ANALYSIS METHOD BASED ON POWER BALANCE AS APPLIED TO WIND DRIVEN FLOW

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ABSTRACT

Currently, various studies have demonstrated some doubt about the accuracy of the orifice equation when applied to the calculation of cross-ventilation. As a result, a computational fluid dynamic (CFD) simulation is considered the best method of analyzing cross-ventilation properties under present conditions. However, repetition of CFD analysis to determine the optimum ventilation performance is particularly complex. Accordingly, a flow network model that corresponds to cross-ventilation was developed and suggested as a more efficient means of determining the optimal opening conditions. At least one instance of CFD analysis using a model with openings is necessary to investigate the airflow property around a building. The suggested flow network model was established by utilizing the results of the CFD analysis, and relaxing the total pressure loss coefficients.

KEYWORDS

Power Balance, Ventilation Rate, Network Model Analysis, Pressure Loss Coefficient

INTRODUCTION

The fluid mechanics of cross-ventilation with open windows are different from those of air infiltration through cracks. Various studies have provided useful information for the understanding of different aspects of cross-ventilation phenomena (Karava P 2004). As referred by Sandberg (2004), airflow approaching the building has a choice, to flow through the opening or past the building. When the opening is sufficiently large, the wake behind the building disappears with the result that the airflow properties investigated by a sealed model do not correspond to those for cross-ventilation. Various studies have proposed the modeling of cross-ventilation (Murakami et al. 1991, Sandberg 2002, Ohba et al. 2004, Kurabuchi et al. 2004). The application of a power balance model (energy conservation law) was proposed by Kato (2004). This modeling noted that the dynamic pressure, neglected in the assumption of small openings (i.e. the static pressure difference between the front and the back of an opening is considered to be equal to the total pressure difference), must always be taken into account. Non-standard values for outlet pressure loss coefficients have been reported through wind tunnel experiments. However much more work needs to be done to provide design data for the calculation of ventilation.

CFD analysis is considered the optimal method to predict cross-ventilation properties under present circumstances. However, repetition of CFD analysis to determine the opening conditions for optimal ventilation performance is excessively troublesome. A flow chart for planning the optimal ventilation property by CFD analysis alone is shown in Figure 1. It might be useful in reducing the number of repetitions of CFD analysis and calculation costs by developing a more efficient method of predicting an outline of the ventilation properties. At least one instance of CFD analysis using a model with openings is necessary to investigate the airflow property around a building. Then, the developed flow network model which corresponds to the cross-ventilation characteristics analyzed by the CFD analysis is suggested as a more streamlined method of determining the optimal opening conditions; especially the opening sizes. A flow chart for planning the optimal ventilation property by CFD analysis and the developed flow network analysis is shown in Figure 2. In order to develop the flow network model correspond to cross-ventilation, the parameter for the airflow network model –total pressure loss coefficient – was reconsidered.

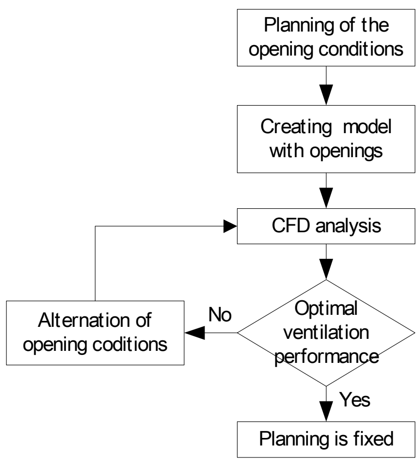


Figure 1. Flow chart for planning by only CFD

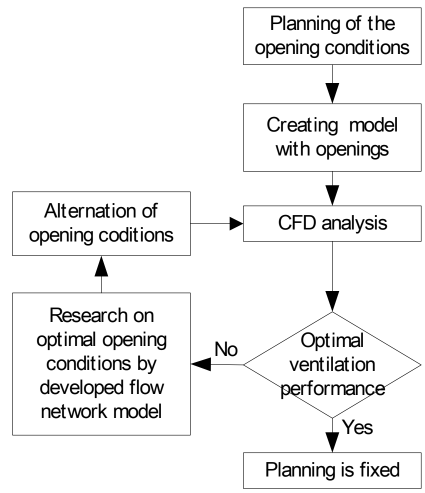


Figure 2. Flow chart for planning by CFD and developed flow network model analysis

