Evaluation and Design of Natural Ventilation for Houses in Thailand
การประเมินและออกแบบการระบายอากาศโดยวิธีธรรมชาติสำหรับบ้านพักอาศัยในประเทศไทย

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Abstract

This research paper presents guidelines for evaluation and design of natural ventilation for suburban houses in Thailand which is a part of building energy code development for residential buildings. The initial studies find that it is possible for natural ventilation to achieve thermal comfort conditions in place of mechanical air-conditioning systems, especially in winter. The experimental research is divided into two parts: environmental arrangement and building opening. By measuring air conditions flowing through different generic types of environment, it is found that the best environment is that covered with large trees. Computational fluid dynamics studies on generic houses discover that cross ventilation is more effective than two-side ventilation, and is much more effective than one-side ventilation. In general, increasing the size of openings improves the effectiveness of natural ventilation. However, the optimum effective opening area in rectangular rooms is found to be 20 percent of functional floor area. The findings from this research lead to the house evaluation method by factors of orientation and size of building openings. The method is successfully tested with different types of houses.

บทคัดย่อ

บทความวิจัยนี้นำเสนอแนวทางการประเมินและออกแบบการระบายอากาศโดยวิธีธรรมชาติสำหรับบ้านพักอาศัยในเขตชานเมืองของประเทศไทย เพื่อเป็นส่วนหนึ่งในการพัฒนากฎหมายควบคุมการใช้พลังงานในอาคารพักอาศัย การศึกษาเบื้องต้นพบความเป็นไปได้ในการใช้การระบายอากาศโดยวิธีธรรมชาติเพื่อความสบายเชิงอุณหภาพทดแทนการใช้เครื่องปรับอากาศ โดยเฉพาะอย่างยิ่งในฤดูหนาว การวิจัยเชิงทดลองแบ่งเป็นการทดสอบสองด้าน ได้แก่ ด้านการจัดสภาพแวดล้อมและด้านช่องเปิดอาคาร การวัดสภาพอากาศที่ผ่านสภาพแวดล้อมทั่วไปรูปแบบต่าง ๆ พบว่า สภาพแวดล้อมที่มีต้นไม้ใหญ่ปกคลุมเป็นสภาพแวดล้อมที่ดีที่สุด ส่วนการศึกษาด้านช่องเปิดของอาคาร โดยการคำนวณพลศาสตร์ของไหลจำลองลักษณะการเคลื่อนที่ของอากาศในบ้าน

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ทั่วไป พบว่าการระบายอากาศแบบข้ามฟากมีประสิทธิภาพดีกว่าแบบที่มีช่องเปิดสองด้าน และดีกว่าแบบที่มีช่องเปิดด้านเดียวมาก โดยทั่วไป การเพิ่มขนาดของช่องเปิดจะเป็นการเพิ่มประสิทธิภาพของการระบายอากาศ แต่สัดส่วนของช่องเปิดที่เหมาะสมสำหรับห้องรูปทรงสี่เหลี่ยมผืนผ้าคือร้อยละ 20 ของพื้นที่ใช้สอย ผลจากการศึกษานำไปสู่การเสนอวิธีประเมินผลอาคารบ้านพักอาศัยโดยใช้ปัจจัยด้านทิศทางและขนาดช่องเปิดอาคารเป็นหลัก ซึ่งได้ทดสอบกับบ้านพักอาศัยรูปแบบต่าง ๆ อย่างได้ผลแล้ว

Keywords (คำสำคัญ)

Natural Ventilation (การระบายอากาศโดยวิธีธรรมชาติ)
Generic House in Thailand (บ้านพักอาศัยทั่วไปในประเทศไทย)
Building Energy Codes (กฎหมายควบคุมการใช้พลังงานในอาคาร)
Computational Fluid Dynamics (การคำนวณพลศาสตร์ของไหล)
Thermal Comfort (ความสบายเชิงอุณหภาพ)
Building Opening (ช่องเปิดอาคาร)
Building Environment (สภาพแวดล้อมอาคาร)

1. Introduction

Energy shortage is currently one of the most important worldwide concerns. In Thailand, energy consumption in building sector, especially in residential buildings, accounts for a large portion of the consumption for the whole country. The Department of Alternative Energy Development and Efficiency (DEDE) has envisioned this and tried to develop energy codes for residential buildings, especially for houses. Initially, energy evaluation methods are drafted for the purposes of building classification and evaluation.

Natural Ventilation represents one of the main criteria in the evaluation since it can create thermal comfort for occupants and help save a large amount of energy from mechanical air-conditioning systems. However, judging natural ventilation is a very difficult task due to the lack of adequate supporting research in this field. This research aims to create evaluation criteria of natural ventilation for houses and offer guidelines for creating environment and building components that best encourage natural ventilation. This should be useful for both architects and residents to help save energy by means of natural ventilation. The findings should also benefit future studies of natural ventilation for other building types.

