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Residential Unit Design for Natural Ventilation in Tropical Multi-Family High-Rises With a Double-Loaded Corridor

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ABSTRACT

This research investigates practical methods to improve the efficiency of natural ventilation in residential units of multi-family high-rises without additional areas. Typical studio- and one-bedroom-types of small units were redesigned using: 1) air post, 2) transom window, 3) buffer space with one corridor opening and 4) buffer space with two corridor openings. The simulation study using a CFD program to reveal that the indoor average air velocity coefficient (C_v) in the best redesigned case (0.46) significantly improves from the base case (0.01). The paper demonstrates an example of application to an actual climate in Bangkok, Thailand. It was found that the proposed redesign using buffer spaces can considerably help upgrade the living conditions of the occupants in terms of both thermal comfort (24 hours vs. 0 hours in the comfort zone per day) and indoor air quality (24 hours vs. 8–17 hours that pass the minimum ventilation requirement per day) in the transitional month of February.

Keywords: air velocity coefficient, residential unit design, multi-family high-rise, double-loaded corridor, buffer space

INTRODUCTION

Urbanisation and the growing population in today's big cities around the world have created the needs for densely built multi-family high-rises (Peters & Halleran, 2021; Sha & Qi, 2020). Mainly driven by economic aspects, these condominium, apartment and dormitory building typologies share one distinct characteristic: small residential units are closely located and connected by double-loaded corridors (Seo et al., 2014), especially in tropical developing countries (Kumar et al., 2021). Such configuration generally allows only one opening on the external wall in each unit and causes poor single-sided ventilation, which is inadequate to provide thermal comfort for the occupants (Prajongsan & Sharples, 2012), in particular for a room that has a depth two times larger than its height (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE], 2019). Consequently, people need to rely on air-conditioning systems for cooling in these buildings (Tong et al., 2021) hence significantly increasing energy consumption.

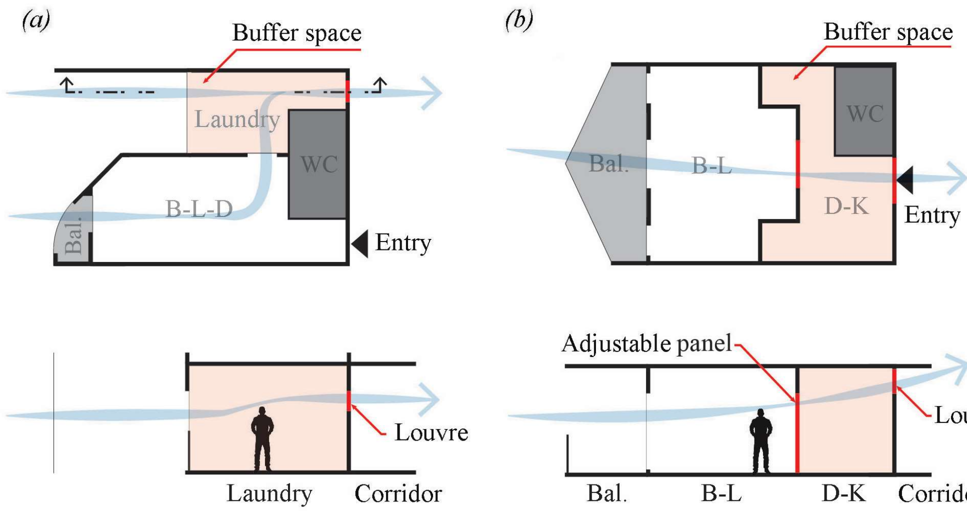
In general, natural ventilation has effectively been used for cooling in buildings in tropical climates because the ambient air temperatures are often close to comfort temperatures (Mediastika et al., 2018). The strategy helps reduce significant amounts of energy that otherwise would be consumed by air-conditioning systems (Panraluk & Sreshthaputra, 2020) and therefore represents an easier path to achieve a low emission goal (Aynsley & Shiel, 2017). In addition, the recent pandemic situation has raised the importance of increasing fresh air (Lazar & Chithra, 2021; Takkanon, 2021) which can be achieved more effectively by natural ventilation (Ohba & Lun, 2010). Natural ventilation is therefore superior to mechanical systems in terms of preventing airborne contagion (Hobday & Dancer, 2013) and improving indoor air quality (Weerasuriya et al., 2019) because it generally provides a larger volume of fresh air or higher air changes per hour (ACH).

High-rise buildings can better benefit from natural ventilation than low-rise buildings due to fewer influences from the surroundings (Tong et al., 2017). Cross ventilation provides much higher indoor air velocities than single-sided ventilation (Evola & Popov, 2006; Tantasavasdi & Inprom, 2021) but it can rarely be applied to high-rise residential buildings because of their compact form (Aflaki et al., 2018). There have been previous studies to improve natural ventilation by adding vertical wind paths such as air wells (Seo et al., 2014) and ventilation shafts (Choi et al., 2014; Prajongsan & Sharples, 2012). Solutions of adding horizontal wind paths have also been studied (Zhou et al., 2014). Although previous studies demonstrate effective methods to improve natural ventilation in high-rise residential buildings, these solutions mainly focus on large units and/or have small floor plates. They also need extra space, which might not be economically viable in actual practice.

Small residential units better represent today's normal practice; however, applying natural ventilation to the limited conditions of the small units posts a more challenging effort than that for larger units. There have been studies focusing on design elements for small units such as an operable ventilation grill next to the unit door called an air post (Sreshthaputra, 2016) and an opening above the unit door known as a transom window (Aflaki et al., 2018; Liu et al., 2021). Both solutions could work in today's actual conditions of double-loaded corridors with no extra space needed. The addition of adaptable in-between spaces to the units can create a desired balance between public and private spaces for residential buildings such as student housing (Awal, 2022). This creates buffer spaces that also enhance cross ventilation. We surveyed actual buildings and found innovative unit planning solutions that use the concept of buffer space (Figure 1). A suburban high-rise dormitory was designed with a side balcony connected to the studio-type unit that allows airflow through the corridor while maintaining the occupants' privacy. Another urban high-rise dormitory has a dining and kitchen area separating the bedroom and living space from the corridor which also aids natural ventilation in the units. It is essential that these solutions for small units be scientifically evaluated and compared under the same actual conditions.

