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Abstract

This article reports the results of continuing research into the impact of the opening orientation and opening size on the natural ventilation of generic detached houses. The CFD simulation of 72 ventilation cases is generalized from actual houses surveyed in the suburban areas of Bangkok. It is discovered that larger opening in general allows higher indoor air velocities than smaller opening. In most cases, the Venturi effect proves to be efficient in terms of indoor air velocities up to approximately 1:1.5 proportion of inlet to outlet opening area. In terms of air distribution, it is found that the opening size and the ratio of inlet to outlet opening area do not have much impact on the uniformity in small square rooms. In large rectangular rooms, the Venturi effect improves the uniformity in two- and three-sided ventilation cases. In cross ventilation cases, however, the uniformity depends on the opening size. The results lead to the prediction of airflow and comfort which is demonstrated by an example of application on an actual building.

บทคัดย่อ

บทความนี้รายงานผลการวิจัยที่ต่อเนื่องของการระบายอากาศโดยวิธีธรรมชาติในบ้านเดี่ยวที่มีลักษณะทั่วไป โดยมีผลจากปัจจัยสำคัญในด้านทิศทางและขนาดของช่องเปิด การจำลองด้วยการคำนวณพลศาสตร์ของไหลใน 72 กรณีศึกษา ที่ทำให้เป็นลักษณะทั่วไปจากบ้านจริงที่สำรวจในเขตชานเมืองของกรุงเทพมหานคร พบว่า โดยทั่วไปช่องเปิดขนาดใหญ่จะให้ความเร็วลมภายในที่มากกว่าช่องเปิดขนาดเล็ก นอกจากนี้ ในกรณีส่วนใหญ่ปรากฏการณ์เวนทูรีมีประสิทธิภาพที่ดีในแง่ของความเร็วลมภายใน จนกระทั่งสัดส่วนของขนาดช่องเปิดลมเข้าต่อช่องเปิดลมออกลดลงถึงประมาณ 1:1.5 ในประเด็นของการกระจายตัวของอากาศภายในห้อง พบว่า ขนาดของช่องเปิดและสัดส่วนของขนาดช่องเปิดลมเข้าต่อช่องเปิดลมออก ไม่ส่งผลต่อความสม่ำเสมอของลมมากนักในกรณีของห้องสี่เหลี่ยมจัตุรัสที่มีขนาดเล็ก ในกรณีของห้องสี่เหลี่ยมผืนผ้าที่มีขนาดใหญ่ ปรากฏการณ์เวนทูรีจะเพิ่มความสม่ำเสมอของลมในการระบายอากาศแบบที่มีช่องเปิดสองและสามด้าน แต่ในการระบายอากาศแบบข้ามฟาก ความสม่ำเสมอของลมจะขึ้นอยู่กับขนาดของช่องเปิด ผลจากการศึกษานำไปสู่การคาดการณ์การไหลเวียนของอากาศและความสบายที่เกิดขึ้นได้ ด้วยการแสดงตัวอย่างในอาคารจริง

Keywords

Airflow Prediction (การคาดการณ์การไหลเวียนของอากาศ)
Natural Ventilation (การระบายอากาศโดยวิธีธรรมชาติ)
Generic House (บ้านพักอาศัยทั่วไป)
Computational Fluid Dynamics (การคำนวณพลศาสตร์ของไหล)
Building Opening (ช่องเปิดอาคาร)

1. Introduction

Natural ventilation represents the simplest yet perhaps one of the most effective passive cooling strategies for buildings in hot-humid climates. Its application is vast especially for residential buildings in suburban and rural areas such as detached houses. This research focuses on wind-driven natural ventilation whose purpose as a passive cooling strategy is to achieve high indoor air velocities with the air that has appropriate temperature and relative humidity. The method has been applied effectively to vernacular buildings, especially in hot-humid climates for a long time. Today, however, denser urbanized areas and higher temperature due to climate change limit the application of natural ventilation. Consequently, designers need a better understanding of building physics to be able to effectively apply the strategy to their buildings. Although there are a number of qualitative studies for wind-driven natural ventilation, it has been suggested that there should be more quantitative studies to develop the principles of natural ventilation design for hot-humid climates (Chenvidyakarn, 2007).

The work in the article “Evaluation and design of natural ventilation for houses in Thailand” (Tantasavasdi, Jareemit, Suwanchaiskul, and Naklada, 2007) discussed the impact of openings on the natural ventilation of generic houses. The present paper presents the continuing study of that previous work. It focuses on the opening orientation (two-sided, three-sided, and cross ventilation), opening size (10-25% of floor area), and the ratio of the inlet to outlet opening area (varying from 1:2 to 2:1).

The paper starts from a review of related natural ventilation theories in Section 2. Study methods and results are then described in Section 3. Next, the findings from the study are applied to an example of actual building in Section 4. Discussion of how to improve a generic design and opportunity for future research is provided in Section 5. Finally, Section 6 presents a conclusion from the study.

2. Review of Related Theories

According to Givoni (1994), there are five major building components that affect wind-driven natural ventilation including the shape of the building, geometrical configuration, orientation of opening, window size and type, and subdivision of interior space. However, for such small houses located on small land lots in this study, the key factors are those regarding opening including the orientation and size. They will be the main parameters of this study.

