The Effect of Wing-Walls and Balcony on Wind Induced Ventilation in High-Rise Residential Units

อิทธิพลของผนังยื่นและระเบียงต่อการเหนี่ยวนำลมธรรมชาติในห้องพักอาคารสูง

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Abstract

Applying wing walls is a well known method of increasing the natural ventilation of a single-sided opening. A survey of the current application of wing walls in residential units shows that they do not encourage natural wind ventilation. This study presents numerical results of the ventilation produced by wing walls and a balcony, using various dimensions and combinations, for a wind direction of 0.0 to 90.0 degrees normal to the opening of a residential room of 6.0 x 6.0 m^2. The three-dimensional simulations, created using a CFD package called PHEONICS 3.5, are compared with the results of the experiment of Givoni. As the simulation results agree with the experimental results, the derived computational model is further investigated for the room without a partition and installed with various sizes of wing walls, openings and balconies. The simulation results for the residential room show that wing walls with a width of 2.0 and 4.0 m and a distance between the openings of 2.0m and 4.0 m in a wind direction of 30.0 to 75.0 degrees increase the ventilation significantly. Usually, the balcony obstructs the ventilation by 40.0-55.0%, but it can increase the ventilation for a wind direction of 90.0 degrees. Taking into account the pressure difference of a tall rectangular building, residential units with good ventilation should be located at the edge of the building with an upstream wind.

บทคัดย่อ

การประยุกต์ใช้ผนังยื่นเพื่อเพิ่มการระบายอากาศวิธีธรรมชาติสำหรับช่องเปิดด้านเดียวเป็นที่รู้จักกันโดยทั่วไป อย่างไรก็ตามการสำรวจพบว่าการใช้งานผนังยื่นในอาคารที่อยู่อาศัยในปัจจุบันไม่ได้เพิ่มการระบายอากาศที่อาศัยลมธรรมชาติ การศึกษานี้แสดงผลการจำลองของการระบายอากาศจากการใช้ผนังยื่นและระเบียงหลายขนาดในทิศทางลม 0.0 ถึง 90.0 องศากับช่องเปิดของอาคารพักอาศัยขนาด 6.0 x 6.0 ตารางเมตร ผลการจำลองห้อง 3 มิติด้วยโปรแกรมสำเร็จรูป PHEONICS 3.5 ถูกนำไปสอบเทียบกับผลการทดลองของ Givoni ผลการจำลองที่ได้มีความสอดคล้องกับผลการทดลอง จึงนำแบบจำลองดังกล่าวไปศึกษาขนาดของผนังยื่น ช่องเปิดและระเบียงสำหรับห้องพักที่ไม่มีผนังกั้นภายใน ผลการศึกษาได้แสดงว่าห้องที่มีผนังยื่นยาวตามแนวผนัง 2.0 และ 4.0 เมตร และมีช่องเปิดห่างกัน 2.0 และ 4.0 เมตรจะเพิ่มการระบาย

อากาศได้อย่างมีนัยสำคัญเมื่อทิศทางลมอยู่ระหว่าง 30.0 ถึง 75.0 องศา โดยทั่วไประเบียงจะกั้นการระบายอากาศถึง 40.0–55.0% แต่เมื่อลมมาในทิศตั้งฉากกับช่องเปิดพบว่าระเบียงจะเพิ่มการระบายอากาศได้ เมื่อพิจารณาผลต่างของความดันอากาศรอบอาคารสูงทรงสี่เหลี่ยมผืนผ้า ห้องพักที่มีการระบายอากาศธรรมที่ดีได้แก่ห้องที่อยู่ริมอาคารและอยู่ต้นลม

Keywords

Natural Ventilation (การระบายอากาศโดยวิธีธรรมชาติ)
Wing Walls (ผนังยื่น)
Single-sided Ventilation (การระบายอากาศด้านเดียว)
Computational Fluid Dynamics (การคำนวณพลศาสตร์ของไหล)

1. Introduction

For buildings, natural ventilation by wind is an effective measure to improve indoor air quality, provide thermal comfort and save energy. An increase of ventilation from 10 liter/person to 20 liter/person decreases the symptoms of sick building syndrome significantly (Seppänen et al., 1999). According to one survey (Cho et al., 2007), occupants feel comfortable as they can feel wind flow across their body. For this reason, adequate air velocity in the occupied space is required. An air velocity of 0.2-1.0 m/s in the occupant space is sufficient to provide thermal comfort for Thai people (Khedari et al., 2000) and an increase in air velocity of 1 m/s causes humans to feel a decrease in temperature of 3 degree Celsius (Lechner, 2001). In the hot and humid climate, natural ventilation in typical houses depends primarity on the opening area and the ratio of inlet and outlet openings (Tantasavasdi et al., 2009). Air-conditioning is now considered an important input in the design of the building to provide thermal comfort for its occupants and it consumes for 50-70% of a building's energy consumption (Nicol, 2009). Hence, the idea of using natural ventilation design to provide thermal comfort presents a very interesting alternative.

High-rise buildings in the US, Korea and Thailand have center-core structures such that the residential units are only externally facing on one side. This results in a one-sided opening, and the application of a wing wall has been suggested to increase ventilation (Allocca et al., 2003; Cho et al., 2007). The wing wall is a wall protruding normal to the surface of the building, usually located between two openings. The wind pressure difference between the windward and the leeward surfaces of the wing walls causes the ambient wind to flow into and out of the room. For single-sided ventilation without a wing wall, high air velocity is found near the openings and the air velocity decreases substantially with the depth of the room (Gan, 2000). According to the experimental results of Givoni, two openings with two wing-walls increase the air velocity inside the room by 3 times compared to those without wing-walls (Givoni, 1994). Shading devices were found experimentally to reduce ventilation by 30-50% compared to those without shading devices (Argiriou et al., 2002).