TOTAL PRESSURE LOSS COEFFICIENT CORRESPONDING TO CROSS-VENTILATION

If the openings for cross-ventilation are not small enough, the airflow through those openings still preserves part of their dynamic pressure when they stay inside the room. That is, they reach the leeward windows before completely dissipating their kinetic energy into heat. This means that the total pressure losses at openings vary greatly according to the degree of energy preservation after the opening. The total pressure loss is much smaller if the dynamic pressure is preserved and dissipation decreases. The degree of energy preservation is influenced by the flow fields inside and outside formed by the configuration of the building and each window. A simplified energy preservation equation (Equation 1) is as follows (Kato 2004):

$$\sum_m Q_m \frac{1}{2}\left(\frac{Q_m}{A_m}\right)^2 + \sum_m Q_m \left(P/\rho\right)_m + LP = 0 \qquad (1)$$

By establishing a room as a control volume, Equation 2 is obtained:

$$\sum_i PW_i = \sum_j PW_j + LP \qquad (2)$$

When it is assumed that the airflows discharged from the openings dissipate most of their kinetic energy as heat at the leeward openings, the total lost power of the airflow through a room is expressed as follows:

$$LP = \sum_i Q_i \cdot P_{ti} - \sum_j Q_j \cdot P_{sj} \tag{3}$$

Then, the total lost power of each room in a CFD analysis is obtained using Equation 3.

On the other hand, total lost power evaluated in a flow network model analysis is expressed as follows:

$$LP = \sum_i \zeta_i \frac{1}{2}\rho\left(\frac{Q_i}{A_i}\right)^2 \cdot Q_i + \sum_j \zeta_j \frac{1}{2}\rho\left(\frac{Q_j}{A_j}\right)^2 \cdot Q_j \tag{4}$$

The calculation results from Equations 4 and 5 should be the same to make the airflow network model analysis correspond to cross-ventilation. Then the individual total pressure loss coefficients are obtained using the suggested function $f(\theta_{ij})$ as follows:

$$\zeta_i = f_i(\theta_{ij}) \cdot \xi = \min\{r(1-\sin^{0.7}(1.8\theta_{ij})) + 1.1\sin^{0.7}(1.8\theta_{ij})\} \cdot \xi \quad (j = 1,....,n) \tag{5}$$

$$\zeta_j = f_j(\theta_{ij}) \cdot \xi = \min\{r(1-\sin^{0.7}(1.8\theta_{ij})) + 1.1\sin^{0.7}(1.8\theta_{ij})\} \cdot \xi \quad (i = 1,....,n) \tag{6}$$

where θ_{ij} is defined as the angle between a perpendicular line from the windward opening surface through the center and a line from the center of the windward opening to the center of the leeward opening, as shown in Figure 3. $f(\theta_{ij})$ is a function defined to approximate the experimental result from investigating the correlation between θ_{ij} and the total pressure loss coefficient by Ishihara (1969), as shown in Figure 4. $f(\theta_{ij})$ is based on the idea that the value range from r to 1.1 depends on a variable θ_{ij}. The unknown value r for each room is obtained to solve simultaneous equations: Equations 3 ~ 6 using one instance of CFD analysis. However, if θ_{ij} is more than $\pi/9$, it is assumed that the conventional pressure loss coefficients could be adapted and $f(\theta_{ij})$ is considered to equal 1.

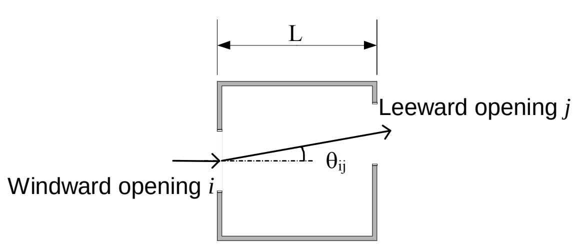


Figure 3. Definition of θ_{ij}

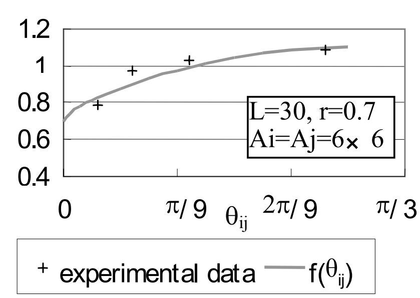


Figure 4. experimental data (Ishihara 1969) and $f(\theta_{ij})$

CASE STUDY USING DEVELOPED FLOW NETWORK MODEL

A case study of the developed flow network model was performed to validate the suggested total pressure loss coefficients. The Model House at Hanoi built in Hanoi, Vietnam, was used as a model building for the case study. The cross sections of the building are shown in Figure 4. This building is an apartment house comprising six dwellings; Houses A~F. In this study, Room C3 which are arranged in the center of the apartment were selected for analyses. The plans of the room, and the locations of the openings (3a~3c) are shown in Figure 5.