The previous work (Tantasavasdi et al., 2007) shows that in suburban generic houses, single-sided ventilation gives very low indoor air velocities in the range of 0.04-0.06 m/s. Cross ventilation provides higher indoor air velocities (0.44-0.67 m/s) than two-sided ventilation (0.43- 0.55 m/s). It is also found that the effective opening area of 20% of the floor area represents the optimum size that gives best average indoor air velocity. However, these results are based on the inlet that is equal in size to the outlet. Different ratios of inlet to outlet could give different results. For example, small inlet could cause the stronger Venturi effect than large inlet. The air that is squeezed through a bottleneck such as small openings has higher velocities. This could change not only the average air velocity but also the variation in the air velocity within the space. In general, the air velocity in each area within the room should be similar otherwise occupants could face discomfort in some area that might be too stagnant while the other be too windy. The uniformity of air velocities within the space therefore represents another significant parameter to evaluate natural ventilation efficiency as it measures how evenly the air is distributed within a room. All of these factors will be the subject of the present study.

3. Methods and Results

This section addresses the methods of the study and explains the simulation results. It starts from the survey of actual physical conditions of generic houses in Bangkok which are later generalized to ventilation cases. Then, the CFD program validation and result verification processes are discussed, followed by the model setup and measurement method. Finally, the simulation results are displayed and analyzed.

3.1 Survey Results

This research uses 48 houses from 16 housing projects situated in the northern and eastern suburbs of Bangkok as a population sample. These are the areas where most of the generic houses in the region are located and have highest potential for future expansion. The survey finds that the most popular lot size is 14 x 17 m (approximately 240 sq.m.) and accommodates a two-storied house of approximate dimensions 10 x 10 m. Typical functions include covered car parking area, a kitchen, living and dining area, and a restroom on the first floor; and three bedrooms and two bathrooms on the second floor. It is common practice to have most structures in 4 x 4 m grid systems, partly due to the span of prefabricated flooring systems. Functional floor areas follow the structures and therefore have the dimensions of either 4 x 4 m or 4 x 8 m as shown in Figure 1. Major interior rooms that require larger space including living and dining area on the first floor and master bedroom on the second floor use the 32-square meter rectangular shape of 4 x 8 m while smaller bedrooms on the second floor occupy the 16-square meter square shape of 4 x 4 m. Moreover, most people believe that it is inauspicious to have the house entrance facing west. In fact, it is found that most of the houses have north or south entry.

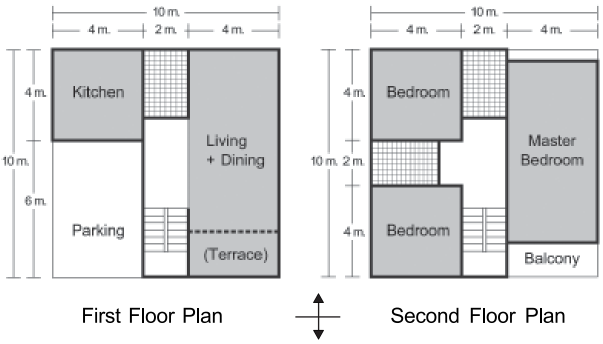
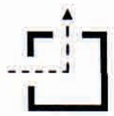
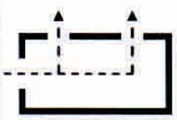
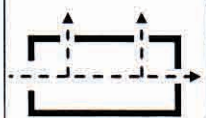
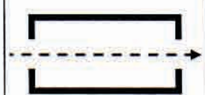


Figure 1. Typical floor plans of generic detached houses.

There are three effective wind-driven natural ventilation types found during the survey including two-sided, three-sided, and cross ventilation, all of which are categorized according to their opening orientation in relation to the prevailing wind. All of these ventilation types can be found in larger rectangular rooms, while only two-sided ventilation is found in smaller square rooms. Single-sided ventilation is also found in a few samples but since it is a very ineffective method, it is omitted from this study. The survey finds the opening areas varying from 10 to 25 percent of the functional floor areas. The ratio of inlet to outlet openings also varies from 2:1 to 1:2. All of the cases are generalized in Table 1. The study uses regular windows that have the opening height of 1.1 m. This limits the highest possible opening areas in some of the rectangular shape cases to 20 percent of the floor areas because at such percentage, either the width of the inlet or outlet is already equal to the width of the wall.

It is assumed in this study that only one opening occupies a short 4-meter wall. In the plan, it is located at the center of the wall which occurs in most actual cases. However, two openings occupy the longer 8-meter walls, each of which located in the middle of the bay of the structure. All of the outlet openings have equal size. This also corresponds to the common practice.

Table 1. Summary of all case studies.

Type of Room and Orientation of Opening	Ratio of Inlet to Outlet Opening	Percentage of Opening Area to Functional Floor Area			
		10	15	20	25
16 sq.m., two-side	2:1	O	O	O	O
	1.5:1	O	O	O	O
	1:1	O	O	O	O
	1:1.5	O	O	O	O
	1:2	O	O	O	O
32 sq.m., two-side	2:1	O	O	O	X
	1.5:1	O	O	O	X
	1:1	O	O	O	O
	1:1.5	O	O	O	O
	1:2	O	O	O	O
32 sq.m., three-side	2:1	O	O	O	X
	1.5:1	O	O	O	X
	1:1	O	O	O	O
	1:1.5	O	O	O	O
	1:2	O	O	O	O
32 sq.m., cross	2:1	O	O	O	X
	1.5:1	O	O	O	X
	1:1	O	O	O	O
	1:1.5	O	O	O	X
	1:2	O	O	O	X

3.2 Validation of the CFD Program and Result Verification

This study uses a CFD program named PHOENICS (CHAM, 2008) to simulate the airflow of all the 72 cases. The conditions are steady-state and the model type is k-epsilon to accommodate turbulence in the airflow. Before the simulation of the ventilation cases, a validation of the program has been made. Ten CFD results are compared with those from wind tunnel (Ernest, Bauman, and Arens, 1991) using identical settings of cross-ventilated simple rooms with openings that range from 5 to 25% of the floor areas, the configurations similar to those in the present research. The comparisons are then plotted in Figure 2. Each point on the chart represents the average indoor air velocity as percentage points of the outdoor air velocity. Each value is averaged from 20 measurement points evenly distributed within the room. It is found that the results from both sources have similar trend and demonstrate small discrepancies in the order 20 percent or less. Such setups are further used in the cases for this study.

