Estimation on the effectiveness of the cross ventilation as a passive cooling method for houses

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ABSTRACT

The integration of research outputs on the cross ventilation is tried in order to quantify the reduction of cooling energy, by raising the stepwise questions and by reviewing existing knowledge useful to find solutions. Through the integration, it will be possible to estimate the sensitivity of errors of discharge coefficients and wind pressure coefficients on the cooling energy and to determine the necessary accuracy.

1. INTRODUCTION

The cross ventilation can be defined as to exchange large amount of air between the indoor space and the outdoors generally by using wind pressure and plural windows. Among its functions, passive cooling is focused on in this paper. The quantification of its effectiveness on energy saving is a key issue, and the prescription of the design method for the cross ventilation is needed.

2. RELEVANT QUESTIONS TO REACH THE KEY QUESTION IN THE TITLE

In order to solve the question, how much cooling energy can be reduced by the cross ventilation (Q1) as shown in Table-1, it should be broken down to more concrete questions even with some inevitable limitations for the clarification. It seems that the two derivative major questions (Q2 and Q3) and seven relevant questions (from Q2a to Q3c) in Table-1 should be focused upon in order to clarify the tasks to reach the final solution of the Q1.

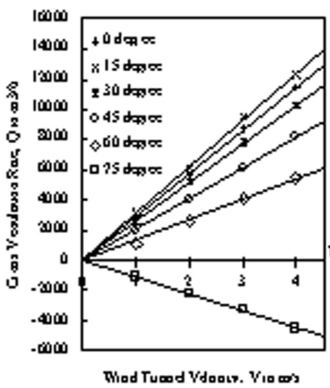
Table 1 Key and relevant questions to be solved

Q1: How much cooling energy can be reduced by the cross ventilation?
Q2: How can the rate of the cross ventilation be predicted under a certain condition for buildings and wind?
Q2a: How can the wind pressure on the building envelope be known?
Q2b: How can the rate of the cross ventilation rate be predicted, if the openings and the wind pressure are given?
Q2b1: How can the orifice flow equation be applied to the inflow opening?
Q2b2: How can the orifice flow equation be applied to the outflow opening or to the combination of both openings?
Q3: How can the reduction of the cooling energy be predicted under a certain condition for the rate of the cross ventilation, buildings and weather?
Q3a: How can the operation of openings by occupants be modelled?
Q3b: What is the accuracy of the coupled heat and airflow simulation tool on the cooling load prediction?
Q3c: How should the energy consumption by cooling equipment be calculated from cooling load?

3. TRIALS TO SOLVE EACH QUESTION

3.1 Q2

As a method to solve the Q2, the application of the orifice flow equation and wind pressure coefficients obtained with the bluff scale model of buildings (orifice equation approach) has been assumed in many existing works, although there is also a standpoint against the application. A few researchers have been searching for completely different approach by using CFD or any methods to make a correction for the orifice equation approach. Such negative standpoint has been based mainly on the fact that there is a possibility for the orifice equation approach to underestimate the ventilation rate when the inflow after passing the first opening takes a certain route. The fact is true, but is not special to wind induced ventilation nor to large openings. It usually happens even to normal components of ventilation systems, such as natural vents, of which airflow resistance have to be estimated as a single component, not as plural airflow resistances in series, which could be synthesized on calculation. If this phenomenon is anticipated, it can be overcome simply by estimating the airflow resistance by plural openings as a whole. In addition, it seems that the frequency of such close connection by the airflow between windows or doors is not very high in actual buildings, taking the shape of the airflow as a jet into consideration. The way to determine the coefficient in the equation should be compromised based on the experiences in the near future, but the linear relationship between the outdoor reference velocity and the ventilation rate does exist as shown in Figure 1, which is one of the reasons why the authors take affirmative viewpoint on the application of the orifice equation approach.



Wind Dir.		a (Q=aV)	R^2
+	0	2877	0.9993
×	15	3105	0.9993
	30	2585	0.9990
	45	2046	0.9996
◇	60	1357	0.9912
□	75	-1121	0.9995

Figure 1: Linear relationship between the wind tunnel velocity and the cross ventilation rate

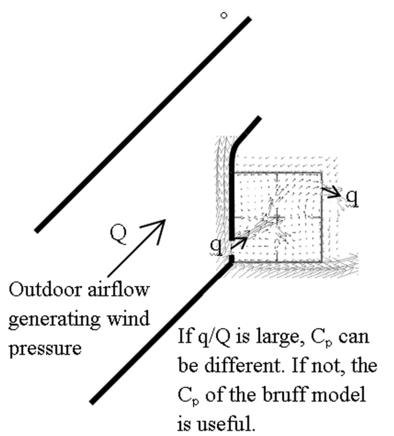


Figure 2: Conceptual explanation on the usefulness of the wind pressure coefficient, Cp, and its possible loss of the accuracy if the cross ventilation rate is not negligible compared with the outdoor airflow, which generates the wind pressure.