This study assumes insignificant difference between the indoor and outdoor air temperatures and therefore the buoyancy effect is excluded. The high wind velocity of nearly 3.0 m/s also diminishes the buoyancy effect near the two openings located at two different heights (Gan, 2000; Allocca et al., 2003) for single-sided ventilation where the air enters and leaves the space through one opening or two openings located at different heights. The 3D simulation using the k-ε model is applied in this study since it shows good agreement with the experimental results for the external flow and there is insignificant effect of turbulence intensity from the wind (Mak et al., 2007). The investigation focuses on the effect of facade components, such as a wing wall between two openings and a balcony, on the air velocity distribution inside the room. The room is simulated by PHEONICS 3.5 (CHAM, 2002), a computational fluid dynamics program, and is validated by the experimental results of previous studies (Givoni, 1994). The validated simulation model is parameterized with the building components: the width of the wing walls, the distances between the openings, and the presence of a balcony to determine the appropriate dimensions of the building components that provide a high air velocity in the space. The simulation results of the air velocity inside the room are discussed in terms of the coefficient of average air velocity (C_v) and the coefficient of standard deviation (C_{sv}). The characteristics of the façade components in existing high–rise residential buildings are discussed and appropriate façade components to encourage natural ventilation are suggested.

2. The Typical Units of High-rise Residential Buildings

We surveyed 1-bedroom residential units with an area of 30.0-40.0 m^2 in Thailand, China, the Philippines and Abu Dhabi, and found that the residential buildings had an average height of 120 meters with a typical space plan as shown in Figure 1. Most of these rooms have 1) a protruded or set-back area outside the room, 2) a room partition parallel to the depth of the room, and 3) two openings: a door with balcony and windows without a balcony. The purposes of this space plan is to provide ventilation, lighting, external views and space to the room. The effect of the external area with openings and balcony in existing residential buildings in terms of ventilation will be discussed later in this paper. The effect of room partition on ventilation is not considered in the simulation model in this study.

3. Numerical Simulation

3.1 Comparison of Simulation Results with Experimental Results

In the previous experiments of Givoni, a room model with dimensions of 0.65 m x 0.65 m x 0.5 m (*H*) with and without external wing-walls was tested in the wind tunnel. The working section