The research begins with initial studies that include literature review of ventilation and thermal comfort theories and analysis of climate in Thailand, leading to research assumption as presented in Section 2. The experimental research is divided into two parts: the test of environmental factors by measuring conditions of the air flowing through different generic arrangements of environment in Section 3, and the study of generic building openings by comparing the computational fluid dynamics (CFD) results of cross ventilation, two-side ventilation, and one-side ventilation in Section 4. Then the evaluation method of natural ventilation for houses and the test of the proposed method with different types of houses are presented in Section 5. Finally, the conclusion and design guidelines for houses in Thailand are drawn in Section 6.

There are a few limitations to this study. Two-storied suburban houses on land lots of 200-240 square meters with functional floor areas that do not exceed 240 square meters represent the samples of population in the research. These numbers are mostly found in typical housing projects at the present times. Building and environmental factors are limited only to those within the property lines of each house because it is almost impossible to foresee the future changes beyond the property lines. Weather data are acquired from the Department of Meteorology. Since the discrepancies of climate in different regions of Thailand are small, this research uses data of Bangkok as the representatives of the country. Lastly, the evaluation of natural ventilation focuses on openings. Those involving environmental arrangements are considered easier to change in the future and therefore will be concluded only as design recommendations.

2. Initial Studies

2.1 Theories of Natural Ventilation

It is known that natural ventilation can be generated by two methods: by thermal force or buoyancy effect, and by wind pressure force or wind-driven effect. In general, wind-driven natural ventilation is easier to achieve because it only needs a low wind speed to create adequate indoor air velocities that help people's heat transfer by means of evaporation. Tantasavasdi et al. [1] study natural ventilation for houses in Thailand and find that the buoyancy effect can create indoor air velocities only as high as 0.1 m/s because the height of a two-storied house is generally not enough to create a strong stack effect. On the other hand, the study finds that wind-driven effect can easily create higher indoor air velocities up to 0.4 m/s. Although other studies suggest that buoyancy effect can be more effective, it needs extra efforts, for example, venting towers [cf. 2]. These are not in common practice yet. Therefore, this research focuses on natural ventilation caused only by wind pressure force, which is more practical in creating thermal comfort for occupants in hot-humid tropical climates.

The main purpose of natural ventilation as a passive cooling strategy is to achieve high indoor air velocities with the air that has appropriate temperature and relative humidity. Factors that influence these parameters can generally be divided into two parts: outdoor environment and building component. It is known that landscape elements such as trees and water bodies can reduce the air temperature while hard-surface elements such as concrete grounds raise the air temperature. In this study, different types of environmental arrangement represent the factors of outdoor environment.

According to Givoni [3], building components that affect natural ventilation include shape of the building, geometrical configuration, orientation of opening, window size and type, and subdivision of interior space. However, since the houses in this study are situated on small land lots, the shape of the building and geometrical configuration do not play major role. Most of the houses share the same factors with compact square shape. Interior spaces of most houses are also very similar. Since the houses are relatively small, most of the interior spaces do not have subdivisions. Therefore, the main factors for this study are the orientation of opening and window size and type.

2.2 Theories of Thermal Comfort

Since the 80's, the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) has continuously been developing thermal comfort standards—known as ASHRAE Standard 55's—for people based upon the studies in laboratories. Although they were internationally accepted, these studies were conducted specifically in moderate climates and therefore provided very low ranges of both temperature and humidity. In contrary, other field studies demonstrate higher ranges of thermal comfort conditions for people in tropical regions since people can acclimatize to warmer climates [4, 5]. The latest version of ASHRAE Standard 55 starts to adopt the idea of acclimatization and gives higher upper limit for thermal comfort that could be as high as 27-28°C and 0.012 humidity ratio for the situations where there is a system to control humidity [6, 7].

Air movement increases people's convective and evaporative heat transfer rates. One feels cooler at a higher air velocity. Khedari et al. [8] study the thermal comfort conditions for Thai people in non-air-conditioned classrooms. In terms of neutral thermal sensation, they find that the occupants accept the temperature range of 27.0-36.3°C under the indoor air velocities of 0.2-3.0 m/s and relative humidity range of 50-80%, as appeared in Table 1. The findings are similar to those suggested by Lechner [9] where air velocities of 0.2, 0.4 and 1.0 m/s can make people feel cooler by 1.1, 1.9 and 3.3°C, respectively. The ASHRAE Standard 55 also gives temperature ranges for naturally conditioned spaces in terms of operative temperature in relation to mean outdoor air temperature. However, it disregards the other two major factors of thermal comfort—humidity and air movement. Therefore, this research bases the thermal comfort ranges and effect of air movement upon the study of Khedariet al.

Table 1. Cooling effect of air movement.