Figure 1

Plans and Sections of Residential Units that Incorporate Buffer Space: (a) Side Buffer in a Studio-Type Dormitory Unit and (b) Front Buffer in a One-Bedroom-Type Dormitory Unit



This research explores the possibility of applying innovative natural ventilation solutions to actual small residential units in multi-family high-rises. The objectives of the study are to assess the air velocities of various design solutions and to demonstrate the application of the findings to an actual climate. In the methods section, we selected typical base cases from a survey and applied solutions to the design, some of which also needed rearrangement of the unit plans. Simulation setups of a CFD program and evaluation methods are also discussed in this section. Then the simulation results are elaborated. The discussion section explains ventilation performance as well as a demonstration of application for thermal comfort and indoor air quality. Finally, a conclusion is drawn with suggestions towards future work. The findings from this study should be beneficial to architects in determining which residential units can take best advantage from prevailing winds.

METHODOLOGY

Selecting a base case and design solutions

We surveyed small residential units in multi-family high-rise buildings with a double-loaded corridor in many tropical countries (Figure 2). It was found that the units vary in size from 30 to 60 m^2 and are comprised of six functional spaces: a living area (L), dining area (D), kitchen (K), bedroom (B), water closet (WC) and balcony (Bal.). There are two room types as follows:

- Studio type*.* The bedroom is merged to the living and dining area in one continuous space and has a window on the exterior wall*.* There can be either a kitchen or water closet that is also connected to the exterior wall*.* In many modern condominiums, there is a sliding door separating the bedroom from the living and dining area*.* Such design is often sold as a one-bedroom type*.*

- One-bedroom type*.* The bedroom is clearly separated from the living and dining area, and each has an opening on the exterior wall*.* The water closet is close to the bedroom while the kitchen is close to the dining area. This is known as a conventional one-bedroom type.

Two base cases were defined from the shared characteristics of each type of the residential units with the size towards the small end at 36 m^2 (Figure 3). In common practice, there is a car parking garage underneath the residential floors. For structural reasons, the width of each unit has to correspond to the width of the parking space. In this case, we use a 5.2-m width to accommodate two parking spaces. The length of the unit is 7.0 m. Each unit has a room height of 2.6 m, which is the normal height in most buildings. There are two openings on the same side of the exterior wall in each unit, creating one-sided ventilation. The opening sizes in each case reflect the actual available space on the exterior walls, the interior functions and the use of a sliding opening type, which is common practice.

The base cases were then modified with design elements or rearranged with the idea of buffer space to encourage cross ventilation. This resulted in four improvement cases for each unit type identified as follows (Figure 4 and 5):

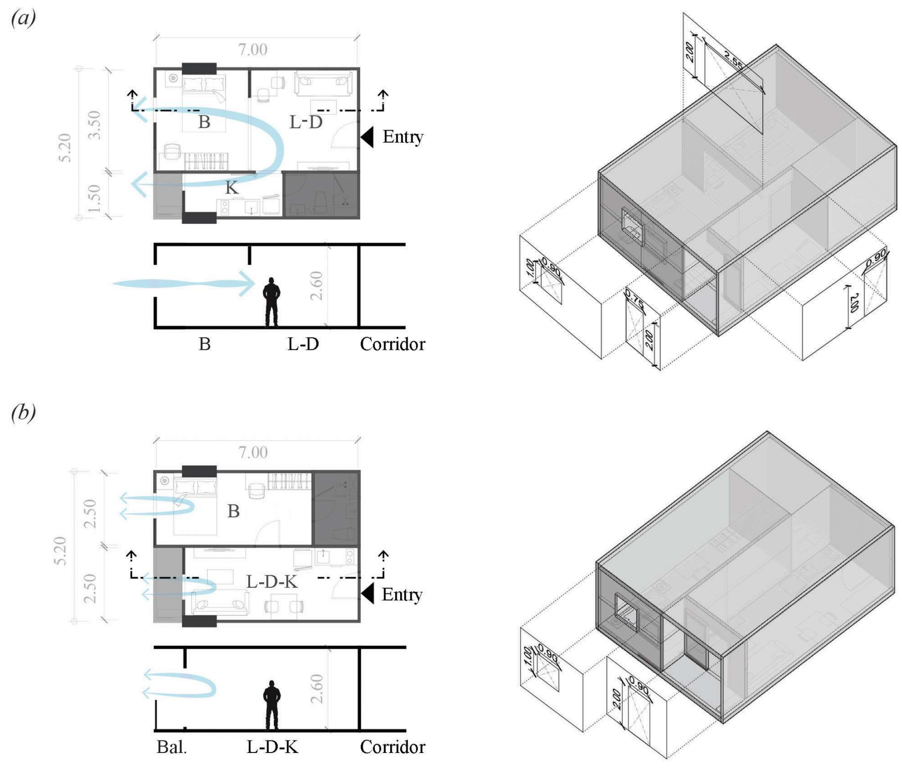
1. Air post (additional operable ventilation grills next to the unit and bedroom doors),
2. Transom window (additional openings above the unit and bedroom doors),
3. Buffer space with one opening (rearrangement of the unit using side or front buffer with one additional opening to the corridor) and
4. Buffer space with two openings (rearrangement of the unit using side or front buffer with two additional openings to the corridor).

Figure 2

Residential Units Found in Tropical Countries: (a) Studio Type and (b) One-Bedroom Type

Figure 3

Plans and Isometric Views of the Base Cases: (a) Studio Type and (b) One-Bedroom Type



The inlet opening sizes in all improvement cases remain the same as the base cases. The outlet opening sizes, however, vary according to each design. They range from 0.12 m^2 in the case of the air post to 2.70 m^2 in the case of buffer space with two openings. The design of the buffer space also varies according to the functional arrangement. The side buffer can only be used in the studio type while the front buffer is more suitable for the one-bedroom type, as demonstrated in the planning of case 3. We further modified the unit plans of both types, and they became case 4, where more outlet openings can be incorporated into the design. It is noted that in the cases of side buffer, the unit needs an extra length of 0.40 m to maintain all the functional spaces, but the total floor areas remain the same.

