environment*, 3(1), 56–72. <https://doi.org/10.1016/j.enbenv.2020.10.005>
- Shankar, K., & Lo, E. (2019). Modelling urban growth for Bangkok and assessing linkages with road density and socio-economic indicators. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-4/W19 (pp. 255–262). <https://doi.org/10.5194/isprs-archives-XLII-4-W19-255-2019>
- Srebric, J., & Chen, Q. (2002). An example of verification, validation, and reporting of indoor environment CFD analyses. *ASHRAE Transactions*, 108(2), 185–194. <https://engineering.purdue.edu/~yanchen/paper/2002-9.pdf>
- Srivastava, S., Zhao, X., Manay, A., & Chen, Q. (2021). Effective ventilation and air disinfection system for reducing Coronavirus Disease 2019 (COVID-19) infection risk in office buildings. *Sustainable Cities and Society*, 75, Article 103408. <https://doi.org/10.1016/j.scs.2021.103408>
- Takkanon, P. (2006, September 6–8). Design guidelines for thermal comfort in row houses in Bangkok. *Proceedings of PLEA2006 - The 23rd Conference on Passive and Low Energy Architecture*, Geneva, Switzerland. https://www.researchgate.net/publication/281628969_Design_guidelines_for_thermal_comfort_in_row_houses_in_Bangkok
- Tantasavasdi, C., & Inprom, N. (2023). Residential unit design for natural ventilation in tropical multi-family high-rises with a double-loaded corridor. *Nakhara: Journal of Environmental Design and Planning*, 22(3), Article 315. <https://doi.org/10.54028/NJ202322315>
- Tantasavasdi, C., Arttamart, S., & Inprom, N. (2025). Combined wind catchers and side windows for cross ventilation in row houses. *Journal of Engineering, Design and Technology*, 23(3), 1039–1056. <https://doi.org/10.1108/JEDT-02-2023-0079>

- Tochaiwat, K., & Pultawee, P. (2024). House type specification for housing development project using machine learning techniques: A study from Bangkok metropolitan region, Thailand. *Nakhara: Journal of Environmental Design and Planning*, 23(1), Article 403.
<https://doi.org/10.54028/NJ202423403>
- Toe, D. H. C., & Kubota, T. (2015). Comparative assessment of vernacular passive cooling techniques for improving indoor thermal comfort of modern terraced houses in hot-humid climate of Malaysia. *Solar Energy*, 114, 229–258.
<https://doi.org/10.1016/j.solener.2015.01.035>
- Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa, M., & Shirasawa, T. (2008). AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. *Journal of Wind Engineering and Industrial Aerodynamics*, 96(1–10), 1749–1761.
<https://doi.org/10.1016/j.jweia.2008.02.058>
- Tominaga, Y., Zhang, X., & Miyakoshi, K. (2024). Wind tunnel experiment on cross-ventilation of generic isolated building with various roof shapes: Impact of roof pitch and eaves. *Building and Environment*, 265, Article 111974.
<https://doi.org/10.1016/j.buildenv.2024.111974>
- Tong, Z, Chen, Y, & Malkawi, A. (2016). Defining the influence region in neighborhood-scale CFD simulations for natural ventilation design. *Applied Energy*, 182, 625–633.
<https://doi.org/10.1016/j.apenergy.2016.08.098>
- United Nations, Department of Economic and Social Affairs, Population Division. (2019). *World Population Prospects 2019, Highlights*.
https://population.un.org/wpp/assets/Files/WPP2019_Highlights.pdf
- World Health Organization. (2021). *Coronavirus disease (COVID-19): Ventilation and air conditioning*. <https://www.who.int/news-room/questions-and-answers/item/coronavirus-disease-covid-19-ventilation-and-air-conditioning>
- Zakaria, M. A., Kubota, T., & Toe, D. H. C. (2015). The effects of courtyards on indoor thermal conditions of Chinese shophouse in Malacca. *Procedia Engineering*, 121, 468–476.
<https://doi.org/10.1016/j.proeng.2015.08.1094>
- Zhu, S., Jenkins, S., Addo, K., Heidarinejad, M., Romo, S. A., Layne, A., Ehizibolo, J., Dalgo, D., Mattise, N. W., Hong, F., Adenaiye, O. O., de Mesquita, J., Albert, B. J., Washington-Lewis, R., German, J., Tai, S., Youssefi, S., Milton, D. K., & Srebric, J. (2020). Ventilation and laboratory confirmed acute respiratory infection (ARI) rates in college residence halls in College Park, Maryland. *Environment International*, 137, Article 105537.
<https://doi.org/10.1016/j.envint.2020.105537>