Air Velocity (m/s)	Acceptable Temperature Range (°C)
0.2	27.0-29.5
0.5	28.5-30.8
1.0	29.5-32.5
1.5	31.0-33.8
2.0	31.2-36.0
3.0	31.6-36.3

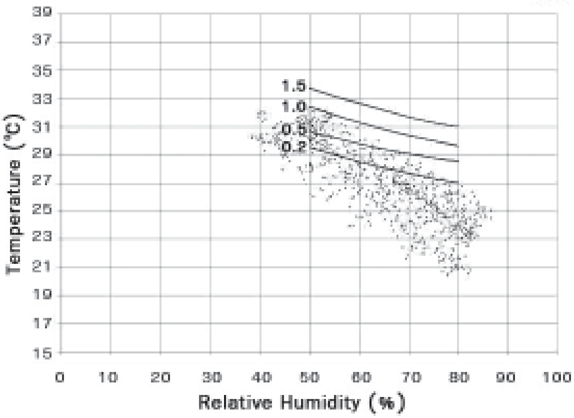


Figure 1. Climatic conditions in December in relation to thermal comfort and cooling effect from air movement.

2.3 Thailand Climatic Analysis

Thailand has a typical hot-humid tropical climate where temperature and relative humidity stay high for almost all year round. The diurnal change is also small. There are two major directions of prevailing wind: cooler northerly/north-easterly wind during the drier months from late October to February, and warmer southerly/south-westerly wind during the monsoon season for the rest of the year. The average wind speed is approximately 2.0 m/s.

Hourly conditions of 11-year weather data from 1994 to 2004 are analyzed on bio-climatic charts. Figure 1 shows an example in the month of December how comfortable people will be with different air velocities. Each line indicates the condition where people would be comfortable under a designated air velocity. In practice, heat gain in a space increases the indoor temperature. A condition under a line, therefore, means it is theoretically possible for such condition to be shifted to the comfortable level by the stated air velocity. However, there is no lower limit for temperature. For such a hot-humid country as Thailand, if the outdoor air temperature is a little too low, the indoor condition can still be comfortable by simply closing some windows. In addition, according to the aforementioned study, the range of 50-80% relative humidity is considered comfortable [8].

Table 2. Number of hour in thermal comfort condition.

Month	Number of Hour in Thermal Comfort Condition as a Result of Natural Ventilation			
	0.2 m/s	0.5 m/s	1.0 m/s	1.5 m/s
January	253	369	436	449
February	101	198	309	405
March	5	64	157	279
April	0	0	28	147
May	0	0	54	160
June	0	23	124	247
July	0	54	116	291
August	0	5	63	228
September	0	0	23	179
October	2	43	123	291
November	135	291	452	479
December	416	540	622	628
Yearly Summary	**912**	**1,587**	**2,507**	**3,783**
Percentage of Hour	**10.41**	**18.12**	**28.62**	**43.18**

The numbers of comfortable hour can be categorized according to various air velocities from 0.2 to 1.5 m/s in Table 2. As can be seen, it is highly possible to achieve comfort condition with natural ventilation, especially during the dry season. In a year, approximately 10 percent of the hours are already within the comfort zone under a very low air velocity of 0.2 m/s. The air velocities of 0.5, 1.0 and 1.5 m/s increase the percentage to 18, 29 and 43, respectively. This initial study encourages further pursuing since natural ventilation is relatively free of charge.

2.4 Research Assumption

All of the initial studies show the potential use of natural ventilation for houses in Thailand and give the assumption: Environmental arrangement and building opening affect the effectiveness of natural ventilation and thermal comfort.

3. Environmental Arrangement

3.1 Survey Results

The survey involves 48 samples of houses within 16 housing projects located in the northern and eastern suburbs of Bangkok which are the areas of the city that possess highest expansion potential. The survey finds that environmental arrangement can be divided into four generic types: large trees, small trees, grass coverage, and hard surface, as shown in Figure 2.

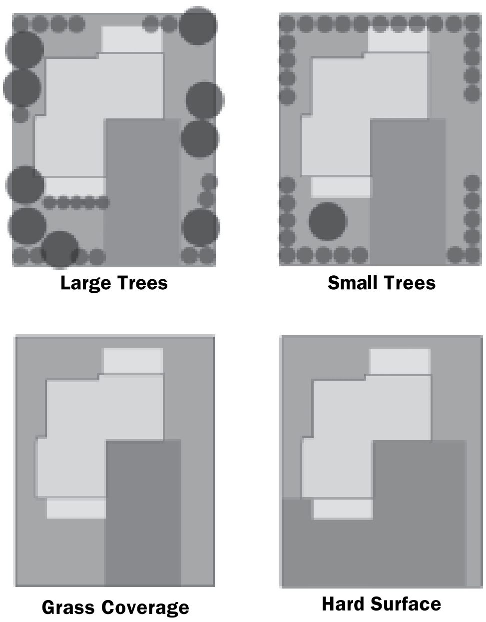


Figure 2. Generic environmental arrangements.

3.2 Measuring Method

A representative from each of the four generic types of environmental arrangement is selected for the study. Temperature and relative humidity are the two parameters measured at the elevation of 1.0 m above the ground since it is the height of most activities. The positions for measurements are shown in Figure 3. Type-k thermocouples are used to measure the information on 15-minute intervals for the continuous period of 72 hours. For temperature, they have errors of ± 0.3°C, which is acceptable for the study.