In conclusion, the design solutions that lead to different room layouts, opening sizes and locations represent the independent variables in this study. The air velocities assessed from each case act as the dependent variable. Control variables include the room types, ceiling height and the location of openings with a perpendicular angle to the wind direction.

Figure 4

Plans and Isometric Views of the Studio Type Improvement Cases: (a) Air Post, (b) Transom Window, (c) Buffer Space With One Opening and (d) Buffer Space With Two Openings

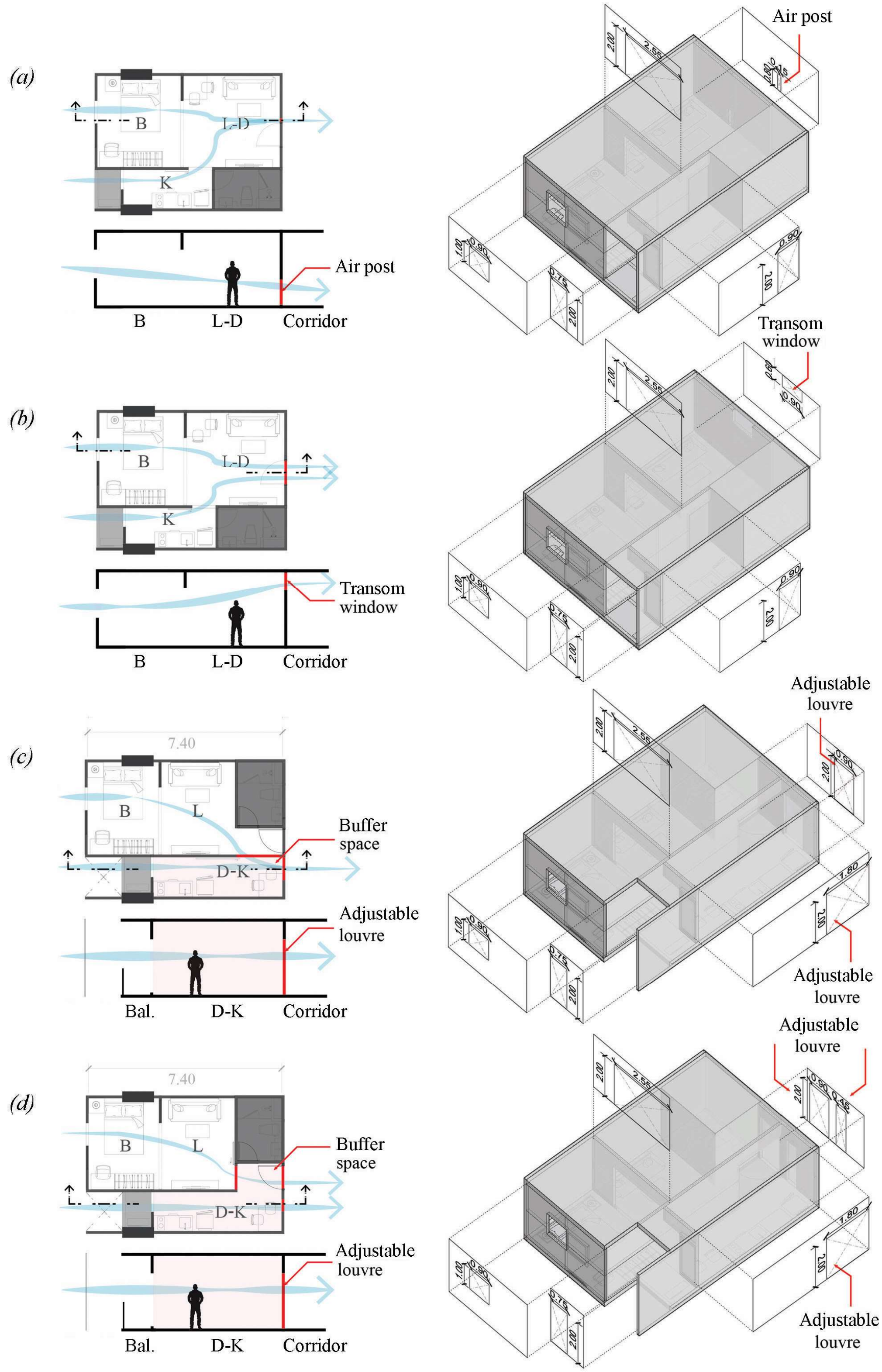
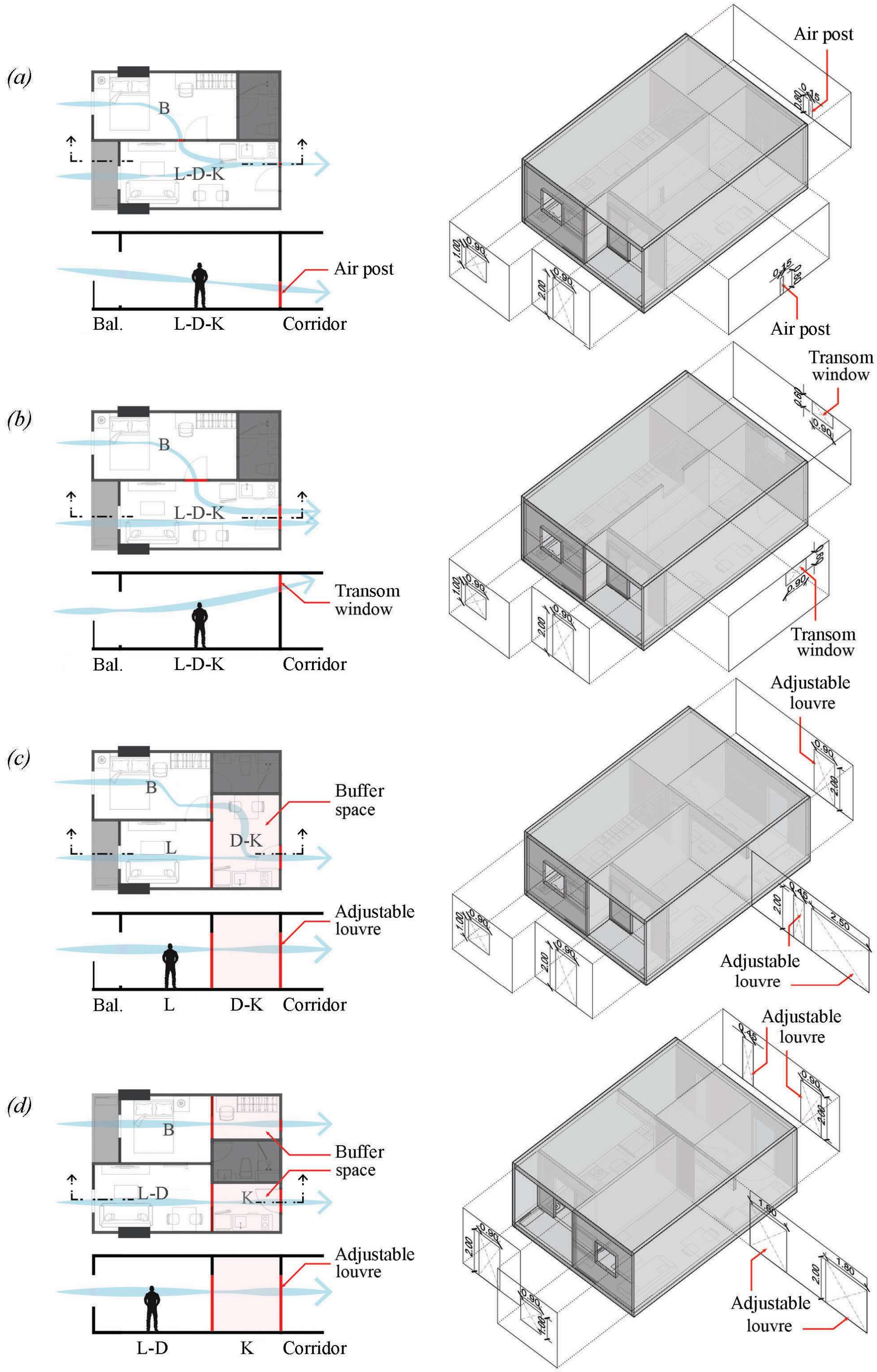