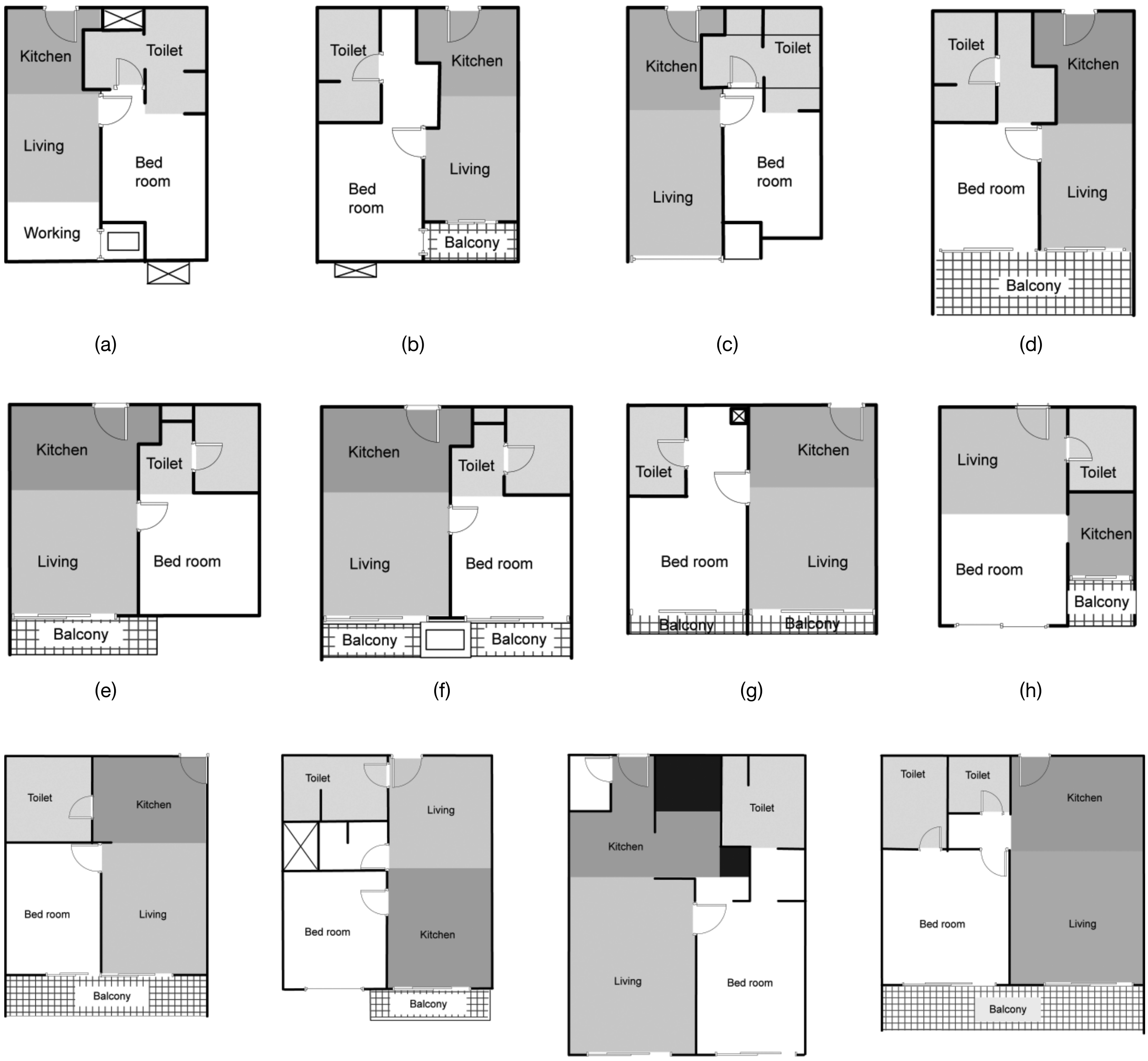


Figure 1. The space planning of residential units in high-rise buildings in (a-h) Thailand, (i-j) Philippines and (k) China and (l) Abu Dhabi.

of the wind tunnel was 2.22 m x 2.22 m x 1.2 m *(H)* and wind directions of 90.0 to 45.0 degrees with a decrement of 22.5 degree were adjusted to flow to the openings and the wing wall. The distribution of the percentages of indoor air velocity to wind velocity *(V_i)* for a wind velocity of 1.27-3.35 m/s are collected. The simulation model of a room with two openings and two wing walls in the computational domain with identical dimensions to Givoni's is constructed in this study, as shown in Figure 2, to validate with the previous experiment of Givoni. The PHEONICS CFD package is used to solve the conservation equations of mass and momentum through the finite volume method. The turbulence model is the k-ε model of the steady flow and the number of tetrahedral structure grids for the three dimensional model is 74,844. The residual sum of pressure value, divided by the absolute sum of the residual values of velocity vector in the x, y and z directions, is set to <0.01 (Chen and Srebric, 2001). The comparative distributions of the V_i for a wind velocity of 2.0 m/s and a direction of 90.0 to 45.0 degrees are shown in Figure 3.

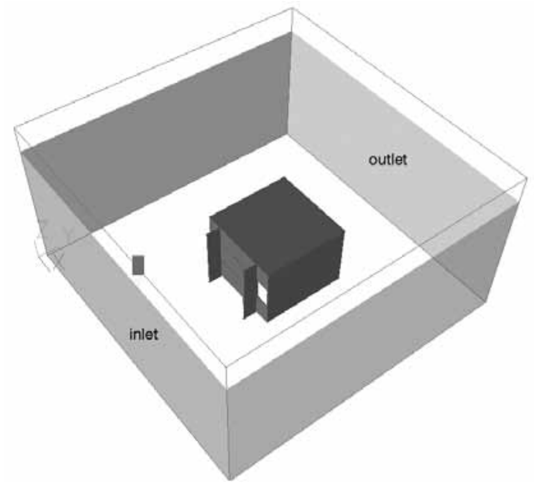


Figure 2. The simulation model in this study.

It is shown in Figure 3 that the simulation results agree with the experimental results for wind directions of 67.5, 45.0, and 22.5 degrees, and that they relatively agree with the experimental results for the wind direction of 90.0 degrees. The differences between the experimental and simulation results in the wind direction of 90.0 and 45 degrees could derive from the limitations of the k-ε model to compute the velocity distribution near the surface (Evola & Popov, 2006). The simulation results for a