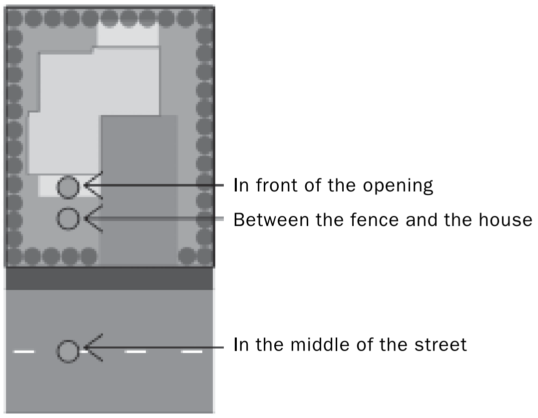


Figure 3. Positions of sensor installation.

3.3 Experiment Results and Analysis

After the measurements, the results are then plotted. Figure 4 shows an example of the environmental arrangement covered with large trees. The temperature in front of the opening (T_i) clearly drops from that in the middle of the street (T_o), especially during the hot hours of the day, while the average relative humidity slightly increases and can be considered negligible. Other types of environmental arrangement show lower decreases of temperature. Figure 5 shows the average temperature difference (T_o-T_i) of each case on hourly basis. For the environmental arrangements covered with small trees and grass, the differences are mostly smaller than those of large trees. The worst case is hard surface where the differences are smallest. In fact, during the hot hours of the day, the temperature increases ($T_i > T_o$).

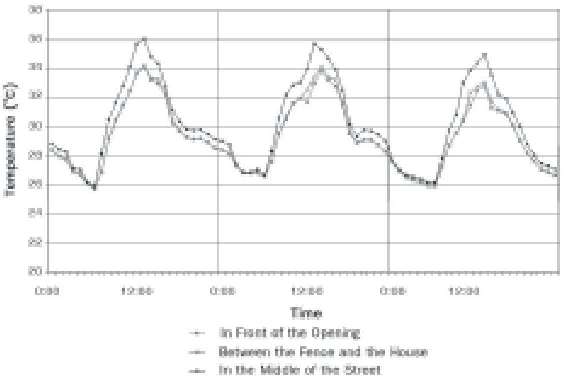


Figure 4. Temperature of the environment covered with large trees.

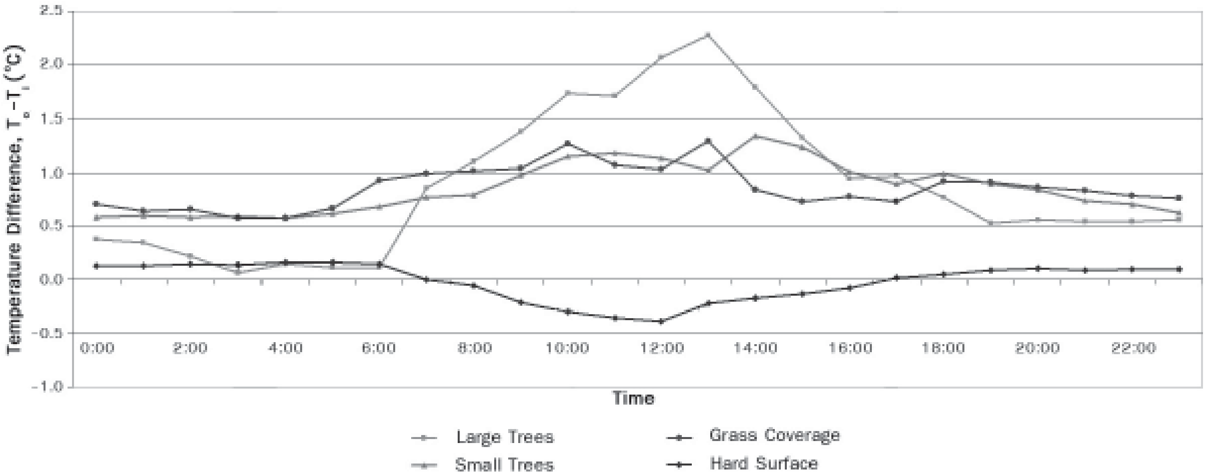


Figure 5. Average temperature difference of environmental arrangement.

4. Building Opening

4.1 Survey Results

The same 48 samples of population are further analyzed in terms of building components. The building shape and configuration that are mostly found are the square shape and compact configuration with the dimensions of 8 to 10 m wide by 10 m long. Functional areas have the dimensions of 4 x 4 m or 4 x 8 m because they are located within the structural grid systems of 4 x 4 m as shown in Figure 6. Rectangular rooms are mostly found on the first floor as continuous public spaces for living and dining and on the second floor as master bedrooms. Square rooms are found only on the second floor as separated bedrooms.