Figure 5

Plans and Isometric Views of the One-Bedroom Type Improvement Cases: (a) Air Post, (b) Transom Window, (c) Buffer Space With One Opening and (d) Buffer Space With Two Openings



CFD simulation setups

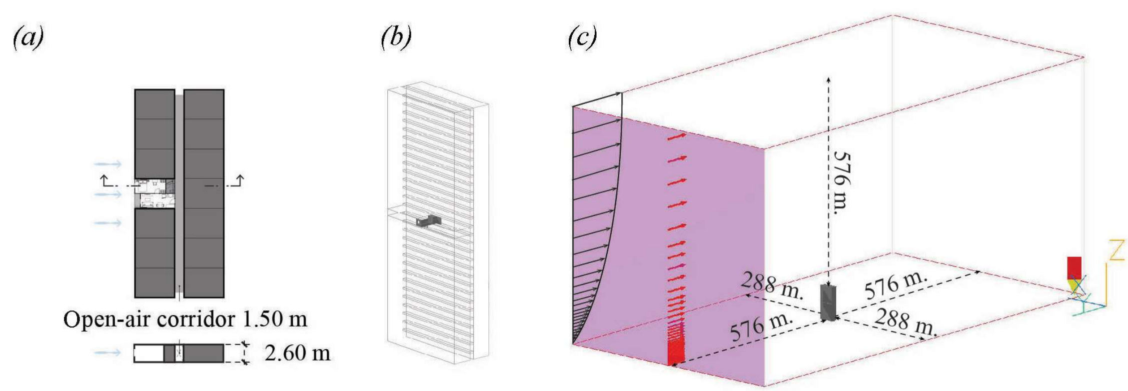
To assess the indoor air velocities in each case, a CFD program (Concentration, Heat and Momentum [CHAM], 2021) was used to simulate the airflow in and around the building. We selected a 30-storey double-loaded corridor building with an I-shape and each floor accommodates seven units on one façade as the case of our study because it is similar to most buildings found in actual conditions. Therefore, the dimensions of the building are approximately 37 m long x 16 m wide x 96 m high. The residential unit case study is placed in the middle of the building with opened windows. Openings in other rooms of the building are assumed to be closed while the openings at the end of the corridor are opened.

In the CFD models (Figure 6), the domain size and boundary conditions need to be carefully considered. For the airflow to properly develop, the building needs to be placed at least three to six times greater than the building height from each domain boundary, similarly to previous studies (Kumar et al., 2021; Liu et al., 2021). The prevailing wind was modeled as several layers of inlets with varied air velocities to imitate the wind profile. No surrounding buildings were input in the models because this study focused on the airflow in and around a generic building, which may have a different surrounding from one case to another in actual conditions. The grid size needs to be small enough to accurately demonstrate the airflow as a result of building geometry. We use the smallest grid size of 0.1 to 0.3 m, which are in the same range as previous study on natural ventilation (Tantasavasdi et al., 2021).

Technically, there are many turbulence models available. We chose the Chen-Kim K-Ɛ model because it is numerically efficient and can effectively replicate airflow in and around buildings in natural ventilation cases (Maragkogiannis et al., 2014). To achieve favorable convergence, each CFD model used 7,000 iterations. The residuals of mass were calculated to be less than 0.1% in all of the cases, which are in the range of convergence (Srebric & Chen, 2002). We can now read the results with confidence of their accuracy.