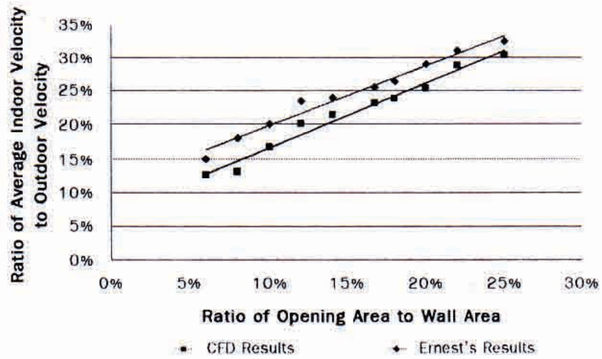


Figure 2. Validation of CFD models.

The CFD results also need to be verified after each simulation is finish to make sure that the results converge. Chen and Srebric (2001) suggest that the residual of mass should not exceed 0.1% of the total mass flow. The residual percentages from all of the 72 simulation result files are calculated when the study is finished. They all well pass such criterion. Both of the program validation and result verification processes help ascertain the accuracy of the simulation results.

3.3 CFD Model Setup and Measurement Method

All of the cases are modeled using a single house with a hip roof. This is the most common in practice because it shades all four sides of the walls. The alteration of the opening orientation and size is made within this setup. The model is then placed in the flow domain that has adequate distances around the house for the air to develop its velocities and accounting for the size of turbulent eddies forming around buildings as shown in Figure 3. The distances from the model inlet boundary to the house and from the upper boundary to the house are six times of the height of the house (H) while those from the side boundaries to the house are 3H and that from the model outlet boundary to the house are 10H. Such settings follow the outdoor simulation rules of thumb that are similar to other outdoor airflow simulation such as the work of Hu and Wang (2005).

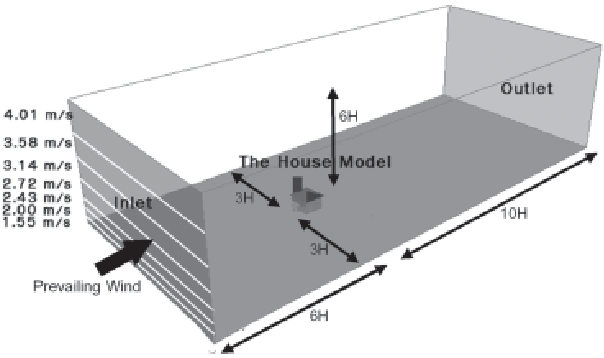


Figure 3. CFD model setup.

The wind profile is also created according to the following equation (Givoni, 1998):

$$V_h = V_{ref} \cdot \left(\frac{h}{h_{ref}} \right)^{\alpha} \qquad (1)$$

where

V_h = wind speed at height

V_{ref} = reference wind speed at height h_{ref}

α = terrain constant (0.28 for suburbs)

In all cases, the original prevailing reference wind speed for the model is estimated to be 2 m/s at the reference height of 5 m above the ground, which derives from the average wind speed of a Bangkok suburb weather station.

In each simulation case, the indoor air velocities are gathered from every square meter at the height of 1 m above the floor, which is the height of most activities. However, to allow the results to be applicable to buildings in other locations as well, non-dimensional measures of air velocity and uniformity are employed in this study. To accommodate this, Ernest et al. (1991) suggest that the average velocity coefficient (C_v) and the coefficient of spatial variation (C_{sv}) should present the average indoor air velocities in relation to the outdoor wind speed and the spatial uniformity of the indoor airflow, respectively. The two parameters can be expressed as:

$$C_v = \frac{1}{n} \cdot \sum_{i=1}^{n} (V_i / V_h) \qquad (2)$$

$$C_{sv} = \sigma_s\ (V_i) / (V_h \cdot C_v) \qquad (3)$$

where

C_v = average velocity coefficient

C_{sv} = coefficient of spatial variation

V_i = mean velocity at interior location i (m/s)

V_h = mean outdoor reference freestream velocity at eave height (m/s)

$\sigma_s(V_i)$ = standard deviation of the n mean interior velocities (m/s)

n = number of interior measurement locations in the model

The outdoor velocity is measured at 1 m above the second floor level. Given the second floor of most houses has an elevation of at least 2.8 m above the ground, the reference height is estimated to be 3.8 m. According to Equation 1, the mean outdoor reference velocity at eave height is calculated to be 1.85 m/s.

3.4 Simulation Results and Analysis

After the simulation, each of the results is interpreted. Figure 4 presents examples of the CFD results from four different cases. The graphic on the left of each case demonstrates the airflow directions and the air velocities. The graphic on the right displays the air velocities read from each square meter within the room. These velocities are later calculated to be C_v and C_{sv}.