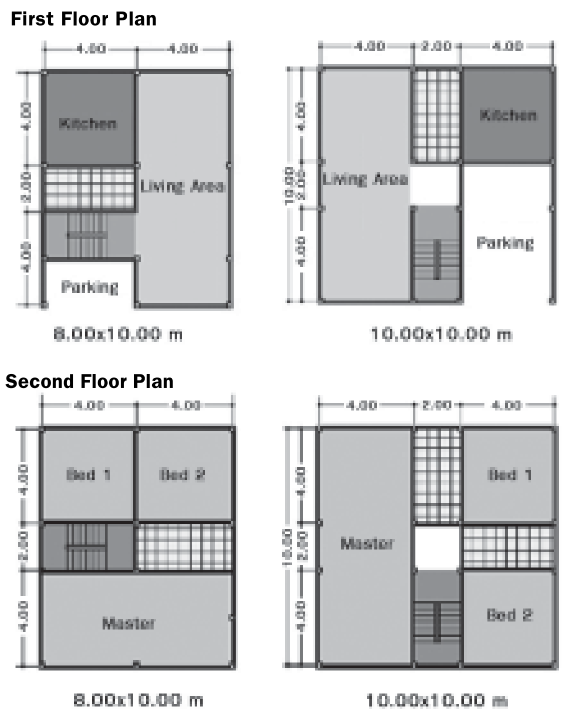
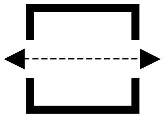
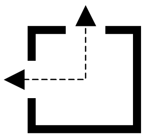


Figure 6. Generic floor plans of the houses.

Orientation of openings can be categorized into three types: cross ventilation, two-side ventilation, and one-side ventilation. The size of the openings varies from 5 to 30 percent of the functional floor areas. There are many types of openings found in the samples, thus effective opening area as a ratio to its functional floor areas represents the parameter in this study. All of the cases can be demonstrated in Table 3.

Table 3. Summary of building opening case studies.

Type of Room and Orientation of Opening	Percentage of Effective Opening Area to Functional Floor Area
	Not found in case studies
	10
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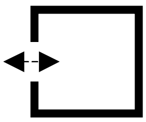	5
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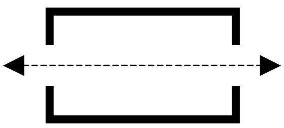	10
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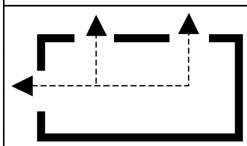	10
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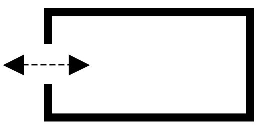	Not found in case studies

4.2 Validation and Verification of the CFD Program

A CFD [10] software is used to simulate the airflow in this study. The conditions in the model are isothermal with k-epsilon turbulence model to account for turbulent airflow. Before the simulations, results from ten CFD cases are compared with wind tunnel results of Ernest et al. [11] for the purpose of validation of the program. All of the cases use a simple building with a variety of opening sizes. For each case, indoor air velocities are measured from 20 measurement points. The average values of all the points comparing to the outdoor velocity are then plotted in Figure 7. The tests indicate that such CFD setups give similar results and trends to those of the wind tunnel.

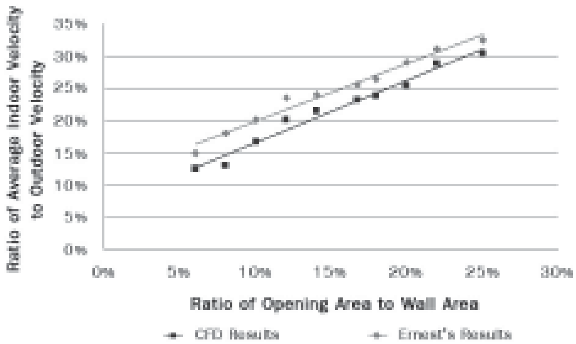

Figure 7. Validation of CFD Models.

Each CFD simulation also needs to be verified for its convergence of the result. Chen & Srebric [12] suggest the residual for mass to be lower than 0.1%. All of the CFD tests in this study well pass such criterion. These validation and verification processes prove the accuracy of the CFD results.

4.3 CFD Model Setup

For the study of all the cases shown in Table 3, a whole house covered with a hip roof is located in the CFD model with enough spaces around it for the wind to develop its velocity as shown in Figure 8. The room size and orientation and size of openings are then altered for each simulation case. The average prevailing wind speed of 2 m/s from the south, measuring at a local meteorology station at the height of 5 m above the ground, can create a wind speed profile according to the following equation:

$$U_H = U_{ref} \cdot \left(\frac{H}{H_{ref}} \right)^a \qquad (1)$$

where U_H is the wind speed at height H, U_{ref} is the reference wind speed at height H_{ref}. The constant a is suggested to be 0.28 for suburbs by Givoni [13].

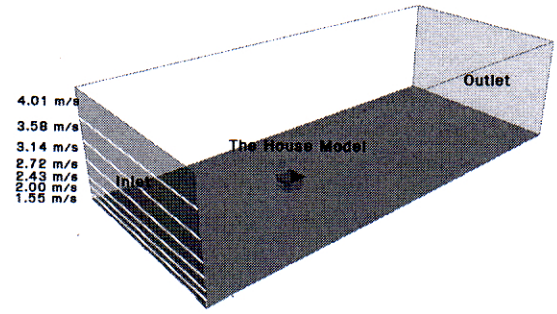

Figure 8. Boundary conditions in the CFD model.