Figure 6

CFD Model Setups Showing (a) Residential Floor Plan and Section, (b) Location of the Unit in the Building and (c) Dimensions of the Domain and Boundary Conditions



Evaluation methods

To evaluate the effectiveness of airflow, we used air velocities of each case in major indoor functional spaces and at the openings (Figure 7). The points of measurement for the indoor air are at the level of breathing zone at 1.1 m above the floor (Srivastava et al., 2021). Values were read from 0.5 x 0.5 m meshes on a horizontal plane of all interior areas except the water closet. For the openings, we measured at the inlet openings and read the values from 0.3 x 0.3 m meshes on vertical plane. It is noted that the mesh sizes we read from the results are larger than the actual grid sizes of the CFD simulation for the purpose of more rapid result reading.

Then we computed the average air velocities of each case as compared to the outdoor air velocities. This results in a non-dimensional value which can be later implemented with any other climatic data to assess thermal comfort and indoor quality. The method was used in many previous studies (Ernest et al., 1991; Tantasavasdi et al., 2021). The equation can be expressed as:

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

where

C_v = average velocity coefficient

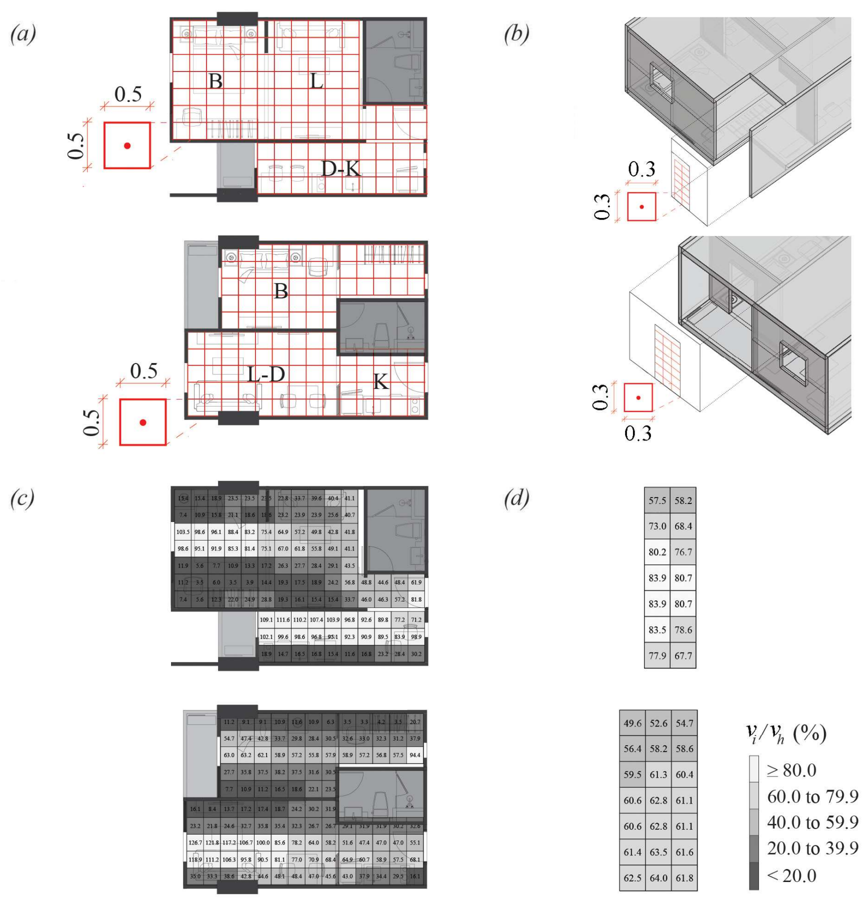
v_i = mean velocity at location i at breathing zone height or at opening (m/s)

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

n = number of measurement location in the model

Figure 7

Air Velocity Measurement Points (a) for Indoor Space and (b) at the Openings and Examples of Air Velocity Analysis (c) for Indoor Space and (d) at the Openings



RESULTS

CFD simulation results showed that the airflow behaviour around the building in many cases are similar (Figure 8). The prevailing wind from perpendicular direction to the building façade created positive pressure at the front and negative pressure at the sides and the back of the building. Since the building is mostly solid, it caused high air velocities at the front and wind shadow at the back. Some of the air entered the unit but its amount depended on the openings within the unit.

The airflow in each of the unit cases can be elaborated in more detail (Figure 9). In the base cases, both the studio and one-bedroom types have one-sided ventilation thus providing very low air velocities. Using equation (1), the C_v can be calculated to be 0.01 for both indoor air and at the inlet openings in both cases.

Improving the units with openings at the corridor increases the air velocities in both types of unit because they create cross ventilation. The air can now exit from the units to the corridor, which is opened to both sides of the building. In the air post cases with the corridor opening size of 0.15 x 0.80 m, the C_v of the indoor air increases to 0.03 to 0.04 while the C_v at the inlet openings increases to 0.06 to 0.07. The air velocities further improve in the larger corridor opening cases. In the transom window cases with the corridor opening size of 0.90 x 0.60 m, the C_v of the indoor air increases to 0.10 while the C_v at the inlet openings becomes 0.23 to 0.26.

The units redesigned with buffer space allow better opportunity to put more corridor openings. Therefore, the air velocities were found to be much higher. The cases with one corridor opening at the size of 0.90 x 2.00 m can provide the C_v of the indoor air from 0.34 to 0.36 and the C_v at the inlet openings from 0.72 to 0.85. Finally, the cases with two corridor openings that have the opening sizes of 0.90 x 2.00 m and 0.45 x 2.00 m can create the best C_v of the indoor air from 0.44 to 0.46 and the best C_v at the inlet openings from 0.76 to 1.00.