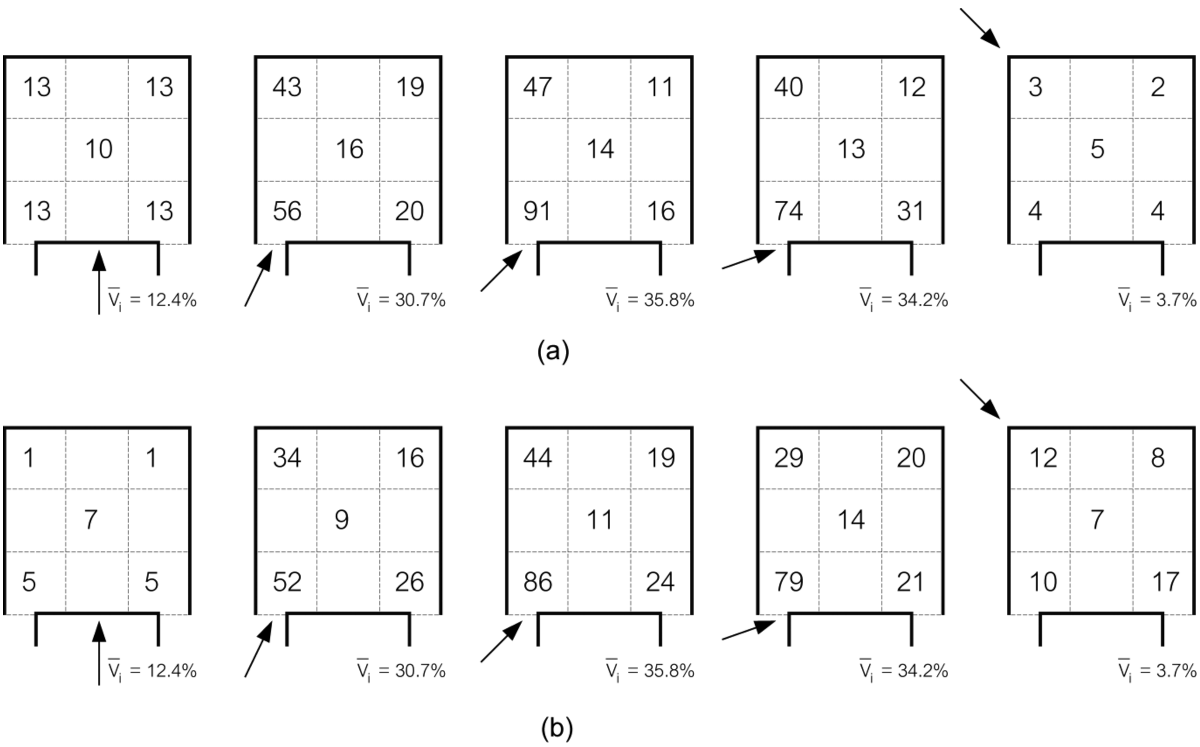


Figure 3. Comparisons of the distribution of the V_i with a wind velocity of 2.0 m/s and a wind direction of 90.0 to 45.0 degrees according to (a) the experimental results (Givoni, 1994) and (b) the simulation results.

wind direction of 45 degrees is excluded since this study is only concerned with the wind flowing to openings on the windward wall. Despite the discrepancy in the experimental results for a wind direction of 90.0 degrees, relatively lower values of air velocity than those for a wind direction of 67.5, 45.0 and 22.5 degrees are obtained.

3.2 Variables and Parameters in the Simulation

The room represents a sample of residential units, with dimensions of 6.0 m x 6.0 m x 2.6 m *(H)* and with an opening area totaling 10.0% of the space area, placed in the middle of the computational domain of 16*H* x 20*H* x 6*H*, as shown in Figure 4. The variables and parameters of the simulated building are presented in Table 1.

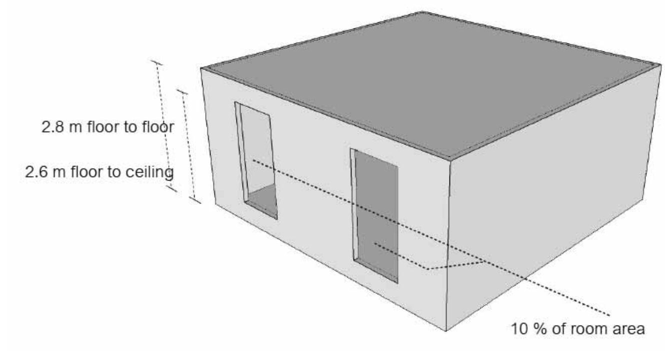
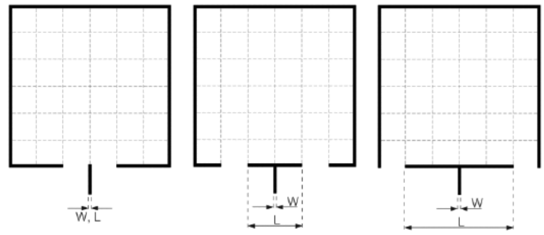


Figure 4. (a) A representative room of the sample buildings (b) the simulation model in the computational domain.

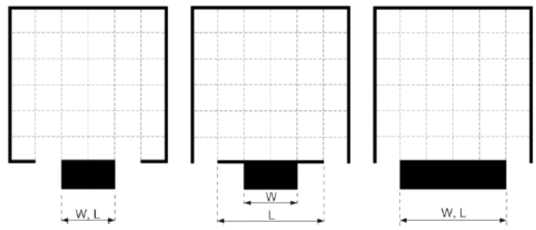
Table 1. Summary of variables and parameters in the simulation.

Independent variables

1. Width of wing walls (W) = 0.1 m, 2.0 m and 4.0 m
2. Distance between the opening (L) = 0.1 m, 2.0 m and 4.0 m

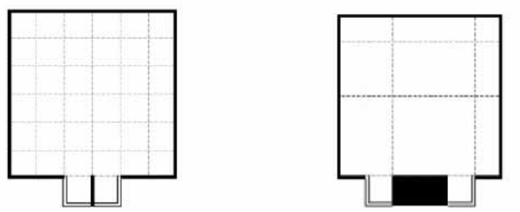


W=0.1 m, L=0.1m W=0.1 m, L=2.0m W=0.1 m, L=4.0m



W=2.0 m, L=2.0m W=2.0 m, L=4.0m W=4.0 m, L=4.0m

3. Balcony



W=0.1 m, L=1.0 m with balcony W=2.0 m, L=2.0m with balcony

4. Wind direction = 0.0 (parallel to the openings), 15.0, 30.0, 45.0, 60.0, 75.0 and 90.0 degree (normal to the openings)

Dependent variable

Air velocity measured at the 1.0 m above the room floor

The values of air velocity distribution in the room are investigated through the value of C_v and C_{sv}, as follows (Earnest et al., 1991):

$$C_v = \frac{1}{2}\sum_{i=1}^{n}\left(\frac{V_i}{V_r}\right) \quad (1)$$

$$C_v = \frac{1}{2}\sum_{i=1}^{n}\left(\frac{V_i}{V_r}\right) \quad (2)$$

where V_i is air velocity (m/s), V_r is wind velocity at reference height, *n* is the number of measuring points and $\delta_s(V_i)$ is the standard deviation of the value of air velocity. In this study, the value of n = 36. The value of the wind velocity is calculated from equation (ASHRAE, 2005):

$$U_H = U_{met}(d_{met} / H_{met})^{amet}(H/d)^{a} \quad (3)$$

where U_H is the mean wind velocity at height *H*, U_{met} is the meteorological station hourly wind velocity measured at height H_{met}, H is the wall height above the ground on upwind building face, H_{met} is the height of the anemometer at the meteorological station, d is the wind boundary layer thickness at the local building terrain (460 m for a large city center), d_{met} is the wind boundary layer thickness at the meteorological station (460 m for a large city), a is the exponent for the local building terrain (0.33 for a large city center), and a_{met} is the exponent for the meteorological station (0.33 for a large city).