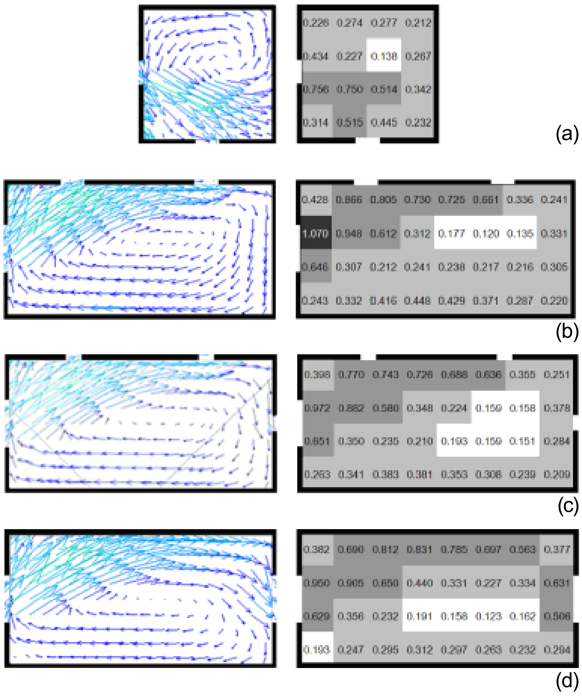


Figure 4. Examples of the CFD results: (a) square room, (b-d) rectangular rooms with two-sided, three-sided, and cross ventilation, respectively.

The air movement can be seen from the study. Since each room is located at a corner of the house as shown in Figure 1 and 3, the air enters the room with an angle although the prevailing wind reaches the house squarely. In every case, high air velocities can be detected in the area between the inlet opening and the exterior side wall which are created by the effect of the building geometry. The prevailing wind moves in such direction because the first negative pressure exists on the two sides of the building. This causes recirculation within the rooms and the area around the center of the room suffers the lowest air velocities. This behavior also causes the air to prematurely exits from the rooms in multiple outlet opening cases (rectangular rooms with two-and three-sided ventilation) in a short circuit manner, lowering their average indoor air velocities.

The results are further plotted in Figure 5 presenting those from small, 16-square meter square

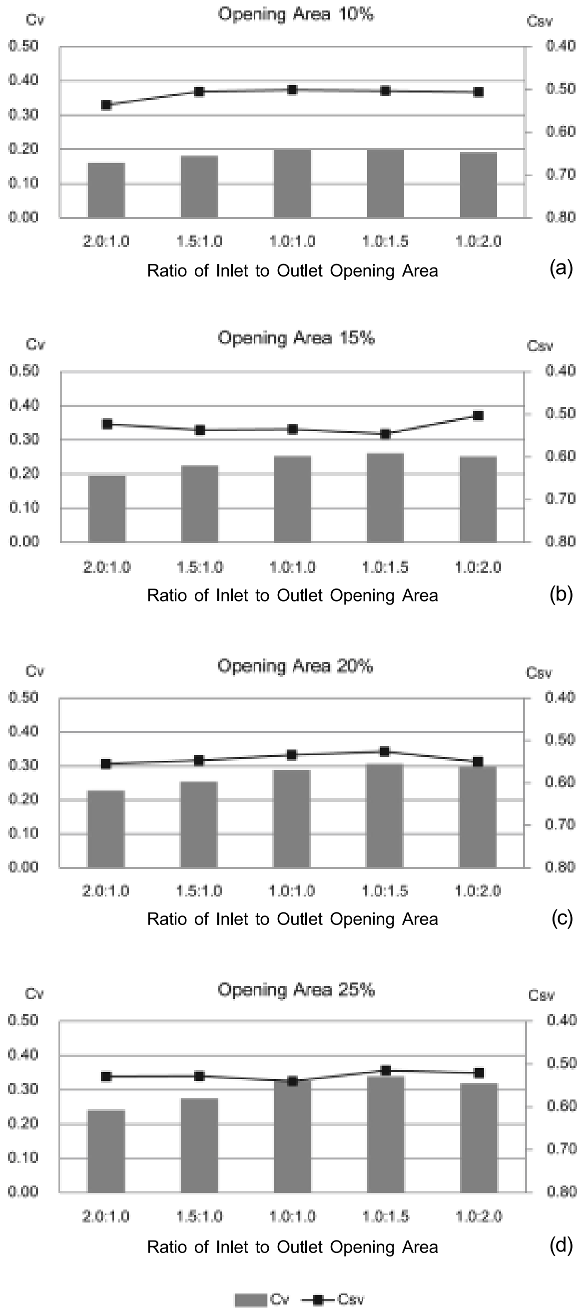


Figure 5. Cv and Csv comparison of the square rooms with two-sided ventilation and a range of percentages of opening area to functional floor area from 10% (a) to 25% (d).

rooms where only two-sided ventilation is possible. The results show that C_v ranges from 0.16 to 0.34 while C_{sv} is very similar in every case, ranging from 0.50 to 0.55. Smaller openings (Figure 5a) give lower C_v than larger openings (Figure 5b-d). This is true for every ratio of inlet to outlet opening. It is also found that for every percentage point of opening area, decreasing the ratio of inlet to outlet opening improves the C_v because of the Venturi effect. However, if such ratio is smaller than 1:1.5, C_v decreases because the inlet is too small to bring in enough volume of air to maintain high velocities through the rooms.

In large, 32-square meter rectangular rooms, all three ventilation types are possible. All of the results are plotted in Figure 6. More variations than square room cases occur in terms of both C_v (0.14-0.39) and C_{sv} (0.43-0.74). In most cases, smaller openings (Figure 6a) give lower C_v than larger openings (Figure 6b-d). The Venturi effect also works for these cases. Decreasing the ratio of inlet to outlet opening area improves the C_v. The best ratio of inlet to outlet is similar to the square rooms at 1:1.5, but only for smaller opening cases (10-15% of opening area to floor area). In larger opening cases (20-25%), the inlet is large enough to bring in adequate volume of air to maintain high velocities through the rooms thus further improving the C_v. In such cases, the Venturi effect further improves the C_v with the decrease of inlet to outlet ratio to 1:2.