As for the wind pressure coefficient, it seems that large cross ventilation rate may change the outdoor airflow and the pressure in it (Figure 2). The magnitude of the cross ventilation rate seems to be related to the ratio of the opening area to the façade area. The effect of the ratio on the wind pressure distribution around the openings seems to be helpful to draw the limit of the ratio from the viewpoint of the usefulness of the wind pressure coefficient for the bluff building models.

3.2 Q2a

For the Q2a, there have been many trials. As for isolated buildings, the wind pressure data based on the wind tunnel experiment have been reported for many types of buildings (Swami et al., 1988, Orme et al., 1994, Sawachi et al., 2007). However, the condition for which the wind pressure information is available is still very limited. The wind pressure information has been used mainly for estimating the infiltration rate through the envelope rather than the cross ventilation, and the information tends to be expressed as a mean value representing wider area. On the contrary, for the calculation of the cross ventilation, the openings are installed so locally that more detailed information on the wind pressure distribution is needed.

There are some works also for the buildings with adjacent buildings or obstacles (Shoda et al. 1956, Wiren 1983, Knoll et al. 1995, Walker et al. 1996, Sawachi et al. 2006). Shoda et al. summarized the wind pressure on the windward and leeward façade depending on the building coverage ratio.

By the sensitivity analysis of cooling load due to the error of the wind pressure estimation, it is possible to know the necessary accuracy for the wind pressure information on buildings isolated or with obstacles.

In the prediction of the wind pressure on the buildings, the wind speed and direction at the building site is also needed. For that purpose, the wind record collected by the nearest meteorological observatory has been relied on, but the appropriateness of using the record from the weather station in a distance should be checked further (Sato et al., 2006).

3.3 Q2b1

As a study for the Q2b1, Ishihara (1969) pointed out that the airflow after the inflow opening is a kind of the jet and that the airflow is contracted when and after passing the opening. He also pointed out the followings.

- The length of the transition region, in which a centreline velocity does not decay, is about five times of the opening width, which is shorter than that of the free jet from a nozzle.
- Due to the airflow along the exterior surface of the building, the airflow angle in the inflow opening tends to be oblique.

Katsuta et al. (1961) investigated the relation between the pressure loss coefficient (the discharge coefficient) of the inflow opening and the ratio of the mean air velocity of the inflow to the outdoor velocity. They pointed out the followings.

- Under stronger outdoor wind, the pressure loss coefficient considerably increases due to the air curtain effect of the outside airflow.
- Generally speaking, the pressure loss coefficient of the inflow opening is larger than that of the outflow opening.
- Wing wall vertical to the façade such as a partition wall in the balcony between residential units is effective to reduce the pressure loss coefficient of the inflow opening.

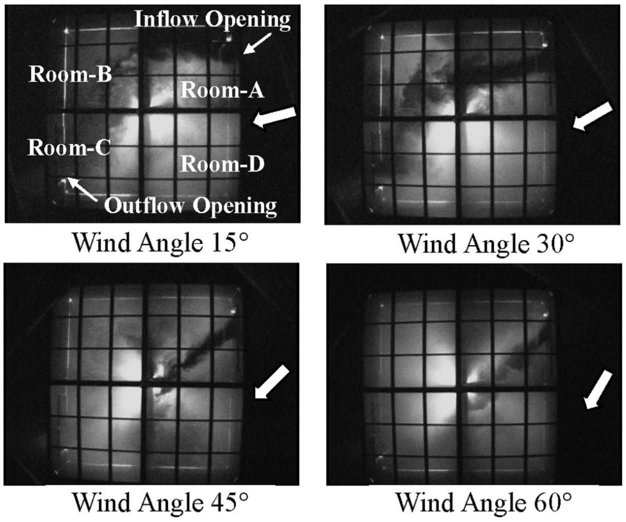


Figure 3: Visualization of the airflow in a room under the cross ventilation, especially the inflow jet, of which width changes depending on the inflow angle

Recently, Kurabuchi et al. (2002) have been focused on the dynamic pressure of the airflow along the surface of the opening instead of outdoor reference velocity.
For contraction tubes, the pressure loss is correlated to the contraction coefficient (Richter, 1958). Therefore, it seems that the pressure loss due to the inflow opening should be correlated to the extent of the contraction. As shown in Figure-3, the visualization of the inflow shows the tendency that the width of the airflow becomes narrower when the inflow angle (the angle between the inflow direction and the normal of the opening) is larger. When these visualizations are compared with existing information on the free jet (Shioji et al. 1991), there are following similar characteristics.
- The incoming airflow entrains the room air on both sides just after passing the opening and forms turbulent vortexes.
- Toward the downstream, it increases its turbulence and the size of the vortexes.
According to the visualization exemplified in Figure-3, if the inflow angle is larger, the size of vortexes in the perimeter of the jet becomes larger and the potential core region as well as the transition region becomes shorter. It looks that the higher turbulence and less extended potential core region might be a cause of larger pressure loss coefficient.