4. Results and Discussions

4.1 The Effect of Wing Walls on Distribution of air Velocity

The simulation results for the application of wing walls can be considered for two cases: in case #1, the openings are situated adjacent to the wing walls (W=L); and in case #2, the openings are situated at a certain distance from the wing wall (W<L). Figure 5 shows the results of case #1: the value of C_v is 0.06-0.29 and the value of C_{sv} is 0.5-1.0 for a wind direction of 15-75 degrees. The high values of C_v and C_{sv} signify a high air velocity and high variation of air velocity in the room, respectively. The wing walls with widths of 2.0 m and 4.0 m (W) and a distance between the openings (L) of

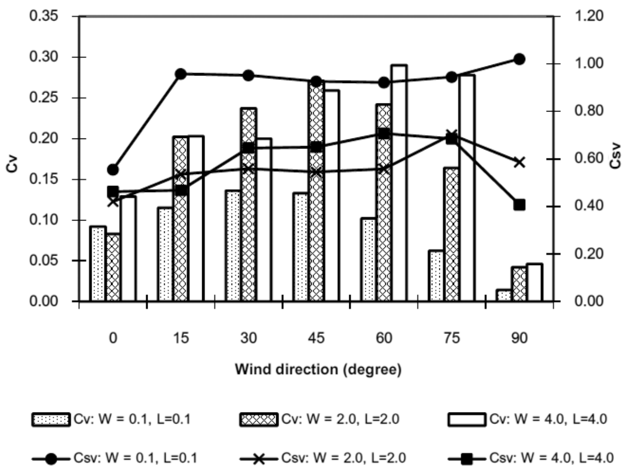


Figure 5. The values of C_V and C_{SV} of the for W = L = 0.1 m, 2.0 m and 4.0 m.

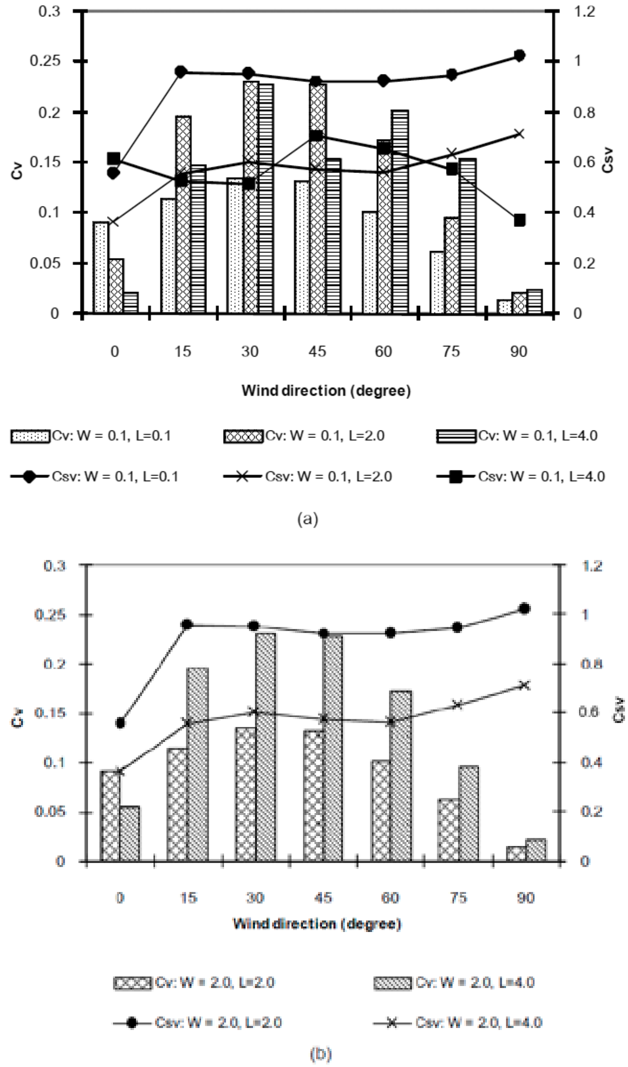


Figure 6. The values of C_v and C_{sv} for (a) W=0.1 and L=0.1 m, 2.0 m and 4.0 m, and (b) W =2.0 and L= 2.0 m and 4.0 m.

2.0 m and 4.0 m show higher values of air velocity and variation of air velocity in the room than that of the wing wall of W= 0.1 m and L=0.1 m, by 2-4 times.

Figure 6a shows the results of case #2. With dimensions of W=0.1 m and L=0.1 m, 2.0 m and 4.0 m, and wind directions of 15.0–75.0 degrees, the values of C_v and Csv are in the range of 0.06 - 0.23 and 0.5-1.0, respectively. Increasing the distance between the openings (L) from 0.1 m to 4.0 m enhances the value of C_v by 1.5-2 times. Figure 6b shows the results of case #2, using dimensions of W=2.0 m and L= 2.0 m and 4.0 m, with wind directions of 15.0–75.0 degrees. The values of C_v and C_{sv} are in the range of 0.06-0.23 and 0.56-1.0, respectively. Increasing the distance between the openings (L) from 2.0 m to 4.0 m enhances the value of C_v insignificantly. For a wind direction of 0 or 90 degrees, the values of C_v are less than 0.1 for all cases. Since the wind velocity in front of the residential unit in this study is 2.46 m/s, the wing walls with a 2.0 m and 4.0 m width, and the openings distance of 2.0 m and 4.0 m, bring an air velocity in the range of 0.49-0.71 m/s into the room. The room with a wing-wall width and opening distance of 2.0 m (Figure 7) results in a higher air velocity than the room with a wing-wall width of 0.1 with the same opening distance (Figure 8), because the wing wall of 2.0m width creates a higher pressure difference between the two openings than the wing wall of 0.1m width (Figure 9).