In the two- and three-sided ventilation cases, the Venturi effect also improves the uniformity as the C_{sv} reduces when the ratio of inlet to outlet opening area decreases. The air velocities at the inlet of the cases that have large ratio of inlet to outlet opening area, e.g. 2:1, are relatively lower than those with smaller ratio, e.g. 1:2 because of the weaker Venturi effect. Such air that has lower velocities quickly exits at the first outlet due to the building configuration and causes a lot of stagnant area in the rooms. This creates large discrepancies of air velocities and the higher C_{sv}. On the other hand, the air that has higher velocities in smaller inlet cases has a different type of movement. Since the outlet is split into two or three openings, the outlet opening size is relatively small. Although some air also exits at the first outlet, the air that has higher velocities in smaller inlet cases can maintain its velocities around the rooms and cause less stagnant area in the rooms. This creates smaller discrepancies of air velocities the lower C_{sv}.

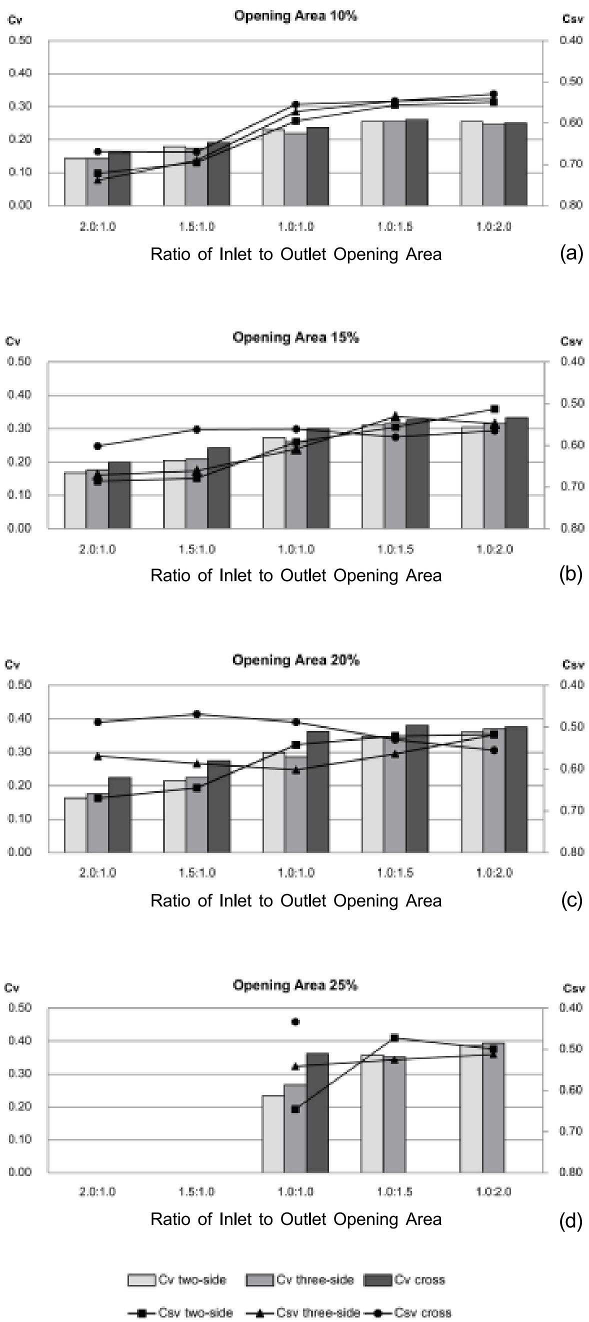


Figure 6. C_v and C_{sv} comparison of the rectangular rooms with two-sided, three-sided, and cross ventilation and a range of percentages of opening area to functional floor area from 10% (a) to 25% (d).

In cross ventilation cases, the uniformity depends on the opening area. It improves with the Venturi effect only in small opening cases (Figure 6a). In larger opening cases, e.g. Figure 6c, the Venturi effect reduces the uniformity. This can be explained as the followings. In smaller opening cases, if the air velocities at the inlet are low such as those with large ratio of inlet to outlet opening area, a lot of stagnant area will occur in the rooms. This creates large discrepancies of air velocities and the higher C_{sv}. If the air velocities are higher at the inlet such as those with small ratio of inlet to outlet opening area, the relatively small outlet will not allow much air to exit from the rooms and cause more recirculation within the rooms. This makes the air velocities within the rooms more uniform and creates lower C_{sv}. In larger opening cases, the air movement is different. The smaller outlet in the cases with large ratio of inlet to outlet opening area will not allow much air to exit from the rooms and cause more recirculation within the rooms. This makes the air velocities within the rooms more uniform and creates lower C_{sv}. On the other hand, the larger outlet in the cases with small ratio of inlet to outlet opening area will allow a lot of air to exit from the rooms and cause less recirculation within the rooms. This creates large discrepancies of air velocities and the higher C_{sv}.

When comparing the orientation of the opening, it is found that cross ventilation is the best in most cases especially in terms of indoor air velocity. This is because the outlet is located at back of the building—the position where highest negative pressure occurs. In two- and three-sided ventilation cases, the air exits at the first outlet opening thus allowing less air to circulate through the rooms and lowering its average velocities. In fact, it is found that two-sided ventilation cases give very similar results to three-sided ventilation cases. The differences in both C_v and C_{sv} of the two categories are less than 3%. In terms of uniformity, cross ventilation is also better in most cases. Short circuit that occurs in two- and three-sided ventilation cases significantly creates discrepancies of the air velocities in the rooms thus lowering the uniformity. This does not happen in cross ventilation cases where the air is more evenly distributed.