It seems that the way how we should assume the pressure loss coefficient depends on the sensitivity of the ventilation rate and other evaluation indices such as cooling load to the pressure loss coefficient. The following factors should be referred when determining the inflow angle and the pressure loss coefficient for the inflow openings.
- The distance to an adjacent building in front of the opening and the building's height. If the opening can receive the wind rather directly with less influence by any obstacles, the wind direction and the distance from the opening to the upstream end of its façade seem to be influential.
- If the opening has a balcony, an eave or wing walls beside itself, it seems that the inflow angle tends to be more perpendicular to the opening. It is because those components around the opening prevent the airflow along the façade from approaching to the opening.

3.4 Q2b2

As for the application of the orifice flow equation to the outflow opening, the following errors have been pointed out in existing studies. Ishihara (1969) carried out the experiment with building models consisted of multiple cubical chambers connected by openings in series, and pointed out that the total pressure loss coefficient for those multiple openings close to each other can be smaller than the synthesized pressure loss coefficient according to the formula. He introduced the coefficient called "interference coefficient" to adjust a synthesized value given by the formula. However, as mentioned in "*3.3 Q2b1*", Ishihara pointed out by himself that the incoming airflow is a kind of the jet. The centreline velocity of the jet is maintained and its half-velocity width is only twice of the opening width in a distance as far as five times of the opening width (Tsuchiya et al., 1983). Based on these facts, it seems quite natural that the underestimation of the airflow rate should occur if the section size of the jet reaching to the second opening is similar to or smaller than the size of the second opening as shown in Figure-4. In the case as shown in Figure-4(b), the total pressure consisting of the dynamic pressure and the static pressure of the jet impinging on the second opening should be used instead of the room static pressure.
If the circumstances as Figure-4(a) or (b) occur in actual buildings, one of the most realistic situations is supposed to be Figure-4(c), in which there are two openings located on the walls adjacent to each other near the corner. However, in such situation, the prediction error for the effect of the cross ventilation on heat removal efficiency may be more important aspect due to worse connection between the airflow and the rest of the room rather than the underestimation of the ventilation rate.
In addition, it is necessary to check the probability that the incoming airflow impinges on another opening. As

many studies pointed out, the direction of the incoming airflow can be changed horizontally and vertically depending on many factors such as the outdoor wind direction and the position of the opening on the building façade. It is rather difficult to reproduce even in the experiment the impingement of the incoming airflow on the second opening, if taking practical situation of the building into consideration. The easiest way usually taken to reproduce the impingement is to suspend an axisymmetric box with two openings on the axis in the wind tunnel. The probability that the impingement on the second opening occurs may be roughly estimated by the ratio of the second opening's area to the total area of the walls facing to the inflow opening, and the practical importance to deal with such error source seems to be much less than the importance from the view point of the scientific interest.

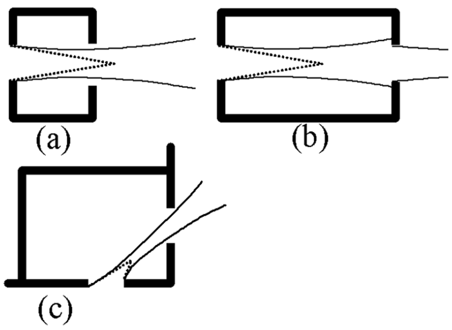


Figure 4: Incoming flow and the location of the outflow opening

Table 3 Example of a) Design Rule and b) Operation Logic of windows

a) In each room, al least two windows on outside walls of different orientation, and the area of the windows is more than (1/m1) times as large as the floor area. If the room can have only one window, another window has to be installed on the outside wall of its adjacent room, which is connected with the room by openings on the partition wall. The size of the windows in that room and in the adjacent room has to be larger than (1/m2) times as large as the floor area of the room and the opening on the partition wall is (1/m3) times as large as the floor area of the room. In these calculations, the ceiling height is assumed to be 2.5 m, and if it is different the necessary size of the windows should be adjusted by the air volume of the rooms.

b) When there is at least one occupant in the room, if the mean radiant temperature, MRT, is higher than T1(°C), the windows are opened. If the MRT is higher than T2(°C), the windows are closed and the air-conditioner is switched on. The usage of the air-conditioner continues until all occupants leaves the room. On the other hand, if the MRT is lower than T2(°C) and higher than T3(°C), the windows are left open. If the MRT after opening the windows becomes lower than T3(°C), the windows are closed. The internal heat and moisture gain due to the occupants' metabolism and electric appliances, etc. has to be scheduled.