Figure 8

Simulation Results of a Unit Within the Building Showing (a) Floor Plan at the Room Height and (b) Section Through the Centre of the Building

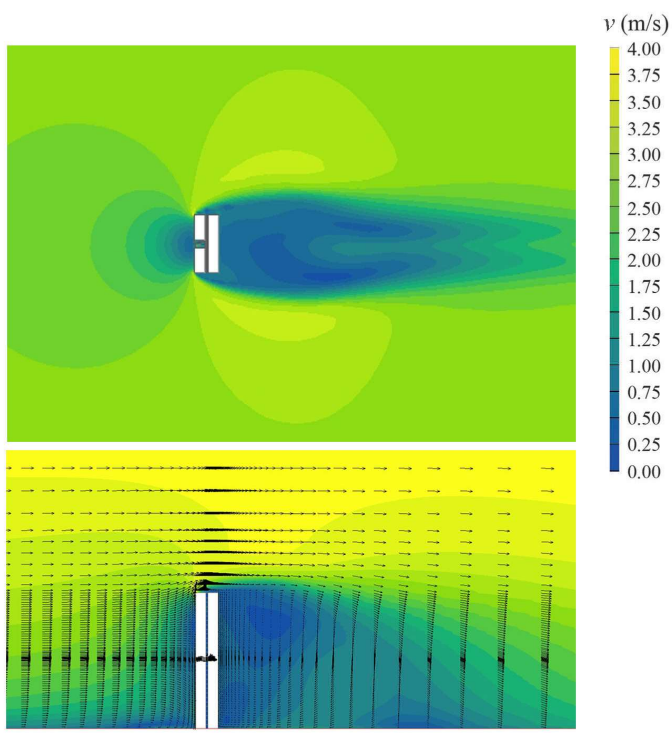
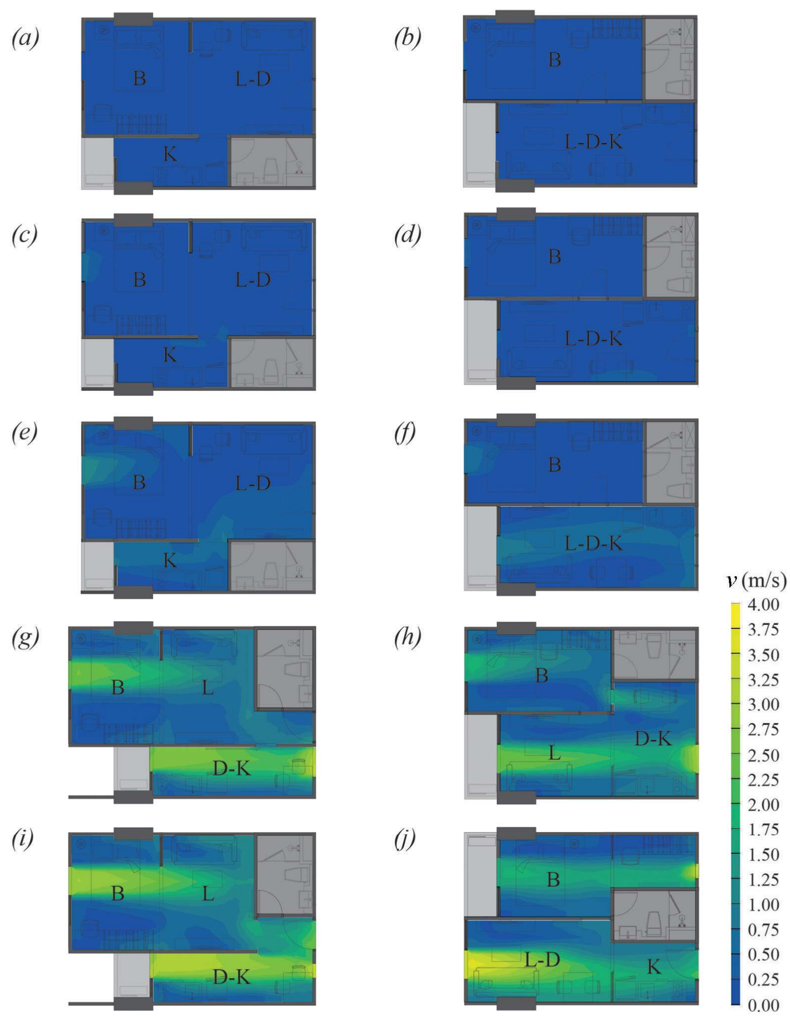


Figure 9

Simulation Results of (Left) Studio-Type Units and (Right) One-Bedroom-Type Units: (a-b) Base Cases, (c-d) Air Post, (e-f) Transom Window, (g-h) Buffer Space With One Opening and (i-j) Buffer Space With two Openings



DISCUSSION

Ventilation performances

The results demonstrate that air velocities vary according to the type of ventilation and size of the openings (Table 1). Cross ventilation provides much better air velocities than single-sided ventilation. This agrees with the previous studies (Evola & Popov, 2006; Tantasavasdi & Inprom, 2021). Design features that encourage cross ventilation including air post (Sreshthaputra, 2016) and transom windows (Aflaki et al., 2018) improve the ventilation rate when compared to the base cases, which agrees with this study. When units have larger outlet opening areas, the C_v of the indoor air and at the openings both increase. This shares a similar trend to the previous study which found that decreasing the inlet-to-outlet ratio improves C_v because of the stronger Venturi effect (Tantasavasdi et al., 2009).

The relationship between the opening area and C_v are further analysed. It was suggested that airflow follows the size of the smaller openings when the sizes of inlet and outlet are not equal (Givoni, 1994). An effective area (A_{eff}) of openings or minimum opening area therefore represents the parameter to determine the airflow for each case. When plotting A_{eff} with C_v (Figure 10), we can see that the trends for the studio-type unit and one-bedroom-type unit are slightly different. The studio units provide marginally higher C_v than the one-bedroom units in terms of both indoor air velocity and air velocity at the openings because they have fewer interior walls to obstruct the airflow.