4.4 Simulation Results and Analysis

For each case, the indoor air velocities at 1 m above the floor are averaged from every square meter in the room. Two examples of the results are shown in Figure 9. The tones in the figure reflect the magnitudes of air velocities.

Increasing the effective opening area generally improves the average indoor air velocity. However, in rectangular rooms, the best effective opening area is approximately 20 percent of the functional floor area (Figure 9a). Increasing the opening area further does not improve the average indoor air velocity. In fact, for the case of two-side ventilation, the average indoor air velocity decreases when increasing the opening area to more than 20 percent (Figure 9b). This is because most of the incoming wind moves directly out of the space through inlet 1 in a short circuit manner due to the effect of building geometry. Very little air leaves the space through inlet 2. Therefore, the optimum effective opening area for rectangular rooms would be 20 percent of the functional floor area. This number coincidently matches that of the traditional Thai house.

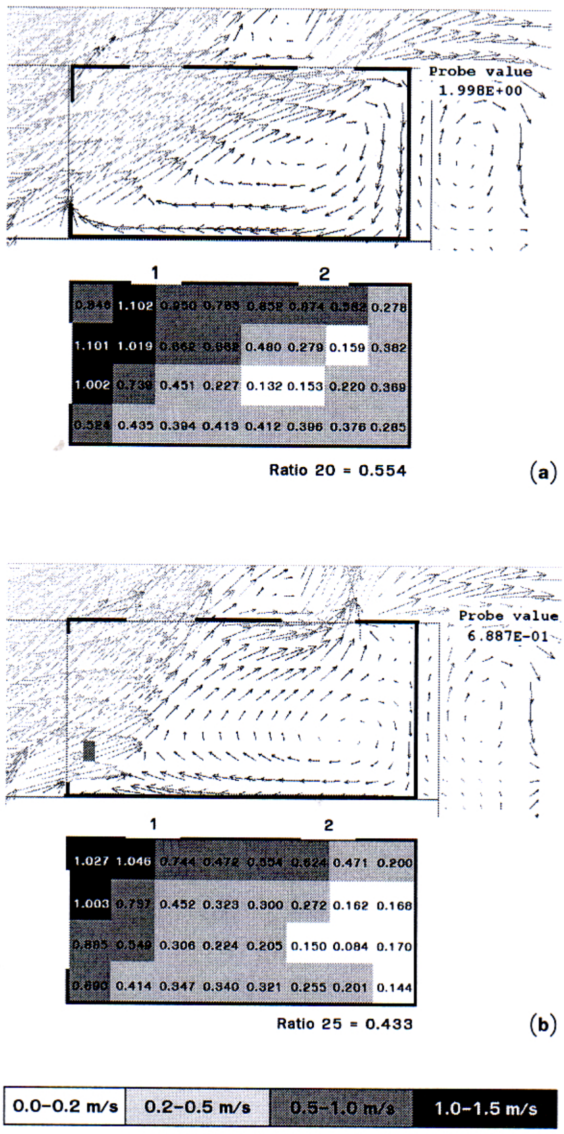

Figure 9. Comparison of indoor air velocities in 32-sq.m rooms with 20 (a) and 25 (b) percent of the effective opening areas.

The average indoor air velocities of all the cases are then plotted in Figure 10. As can be seen, cross ventilation cases provide higher average indoor air velocities than two-side ventilation cases. The opposite openings make the air evenly distributed, resulting in higher indoor air velocities. When considering the prevailing wind from different directions, the cross ventilation cases show further advantages. The wind during the cooler months and that during the warmer months from the opposite direction can enter the spaces with cross ventilation much easier than the others. Therefore, cross ventilation represents the best orientation of opening. The worst cases are those with one-side ventilation where very little air moves into the rooms.

Thermal comfort conditions for all of the cases can be interpreted from the information given earlier in Table 2. The average indoor air velocity of each case can estimate the percentage of hours that falls within the thermal comfort conditions in Figure 10. As can be seen, cross ventilation with large openings can achieve comfortable level for 18 to 29 percent of the time, while one-side ventilation allows less than 10 percent. In general, increasing the opening area improves the indoor air velocity, thus expanding the comfortable hours. The exception is when short circuit occurs as mentioned earlier. This consequently reduces the comfortable hours.