4. Application

The results could lead to the prediction of indoor airflow and comfort in generic detached houses. This section demonstrates an example of the application of natural ventilation on an actual case including climate analysis and the study of comfort condition in each of the interior spaces. The house is assumed to have a configuration as shown in Figure 7 and located in the suburb of Bangkok. Major functions include living and dining area on the first floor, a master bedroom and two bedrooms on the second floor. Rectangular rooms have north- and south-facing openings that create cross ventilation while square rooms have two-sided ventilation. The opening size in all rooms is approximately 20 percent of the functional floor area.

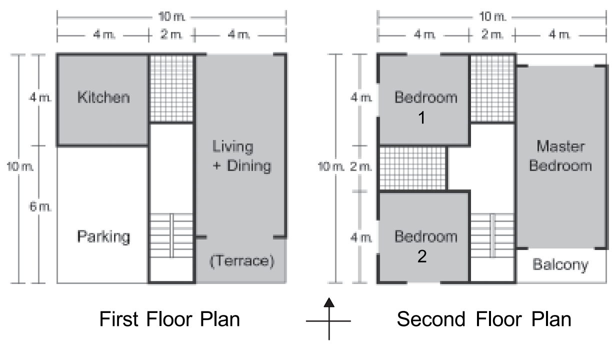


Figure 7. Floor plans of the house example.

4.1 Climate Analysis

Bangkok climatic data (US Department of Energy [DOE], 2009) are analyzed in terms of air temperature, relative humidity, wind speed and wind direction. The psychrometric chart on Figure 8 shows the variation of conditions in different months. The maximum, minimum, and average temperatures and relative humidity are plotted and later transformed into Standard Effective Temperature (SET), the unit developed by Gagge, Fobelets, and Berglund (1986). Under different air temperatures and humidity, people could have the same thermal sensation. Dry air that has high temperature could make people feel the same as humid air with lower temperature because more evaporation could occur on the human skin. SET therefore presents the environmental conditions where people would equally perceive.

The monthly SET values are further analyzed along with thermal comfort conditions. Auliciems (1981) finds that neutral temperature, the median of many people's votes, could be identified as:

$$T_n = 17.6 + 0.31 \cdot T_{o \cdot av} \qquad (4)$$

where

T_n = neutral temperature

$T_{o \cdot av}$ = mean temperature of the month

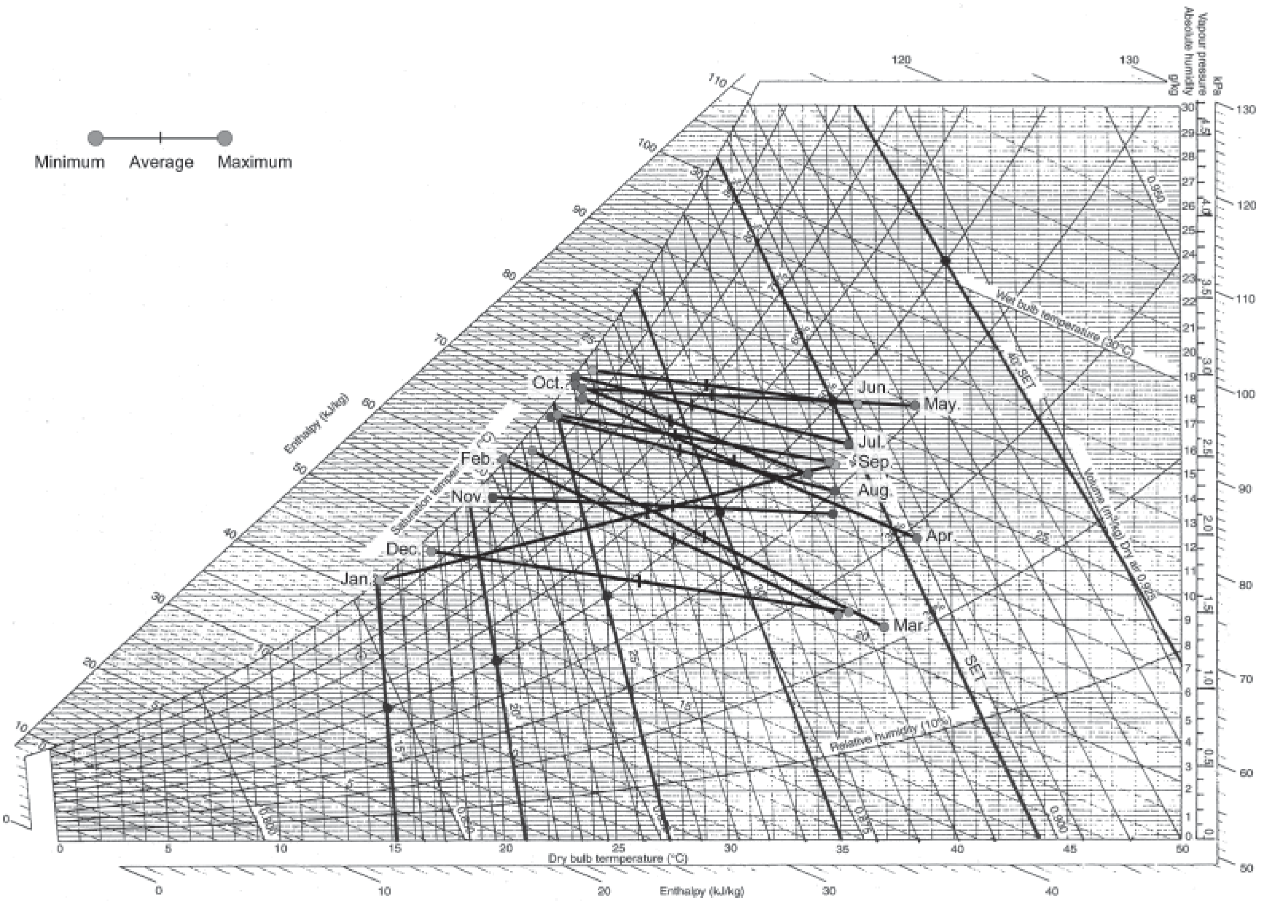


Figure 8. Bangkok monthly air temperature and relative humidity on psychrometric chart (edited from Szokolay, 2004).