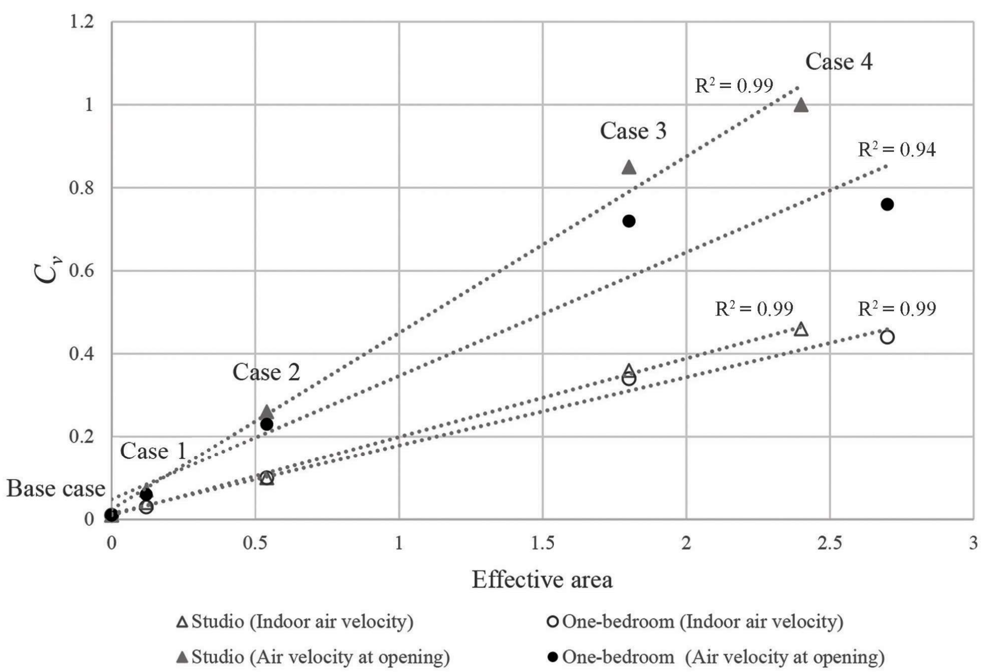
Table 1

Opening Areas and C_v of all the Cases Assessed

Case		Inlet area (m^2)	Outlet area (m^2)	Effective area (m^2)	C_v (Indoor air)	C_v (Opening)
Studio	Base case	2.40	0.00	0.00	0.01	0.01
	Case 1	2.40	0.12	0.12	0.04	0.07
	Case 2	2.40	0.54	0.54	0.10	0.26
	Case 3	2.40	1.80	1.80	0.36	0.85
	Case 4	2.40	2.70	2.40	0.46	1.00
One-bedroom	Base case	2.70	0.00	0.00	0.01	0.01
	Case 1	2.70	0.12	0.12	0.03	0.06
	Case 2	2.70	0.54	0.54	0.10	0.23
	Case 3	2.70	1.80	1.80	0.34	0.72
	Case 4	2.70	2.70	2.70	0.44	0.76

Figure 10

The Graph Showing the Relationship between Effective Area (A_{eff}) and C_v



Application to an actual climate

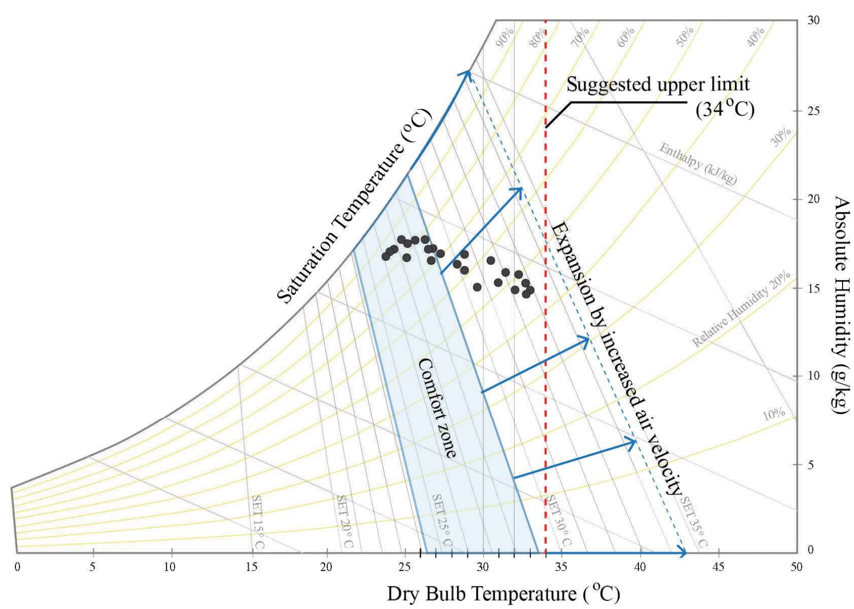
The results from this study can be applied to any tropical climatic conditions. The following section demonstrates an example of application to an actual tropical climate in Bangkok, Thailand. We selected the month of February as the period for the study as it is the beginning of the hot season in the selected location, and it has the same prevailing wind direction from the south as this study when the building is properly oriented east-west. The analysis included both thermal comfort and indoor air quality.

The thermal comfort analysis process encompasses retrieving climatic data including average hourly wind speed, air temperature and relative humidity and then applying the C_v results from this study to the data. Adaptive comfort zone (ASHRAE, 2017) can be calculated (Figure 11), firstly by using monthly average ambient temperature (T_{out}) to identify a neutral temperature (T_n) from the equation T_n = 17.8 + 0.31 T_{out}. The upper boundary of the comfort zone (T_{upper}) can be defined with T_n + 2.5 and the lower boundary (T_{lower}) of T_n – 2.2. The comfort range is adopted along with the concept of standard effective temperature (SET) (Gagge et al., 1986). The upper boundary can be shifted further (dT) with the cooling effect from air movement according to the equation of $dT = 6v_e - 1.6v_e^2$ (Szokolay, 2004) where v_e is a function of average hourly ambient air velocity (v_i) from the equation $v_e = v_i - 0.3$. However, it was recommended that the air velocity should not exceed 2 m/s (Givoni, 1994) and the air temperature should not exceed 34 ℃ when natural ventilation is used for cooling (Liu et al., 2007).