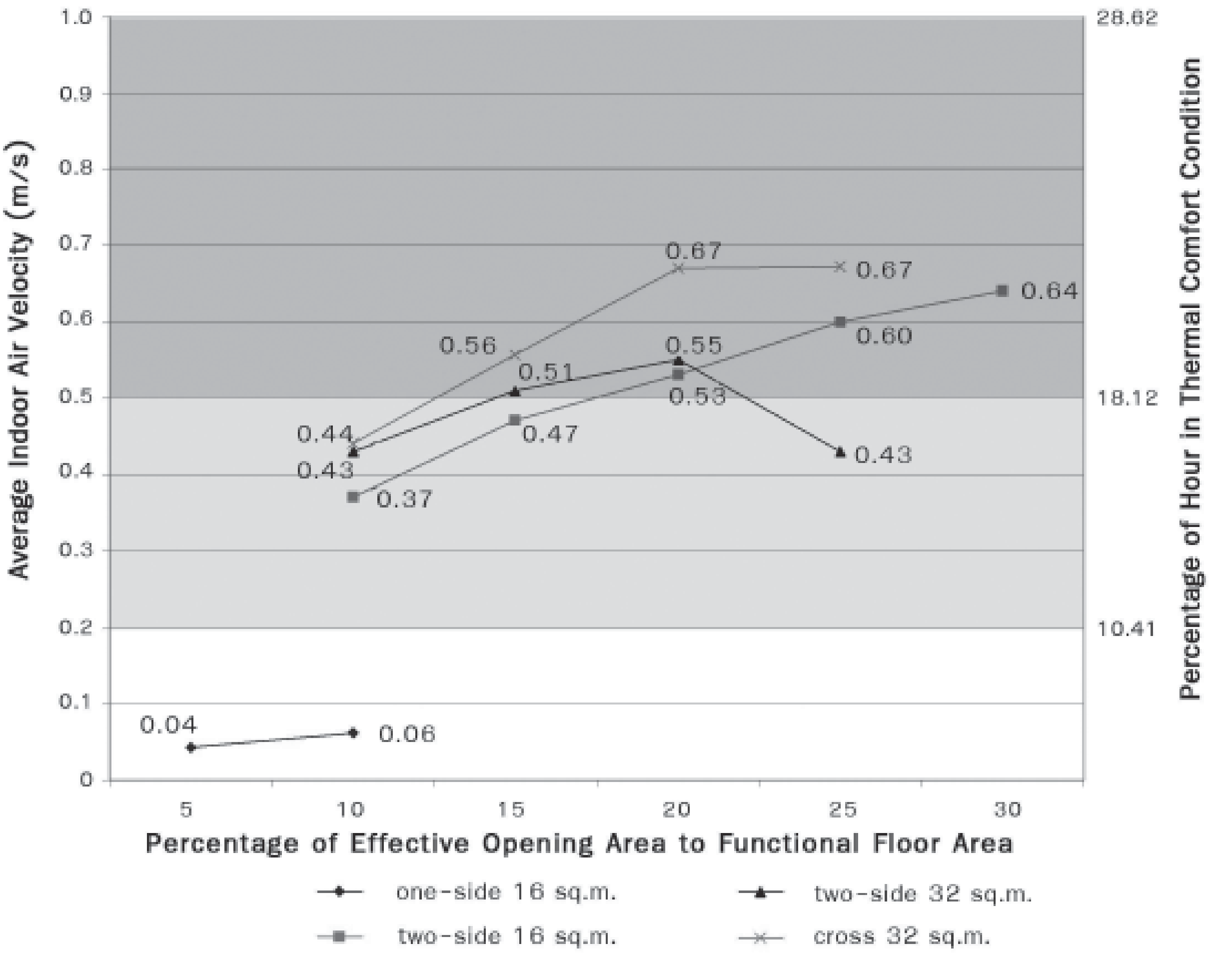

Figure 10. Average indoor air velocity and percentage of hour in thermal comfort condition of all the cases. Numbers on the graph indicate the average indoor air velocities.

5. Evaluation of the Design

5.1 Evaluation Criteria and Method

One-side ventilation generates a very low average indoor air velocity, giving less than 10 percent of comfortable hours. Moreover, heat gains in the space from occupants, appliances, and heat transfer through building envelope further raise the room temperature. The little air that moves into the space can hardly remove the heat, thus the room temperature should be much higher than the ambient temperature. Therefore, houses with one-side ventilation should gain a very low score in the evaluation.

Cross ventilation is slightly better than two-side ventilation in terms of average indoor air velocity and percentage of comfortable hour. However, cross ventilation allows the prevailing wind from opposite directions to freely enter the space, thus expanding the period of natural ventilation usage throughout the year. Therefore, houses with cross ventilation should gain a better score in the evaluation than those with two-side ventilation.

In general, increasing the opening area improves the average indoor air velocity and percentage of comfortable hour. Rectangular rooms have the optimum opening area of 20 percent of the functional floor area. Therefore, the evaluation should also take the size of opening into consideration.

This research proposes a simple evaluation method, equally weighed on the orientation and the size of opening. Assuming the total score for natural ventilation is 4 (out of 100 for the whole building, given by DEDE), each category has the maximum score of 2. For the orientation of opening, cross ventilation gains 2 points, two-side ventilation gains 1 point, and one-side ventilation gains 0 point. For the size of opening, a room with the percentage of effective opening area to functional floor area of 15 or above gains 2 points, that with the percentage between 10 to 14.99 gains 1 point, and that with the percentage of lower than 10 gains 0 points.

In the evaluation process, complications and subjective decisions should be eliminated. The method should be clear and straightforward. Therefore, some common rules have to be made as followings:

1. The only spaces that are considered for natural ventilation are main functional spaces. These include bedrooms, living rooms, and dining rooms. In general cases where most of the first floor areas are inter-connected, all of the areas are considered as one continuous room.