Thermal comfort conditions for each month range from T_n-2.5 to T_n+2.5 in degree celcius (Szokolay, 2004). They can be plotted along with Bangkok weather conditions in Figure 9. The chart shows that the maximum and most of the average conditions are beyond the comfort conditions. Cooling is obviously needed.

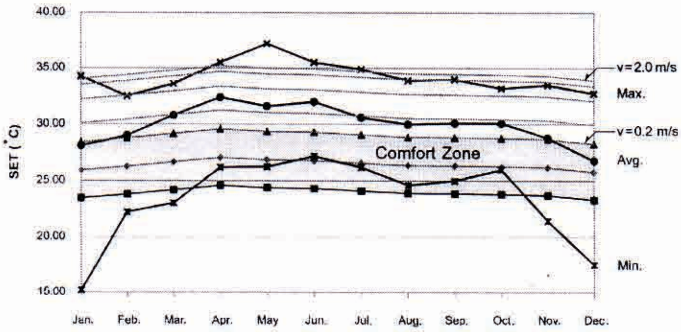


Figure 9. Bangkok monthly SET compared with thermal comfort zone. Natural ventilation potential is expressed as lines above the zone according to air velocities of 0.5, 1.0, 1.5 and 2.0 m/s.

Air movement aids heat transfer from human skin, reducing the skin temperature. Therefore, people feel cooler under higher air velocities as if the air temperature is reduced. Szokolay (2004) gives the reduction effect on temperature as:

$$dT = 6 \cdot V_e - 1.6 \cdot V_e^2 \quad (5)$$

where

dT = cooling effect of air movement

V_e = effective air velocity = $V - 0.2$

V = air velocity (valid up to 2 m/s)

A range of dT between 0.2 to 2.0 m/s is plotted in Figure 9 above the comfort zone, representing natural ventilation potential in Bangkok weather conditions.

Bangkok prevailing wind conditions (DOE, 2009) are presented in Table 2. The average outdoor wind speed ranges from 2.0 to 4.2 m/s and the predominant directions are north in cooler months and south and west in warmer months. This initial climatic study shows that theoretically, natural ventilation could bring the conditions into the comfort zone for most of the time. The exception is some extreme time in warmer months such as from April to June although the average conditions in those months can be comfortable with natural ventilation.

Table 2. Bangkok prevailing wind speed and direction.

Month	Average Wind Speed (m/s)	Predominant Direction
Jan.	2.00	N
Feb.	3.20	S
Mar.	3.00	S
Apr.	3.70	S
May	3.10	S
Jun.	4.20	S
Jul.	3.10	W
Aug.	3.10	W
Sep.	2.50	W
Oct.	2.00	N
Nov.	2.20	N
Dec.	2.40	N

4.2 Comfort Condition

The conditions in each of the four major rooms can be estimated according to the simulation results and the climate data. In each month, the average indoor air velocity in each room is computed from the inversion of Equation 2:

$$V_i = C_v \cdot V_h \quad (6)$$

The outdoor air velocity (V_h) is calculated from Equation 1 using the reference wind speed from Table 2 at the reference height of 12 m. The height of the first floor and second floor functions for the study is 1.0 and 3.8 m above the ground level, respectively. C_v can be read from the simulation results in Figure 5 or 6 along with the opening orientation that corresponds to the predominant wind direction in Table 2.

After finding the average indoor air velocity in each room, the cooling effect of air movement in each room can then be calculated using Equation 5. The reduced temperature is subtracted from the average air temperature to find the actual perceived condition in each room. It is assumed that the indoor temperature is equal to the outdoor temperature, which is a sensible estimation for such a simple study like this. The results are then plotted in Figure 10 and Table 3.

The factor of humidity is already incorporated in the SET. Its upper limit for thermal comfort is not relevant to the study because the upper boundary for relative humidity in Thailand could be as high as 90% (Jitkhajornwanich, 2006). The conditions where the relative humidity exceeds such limit mostly correspond to the lowest temperatures of the months. These conditions can easily reach the comfort level by using minimum ventilation. This allows heat gain to warm the space up thus reducing the relative humidity.

It is found that the rooms that have openings on the north and south and achieve cross ventilation i.e. master bedroom and living and dining room best benefit from the prevailing wind. Both suffer a period of discomfort for three months when the wind is from the west. Functions on the lower level such as the living and dining room face lower outdoor wind speed than those on the second level due to the wind profile. In such conditions, further slight discomfort is discovered in three other months.

The rooms with two-sided ventilation on the second floor i.e. bedroom 1 and 2 also enjoy a long period of comfort. The room that has openings on the south and west such as bedroom 2 can achieve comfort level for nine months. The room that has openings on the north and west such as bedroom 1, on the other hand, suffers a period of discomfort for five months when the wind is from the north. Slight discomfort is also discovered in another month when the prevailing wind speed is a little too low.