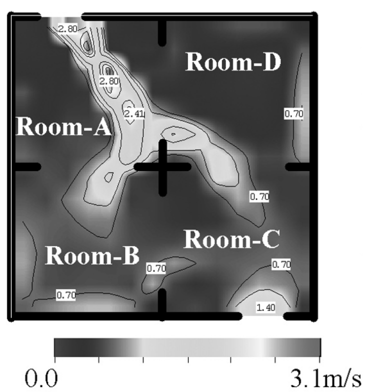
Note: m1, m2, m3 are integers, such as 30, 40, 50.

3.5 Q3a

The Q3, how the reduction of the cooling energy by using the cross ventilation during a certain period can be evaluated and predicted, should be dealt with by breaking down to the Q3a, Q3b and Q3c.

The Q3a is about the determination on the size and the number of openings as well as the logic of the occupants' operation. The design theory of openings to utilize the cross ventilation is to be developed through solving the questions raised in this paper, thus only a tentative design rule in addition to a operation logic are available as shown in Table-3.

In the operation logic shown in Table-3, it is assumed that the occupants operate the windows and the air-conditioners referring only to the mean radiant temperature, but the air velocity could be an influential factor to be taken into consideration in the logic. However, unevenness of the air velocity in the room has made it difficult to include the air velocity in the evaluation of thermal environment. Figure-5 is an example of relative frequency curve of the air velocity inside the building with two openings, each of which has the area of 1/20 of the floor area and the ratio of the opening area (1.5 m^2) to the area of each façade (porosity) is about 9 %. If we choose the mean air velocity in the section of the room (v_1) as a representing indoor air velocity, it can be calculated with the ventilation rate, 2m^3/s and the section area, 13.5 m^2 to be approximately 0.15 m/s, which is much less than the observed air velocity all over the room. On the other hand, if we use the mean air velocity in each opening (v_2) as a representing indoor air velocity, it (1.35 m/s) is much larger than the observed air velocity in many points in the room. These comparisons seems to show the difficulty to determine what kind of air velocity should represent and be included in the evaluation of thermal environment. In addition, the unevenness of the dry-bulb temperature in the room or along the airflow path should have been taken into consideration.



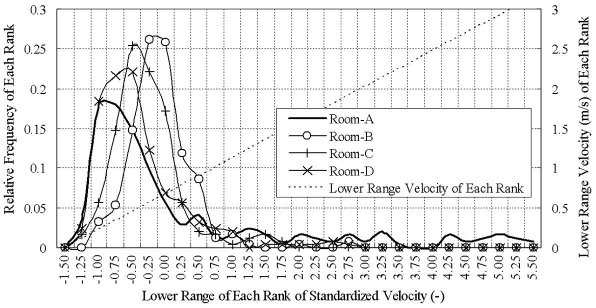


Figure 5: Frequency distribution of absolute velocity in four rooms slightly divided by short side walls for the wind angle 45° (Right) and the configuration of the building model for the experiment (Left) with an example of velocity contour only for 1.2m level, which is one of the five levels above the floor measured and included in the frequency statistics (Sawachi et al., 2004)

3.6 Q3b and Q3c

In the second step to solve the Q3, cooling load calculation should be done following the development of the method to estimate the cross ventilation rate. In the calculation, it is necessary to apply any coupled heat and airflow simulation, in which the internal heat and moisture gain, the solar shading characteristics, the occupants' operation of openings depending on temperature, etc., the heat transport by the cross ventilation and so on should be taken into consideration. It seems that existing validations of the coupled heat and airflow simulation programs should be carefully checked and additional validations might be necessary for conditions, which are similar to those being dealt with for evaluating the effectiveness of the cross ventilation in terms of energy saving.

In the third step, the cooling load should be combined with the energy efficiency of air-conditioners (COP) in order to predict the actual electricity consumption. Since the COP is supposed to be dependent on the relative magnitude of the cooling load compared with the cooling capacity of the machines, a seasonal total efficiency and energy consumption can be reduced considerably if rather small cooling load can be cut by utilizing the cross ventilation as well as better solar shading and any reduction countermeasures to decrease the internal heat and moisture gain.

4. CONCLUSIONS

The requirement for the accuracy of the estimation on the cross ventilation rate should be determined through the sensitivity analysis in the framework of the questions in Table-1.

Recent outputs in the cross ventilation related researches should be integrated into the coupled heat and airflow simulation in order to make the quantitative information on its effectiveness for energy saving more reliable.

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