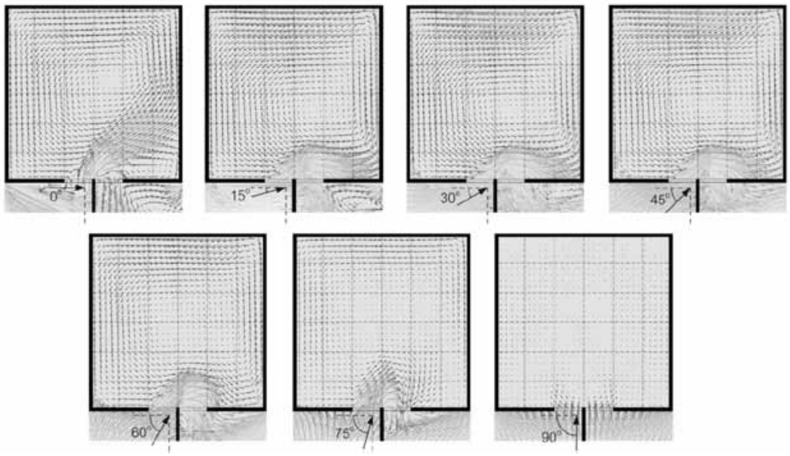


Figure 7. The vector velocity at 1.0 m above the floor for the simulation of the residential unit of W=L=0.1 m.

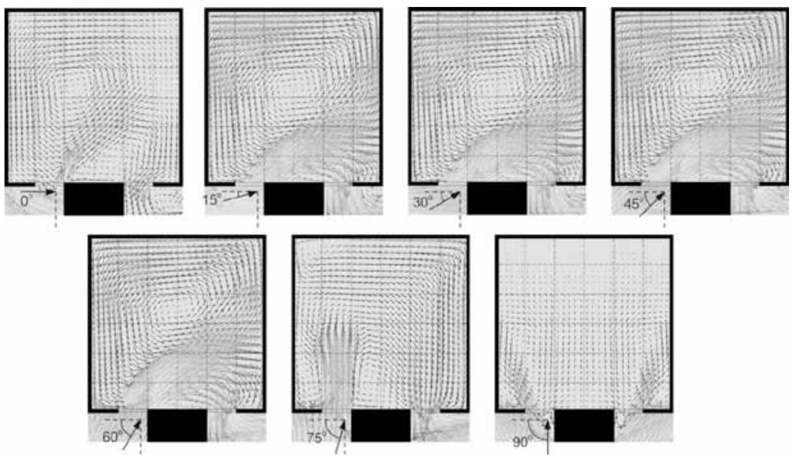


Figure 8. The vector velocity at 1.0 m above the floor for the simulation of the residential unit of W=L=2.0 m.

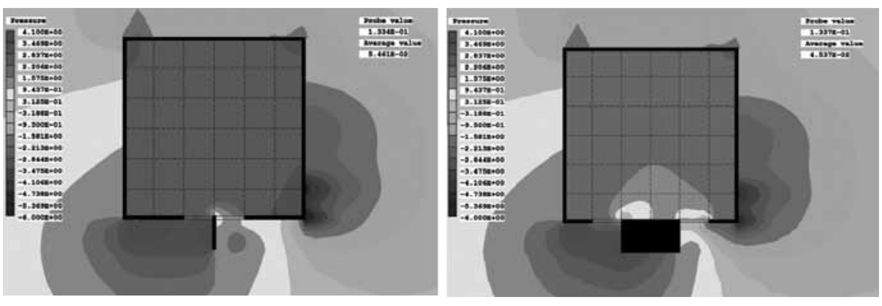


Figure 9. The pressure differences between the two openings for the simulation of the residential unit of W=L=0.1 m and W=L=2.0 m at a wind direction of 60 degrees.

4.2 *The Effect of Balcony and Wing Wall on Air Velocity*

The balcony in this study is enclosed by an opaque wall 1.0m in height that partially obstructs the wind flowing into the opening, i.e. the doors. The provision of balconies alters the wind pressure distribution on the windward wall for low-rise buildings (Chand, 1998). It was shown that wind inducing ventilation is achieved for parts of the building, such as downstream of the top floor for an obliquely incident wind, and near the ends of the wall at the ground and top floors for wind normal to the wall. In this study, we consider one room located near the top floor of a high-rise building, expecting a high rate of wind induced ventilation for both the oblique and normal wind. The representative room is selected to receive a wind velocity of 2.46 m/s, corresponding to the wind velocity at the 33rd floor of a 40-floor building. The results of the simulation of the room with a wing wall of $W = L = 2.0$ m (the highest ventilation) and another with one of $W = L = 0.1$ m (the lowest ventilation) show that the balcony obstructs the wind and ventilation, reducing the maximum value of C_v from 0.25 to 0.12 for both wing walls in a wind direction of 15.0 - 75.0 degrees (see Figure 10). The installation of the balcony increases the value of C_v from 0.05 to 0.1 at a wind direction of 90.0 degrees, but this gain is less than that occurs in the room without balcony with the oblique wind. Overall, the installation of the balcony with the opaque wall reduces the wind entering the room. If the balcony is required to provide an outdoor space for the unit, a balcony which is open and allows air to flow into the room is recommended (see Figure 10). The results of the simulated air velocity (m/s) for the room with $W = L = 2.0$ and $W = L = 0.1$ m with and without the balcony is shown in Figure 11. It is clear that the values of air velocity in the room without the balcony are higher than those in the room with the balcony.