The next step is to determine the indoor air conditions (Table 2). Local hourly wind speed data can be used to calculate along with the wind profile equation and the C_v results from this study to identify the indoor air velocities and the air velocities at the openings. For example, an hourly wind speed in Bangkok in February between 1.96 and 4.20 m/s at a height of 10 m above the ground will give indoor air velocities of 0.02 to 2.75 m/s and air velocities of 0.03 to 5.95 m/s at the openings at a room height of 49 m above the ground. In natural ventilation, the

Figure 11

Climatic Data of Bangkok Plotted with Thermal Comfort Boundaries and the Expansion Limitation of Natural Ventilation on a Psychrometric Chart



cooling from the airflow will take the heat generated in the interior spaces away. Therefore, it is necessary to determine the heat gain of the units. In this case, the heat gain was estimated to be 0.95 Kw from internal gain, assuming the building envelopes are well protected from the sun. Indoor air temperatures can then be calculated from a simple energy balance between heat gain and heat loss by natural ventilation. This heat loss is the product of ventilation rate, which is the product of the opening area and air velocity at the opening, and the air temperature difference (ΔT). It was found that the indoor air temperatures can be raised between 0.1 and 6.0 ℃. The conditions of indoor air temperatures and velocities can then be plotted on a psychrometric chart to determine if each hour stays within the comfort zone or not. In this case, we can count the number of hours that lies within the comfort zone from 0 to 24.

Indoor air quality can also be analysed (Table 3). The process includes the calculation of ventilation rate from the air velocities at the openings. Combined with the volume of the unit, the ACH can be estimated. In this case, the units can have a rate between 3.0 and 686.9 ACH. For modern standards for rooms associated with air-borne infection, it is recommended that a room that has people sharing the space should have a minimum rate of 6 ACH while an isolation room should have a minimum rate of 12 ACH (Allen & Ibrahim, 2021). The number of hours for these units to pass both requirements in this case ranges from 8 to 24 and 0 to 24 for the 6 ACH and 12 ACH rates, respectively.

Table 2

Thermal Comfort Analysis for Units under the Climate of Bangkok, Thailand

Case		Indoor air velocity (m/s)		Air velocity at opening (m/s)		ΔT (° C)		Hours in comfort zone
		Min.	Max.	Min.	Max.	Min.	Max.	
Studio	Base case	0.02	0.04	0.03	0.06	2.8	6.0	0
	Case 1	0.11	0.24	0.20	0.42	1.4	3.0	0
	Case 2	0.29	0.62	0.73	1.56	0.6	1.2	9
	Case 3	1.01	2.15	2.38	5.09	0.2	0.3	24
	Case 4	1.28	2.75	2.80	5.98	0.1	0.3	24
One-bedroom	Base case	0.03	0.06	0.03	0.06	2.5	5.4	0
	Case 1	0.09	0.19	0.17	0.36	1.7	3.6	0
	Case 2	0.28	0.60	0.64	1.38	0.5	1.1	10
	Case 3	0.94	2.01	2.02	4.31	0.1	0.3	24
	Case 4	1.22	2.60	2.13	4.55	0.1	0.2	24

Table 3

Indoor Air Quality Analysis for Units under the Climate of Bangkok, Thailand

Case		ACH		Hours that	
		Min.	Max.	exceed 6 ACH	exceed 12 ACH
Studio	Base case	3.0	6.5	8	0
	Case 1	21.1	45.2	24	24
	Case 2	82.5	176.3	24	24
	Case 3	274.1	586.1	24	24
	Case 4	321.3	686.9	24	24
One-bedroom	Base case	4.6	9.9	17	0
	Case 1	22.5	48.1	24	24
	Case 2	81.8	174.9	24	24
	Case 3	259.2	554.1	24	24
	Case 4	275.8	589.7	24	24

CONCLUSION

This investigation studied design methods to improve natural ventilation in typical residential units in tropical multi-family high-rise buildings that are generally planned with double-loaded corridors and have poor single-sided ventilation. Common units found in tropical countries represented two unit types in our study: studio and one-bedroom. We explored design elements and methods that encourage cross ventilation and integrated them into the base cases, creating four improvement cases for each type of unit. This includes: 1) air post, 2) transom window, 3) buffer space with one corridor opening and 4) buffer space with two corridor openings. For a type of residential unit, all cases have the same inlet opening area but are varied by outlet opening area.

All of the cases were then assessed using a CFD program to analyse the airflow within the units that were put in the middle of a 30-storey I-shape building with the prevailing wind blowing from a perpendicular direction to the building façade. The study used non-dimensional average air velocity, C_v, as the criteria to measure the efficiency of each method. It was found that the C_v of the indoor air and at the openings rely greatly on the effective area of the opening, A_{eff}. It was also found that the studio-type units create slightly better air velocities than the one-bedroom-type units because there are fewer walls to obstruct the air movement.

The results were applied to an actual tropical climatic data of Bangkok, Thailand as a demonstration. It was found that in the transitional month of February, proper design of residential units using buffer spaces can improve the thermal comfort conditions of occupants at all times. Any of the improvement methods can also improve indoor air quality to pass modern standards for air-borne infection prevention. The application, however, has some limitations based upon the assumption that the buildings are well shaded. The outcome would be different as a result of external heat gain if the buildings are not properly protected from the sun.

In actual practice, there might be a concern on acoustic privacy among units in naturally ventilated buildings. Although the concept of buffer space and operable openings could help alleviate the problem, the proposed methods could practically be more suitable to less formal building types, such as a dormitory, rather than a commercially oriented condominium or apartment. In addition, the proposed solutions suggest more unit openings on the corridor, allowing more airflow through the windward side units to the corridor. Although this limits the condition of the corridor to be naturally ventilated for fire safety reasons, the solutions should benefit airflow in the units on the leeward side as well. Investigation on these leeward-side units could be an interesting subject for the future study.

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