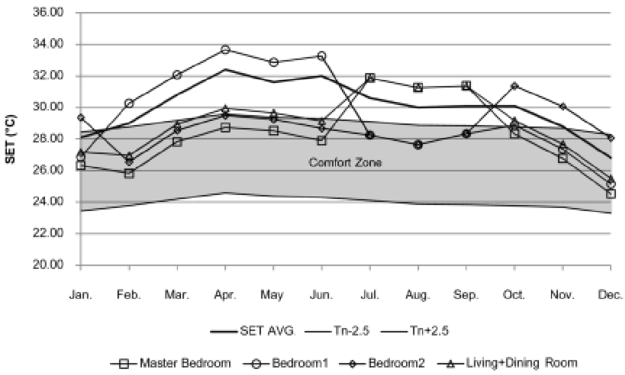


Figure 10. Perceived monthly SET in four major rooms compared with average ambient air and thermal comfort zone.

Table 3. Comfort conditions in four major rooms.

Month	Upper Boundary of Comfort SET (°C)	Perceived SET (°C)			
		Master Bedroom	Living + Dining Room	Bedroom 1	Bedroom 2
Jan.	28.44	26.32	27.18	26.87	29.36
Feb.	28.78	25.82	26.96	30.26	26.54
Mar.	29.18	27.83	28.94	32.06	28.53
Apr.	29.59	28.73	29.94	33.66	29.49
May	29.37	28.52	29.65	32.86	29.24
Jun.	29.31	27.89	29.15	33.26	28.67
Jul.	29.09	31.86	31.86	28.24	28.24
Aug.	28.87	31.26	31.26	27.64	27.64
Sep.	28.84	31.36	31.36	28.33	28.33
Oct.	28.78	28.32	29.18	28.87	31.36
Nov.	28.69	26.76	27.68	27.35	30.06
Dec.	28.28	24.52	25.49	25.14	28.06

■ Comfort ▪ Slight Discomfort □ Discomfort

5. Discussion

As elaborated in the last section, the study finds that natural ventilation alone can allow a generic house to achieve comfort conditions between 6 to 9 months per year. This is worth pursuing because natural ventilation has a relatively low cost. It can help save a great amount of energy for cooling.

To further improve the efficiency of natural ventilation, a few measures should be considered. The prevailing wind in the region has three predominant directions. To be able to capture the wind from different directions, architectural elements such as wing walls and/or landscape elements should be incorporated. This should help improve the indoor air velocities in the months that currently face discomfort. Next, other passive cooling strategies should help reducing the air temperatures. Daytime functions such as living and dining room that are mostly located on the first floor generally have lower air velocities than those on the second floor. This could occasionally cause slight discomfort. Thermal mass could help delay the heat gain and reduce the room air temperatures, shifting the conditions into the comfort level. At night, the room should be flushed to rejuvenate the thermal retention capability of the thermal mass for the next day. Such strategy is proved very efficient for buildings that are mainly used during the day such as Thai Buddhist temples (Sreshthaputra, Haberl, and Andrews, 2004). Evaporative cooling represents another strategy that could complement thermal mass for daytime functions. During the hot hours of the day, the relative humidity is generally low. If moisture contents are added to the warm dry air, the temperature will significantly be decreased. This should further improve the indoor comfort conditions.

The scope of this research is limited to an individual house without any effect from the surrounding buildings to focus on the most significant building component—the opening. In actual contexts, these generic detached houses are mostly located in large housing projects. Site planning plays a great role in altering the airflow around buildings. This could be a subject for future studies. In most actual conditions, the houses may not always be planned in the directions to directly capture the prevailing wind and may have a variation of shapes. The studies of the wind from various angles along with the effect on different building configurations could also be subjects for future studies.

6. Conclusion

This continuing research on natural ventilation for generic houses focuses on parameters regarding opening orientation and opening size. Given the inlet is equal in size to the outlet, the previous research found that the optimum opening area for opening is 20% of the floor area and cross ventilation is generally better than two-sided ventilation. The present work studies more combinations of inlet and outlet size and their impacts on indoor air velocities and uniformity.

The survey of actual houses generates a typical house that includes two configurations of rooms: 32-square meter rectangular shape and 16-square meter square shape. It also creates 72 generic cases whose opening size varies from 10 to 25 percent of the functional floor area and whose ratio of inlet to outlet opening ranges from 2:1 to 1:2. A validated CFD program is used to simulate all these cases. The results are interpreted into two non-dimensional measures: average velocity coefficient and coefficient of spatial variation.

The results find that, velocity-wise, increasing the opening area improves natural ventilation in almost all of the cases. The Venturi effect also improves natural ventilation up to approximately 1:1.5 ratio of inlet to outlet opening area in most cases. In terms of uniformity, the opening size and the ratio of inlet to outlet opening area do not have much effect in square rooms. In rectangular rooms, the Venturi effect improves the uniformity in most of the two- and three-sided ventilation cases. In cross ventilation cases, however, the uniformity mostly relies on the opening size. The Venturi effect helps the uniformity in smaller opening cases but reduces the uniformity in larger opening cases. The overall results show that cross ventilation is the best type of orientation while two- and three-sided ventilation are very similar.

A generic house is tested with the results for the purpose of indoor airflow and comfort prediction using Bangkok climate. It is found that natural ventilation alone can shift the indoor conditions into the comfort level from 6 to 9 months a year. Additional architectural and/or landscape elements should help extend the comfort period along with other appropriate passive strategies such as thermal mass and evaporative cooling. It is wished that along with other future studies such as the effect of site planning and other building factors, passive cooling will become a viable option to reduce fossil fuel consumption in buildings.

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