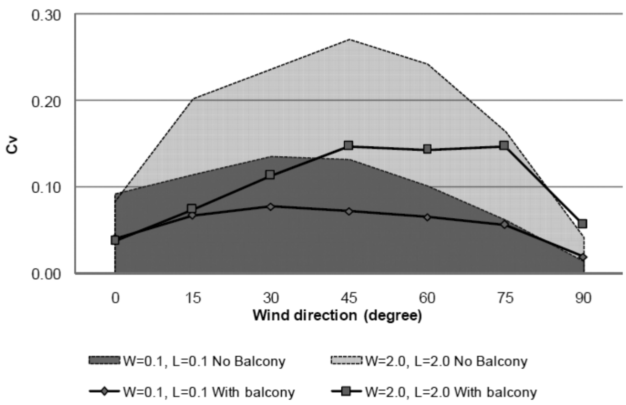


Figure 10. The values of C_v for the simulation of the residential unit of *W*=*L*=0.1 m *W*=*L*=2.0 m with and without the balcony.

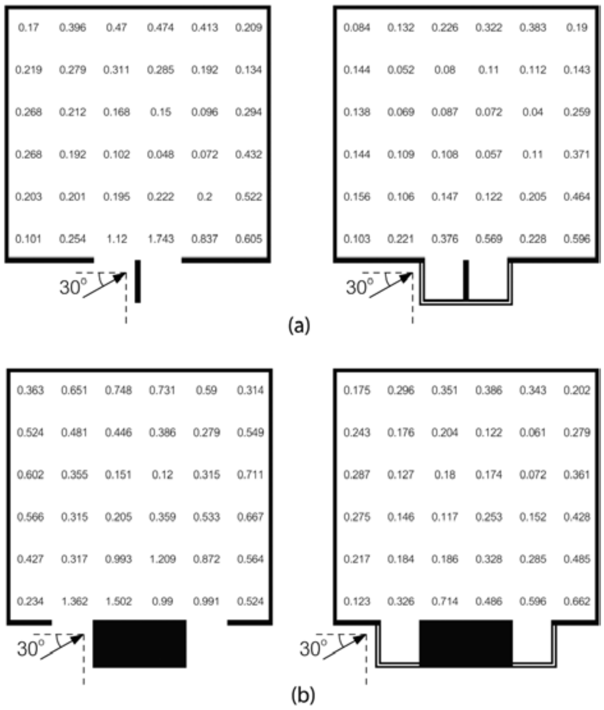


Figure 11. The results of the simulated air velocity (m/s) with a wind direction of 30.0 degree for the room with (a) *W*=*L* = 0.1 m and (b) *W*=*L* = 2.0m, with and without the balcony.

4.3 *The Enhancement of Wind Induced Ventilation to the Room in the High-rise Building*

For the windward surface of the square building, there is a greater difference in the values of the horizontal than the vertical pressure coefficients (Davenport & Hui, 1991). For a wind direction of 0.0-75.0 degrees, it is always differences in the pressure coefficients on the windward and leeward areas that encourage the application of a wing wall to increase the ventilation in a room. For a wind direction of 0.0-15.0 degrees, the wind flows almost parallel to the building, and a room located in the windward area would obstruct the room in the leeward area, as shown in Figure 12a. Therefore, a building with a limited number of residential units on the same floor is suggested. For a wind direction of 90.0 degrees, the large area with zero pressure difference diminishes the ventilation in the area with an impinging wind. However, there is an oblique wind flowing from the middle area to the area at the edge of the building, enhancing the use of the wing wall to increase ventilation in the room (see Figure 12b).

To avoid the impinging wind at the middle of the building, residential units with wind induced ventilation should be located near the edge of the building to receive upstream wind, with the service area located at the middle of the building. Figure 13 shows a schematic of a building with residential units located next to the service area, i.e. the lift lobby. There are only 16 units, without balconies, per floor and each unit does not block the oblique and parallel winds.

4.4 The Current Status of High-rise Residential Building

According to the results of this study, a room with a 2.0 m wing wall at the middle of an external wall, without a balcony, is recommended for a wind inducing room. The residential units in the existing buildings surveyed in this study (Figure 1) are usually units with an air conditioning system and

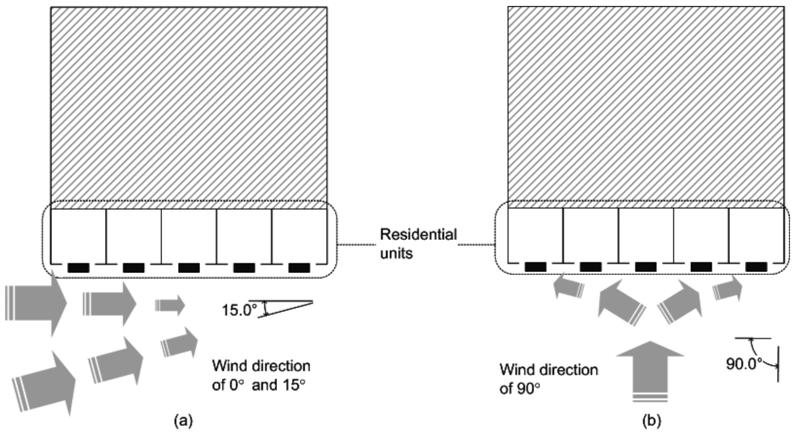


Figure 12. a) Wind in a 0.0-15.0 degrees direction to the building is obstructed by the preceding residential units b) Wind at 90.0 degrees to the building produces oblique wind on the building surface.