2. Effective opening area is the parameter used in the evaluation, not the whole opening area. The effective opening area means the area where the air can enter the space. Therefore, in cases of casements, awnings, and jalousies, the effective opening areas are larger than those of sliding windows. Exterior doors are generally opened and can also be counted as openings.

3. The size of inlets has to be considered equal to that of outlets. In case that a room has unequal inlet and outlet sizes, the effective opening area is then calculated based on the smaller of the two.

4. In general, a house has more than one room. For the score calculation of such case, each room has to be evaluated separately. Then the overall score is computed weighing on the size of each room according to the following equation:

$$S = \frac{\sum_{i=1}^{n} (A_i \cdot S_i)}{\sum_{i=1}^{n} (A_i)} \qquad (2)$$

where S is the overall score of a house, A_i is the area of room no. i, and S_i is the score of room no. i.

5.2 Testing of the Evaluation Method

The proposed evaluation method is tested with 32 selected samples. All of the testing results can then be categorized into four groups according to their overall scores as shown in Table 4. It is found that the overall scores logically reflect the effectiveness of natural ventilation for the houses. In cases of those with two-side and cross ventilation and have large openings, the overall scores are high. Those with two-side and cross ventilation and have fairly large openings gain satisfactory overall scores. Those with two-side and cross ventilation but have small openings, or those with one-side ventilation but have fairly large openings gain fair overall scores. Those with one-side ventilation or small openings gain low overall scores. Therefore, the proposed evaluation method should be appropriate to judge the effectiveness of natural ventilation for houses in Thailand.

Table 4. Category of natural ventilation effectiveness.

Group	Overall Score	Characteristic			
		Orientation of Opening			Effective Opening Area (%)
		Cross	2-side	1-side	
Good	≥ 3.00	◉	◉		14.36-20.46
Satis-factory	2.50-2.99	◉	◉		10.42-15.50
			◉		15.31-19.80
Fair	2.00-2.49	◉	◉		12.14-12.92
			◉		14.38-16.16
		◉	◉	◉	16.25
Poor	< 2.00		◉		11.45
		◉	◉	◉	11.35

6. Conclusion

6.1 Conclusion from the Study

The investigation explores the possibility of natural ventilation for houses in Thailand. Recent studies show that Thai people can be comfortable at a higher temperature than people from moderate climates. Based on these studies and climatic analysis, it is found that natural ventilation can provide comfort conditions for occupants in the houses for a large period of time.

Environmental arrangement affects the air temperature and can be regarded as an important factor influencing natural ventilation. The study finds that the environment covered with large trees can give a higher average temperature drop than the others, especially during the hot hours of the day. It represents the best type of arrangement, which is better than those covered with small trees and grass. Hard surface represents the worst environment.

The most important factors involving building components are the orientation and the size of opening. The study finds that cross ventilation is the best orientation. It can achieve comfortable level for 18 to 29 percent of the time, which is better than two-side ventilation. One-side ventilation is very ineffective and should be avoided. In general, increasing the opening area improves the average indoor air velocity and therefore expands the time of comfort conditions. However, in rectangular rooms, it is discovered that the optimum opening area is approximately 20 percent of the functional floor area.

The research finally proposes an evaluation method for natural ventilation, giving the importance equally to the orientation and the size of opening. The method is tested with samples and found that the results reasonably reflect the effectiveness of natural ventilation for houses in Thailand.

6.2 Discussion

Recent studies regarding thermal comfort have limited the relative humidity to 80% regardless of the temperature. This works against people in hot-humid tropical regions such as Thailand in achieving comfort level by means of passive cooling, especially by natural ventilation. The climate in these regions is normally not very hot comparing to the hot-arid tropical counterparts, but very humid. The climate analysis in this study finds that there is a large period of time where the temperature falls well below the upper temperature limit of comfort but the relative humidity slightly exceeds the threshold, especially during the rainy season. In practice, such air conditions can naturally reach the comfort level because heat gain in the space will warm the air up while decreasing the relative humidity. However, the prediction of such conditions is beyond the scope of this study. It could be a subject for future studies along side with the studies involving thermal comfort conditions at both higher and lower relative humidity levels.

The proposed evaluation method is limited to the houses that have equal inlet and outlet sizes. Future studies should involve a variation of inlet and outlet sizes to better evaluate more complicated cases. The method is also limited only to the building components. In large housing projects, site planning plays a great role in changing the behavior of the wind. The effect of site plan could also be a useful subject for future studies.

6.3 Suggestion for the Design

The results and observations from the study can give a set of design recommendations as followings:

1. The outdoor environment should be that covered with large trees to provide as large shaded green area as possible.

2. A functional space should have openings at least on two walls. Openings only on one wall should be avoided.

3. The positions of openings on different walls should be as far apart as possible to avoid short circuit, or preferably be located at the opposite walls.

4. Maximum effective opening area is recommended. For rectangular rooms, the optimum effective opening area is 20 percent of the functional floor area.

5. The areas with high indoor air velocities are discovered at the positions close to the inlets and to the walls connected to the outdoor—the latter caused by the geometry of the house. These areas are therefore suitable to place main furniture, for example, beds, dining tables, and sofas.

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