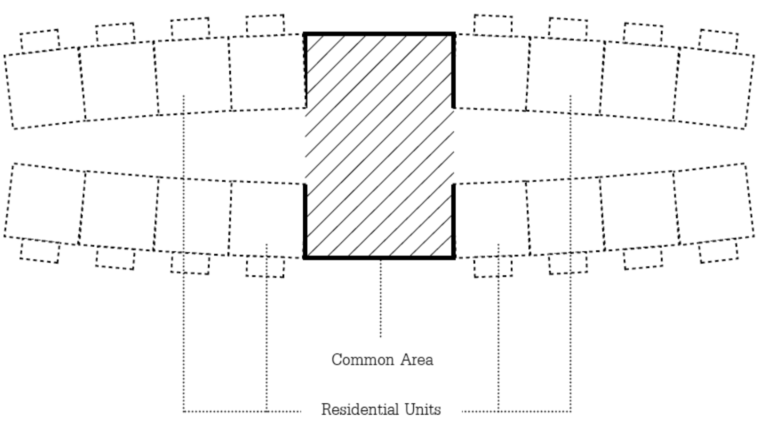


Figure 13. A schematic of one floor of a building with residential units located next to the common area.

the utilization of a wing wall and balcony in these buildings does not provide wind induced ventilation. Presented in Figure 14 are simplified schematic drawings of the existing rooms in Figure 1, demonstrating that the walls of these rooms obstruct the wind (Figure 14a, b), reduce the performance of the wing wall at the middle of the room (Figure 14c, d), only allow wind from the left or right sides (Figure 14e) or lack any wing wall at all (Figure 14f). It can be seen from Figure 14 that a wing wall between the two openings should be applied and any obstructions at the edge of the room should be removed in order to increase the ventilation in the room.

5. Conclusions

Energy conservation, environmentally friendly products and human health are major concerns in architectural design. Utilization of natural ventilation in residential rooms is an approved and effective approach to provide thermal comfort and help reduce annual energy consumption. This study proposes the appropriate installation of a wing wall with or without a balcony to increase the wind induced ventilation. By using the CFD program, PHEONICS, the results from a 3D simulation model are tested with the previous experimental results (Givoni, 1994) and found to be in good agreement for the parallel and oblique winds. Based on the experimental results of Givoni, the computational models of various wing walls are investigated in order to obtain the appropriate wing wall for a typical residential room. In addition, the façade of the existing building is discussed in terms of the performance of wind induced ventilation.

With a wind direction of 0.0 to 90.0 degrees to the building wall and an opening in the residential unit of 6.0 m x 6.0 m, this study shows that wing walls with a width of 2.0 and 4.0 m and a distance between the openings of 2.0m and 4.0m in a wind direction of 30.0 to 75.0 degrees increase the ventilation significantly. The balcony enclosed by the opaque wall obstructs the ventilation through the opening by 40.0-55.0%, though it shows a certain increase of ventilation with a wind direction of 90.0 degrees. Therefore, a residential unit without a balcony is recommended and a balcony with a well-ventilated wall is preferable. Taking into account the pressure coefficient for rectangular-tall buildings, the residential units with the best ventilation are the units on the upper floors and on the edge of the upstream wind. According to the study results, the facade design of existing residential buildings does not support wind induced ventilation.

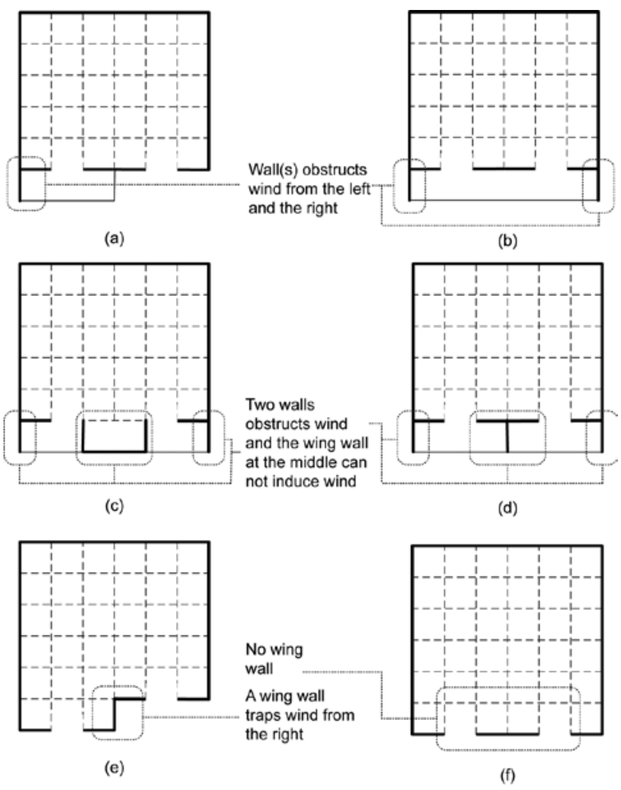


Figure 13. Simplified schematic drawings of units, showing the effects of façade components on ventilation.

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