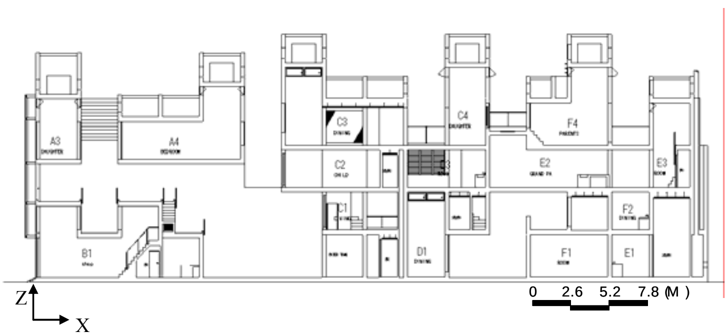


Figure 4. Cross section of the building model

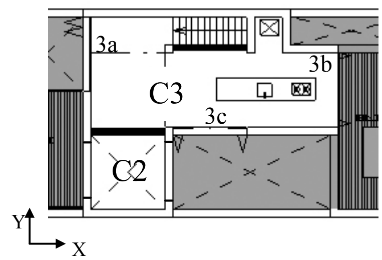


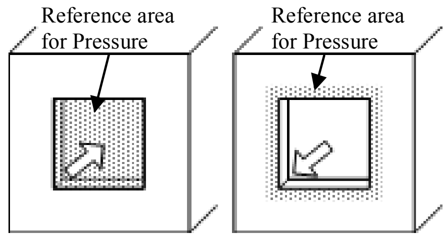
Figure 5. Plan of Room C3

Four flow network model analyses using the suggested total pressure coefficient were performed. The calculation conditions were the same in all cases apart from the opening areas, as shown in Table 1. The values for the pressure coefficients were obtained by one instance of CFD analysis under the opening conditions in Basic Case. (See Appendix A) As the wind pressure for calculating the pressure coefficient, total pressure is assumed on windward openings and the static pressure on the leeward wall around the openings is asuumed on leeward openings, as shown in Figure 6. Then the total pressure loss coefficients were set as suggested in the former sections using the CFD results.

In order to validate the results, CFD analyses were made under the same conditions in each case and the results were compared. The airflow rates analyzed by the developed flow network model and CFD are shown in Table 1. The values estimated by the developed flow network model analyses agree well with those from the CFD analyses. It is considered that the developed flow network analysis could calculate the airflow rate sufficiently well to predict the results using CFD analysis.

Table 1. Comparison of predicting results by developed flow network model and CFD

Room C3	Opening area [m^2]		Airflow rate [m^3/s]		Differential [%]
	3a	3b	Q_{new}	Q_{cfd}	$(Q_{new}-Q_{cfd})/Q_{cfd}\times10^2$
Basic Case	2.0	3.9	-	1.02	-
Case1	1.2	3.9	0.62	0.59	6.5
Case2	2.7		1.38	1.41	-2.1
Case3	2.0	3.1	1.01	1.02	-0.9
Case4		4.7	1.02	1.03	-1.1



a) windward b) leeward

Figure 6. Reference area for pressure coefficient

CONCLUSION

There is some doubt about the accuracy of the conventional flow network model based on the orifice equation for calculating cross-ventilation properties. CFD analysis is considered the best method of analyzing cross-ventilation properties under present conditions. However, repetition of CFD analysis to determine the optimum ventilation performance is particularly complex. Accordingly, a flow network model that corresponds to cross-ventilation was developed and suggested as a more efficient means of determining the optimal opening conditions. Through the validation of the suggested flow network model, it was concluded that the model could calculate the airflow rate sufficiently well to predict the results by CFD analysis. This might result in reducing the time spent determining the optimal opening conditions; especially the opening sizes.

APPENDIX A

The dimensions of the analyzed area for CFD analysis were: length 241.6 m, width 206.25 m, and height 113.5 m, as shown in Figure 7. The building models were located in the center of the area. The wind directions were from the front of the building models as shown by the arrow in Figure 7. The wind flow was assumed to be incompressible and steady. In the process, the High Reynolds Number Quadratic k-ε model (Shih, T.H. et al. 1993) was employed to solve the governing equation for transport of mass, momentum, energy and other flow parameters, wherein thermal transfer was not taken into consideration in these analyses. The pressure and velocity coupling was achieved by using the Semi-Implicit Method for Pressure Linked Equation (SIMPLE) algorithm. The principle of discretization was obtained by applying the Quadratic Upstream Interpolation for Convection Kinematics (QUICK) scheme to advection terms (scalar and momentum equation), and the second-order central differencing scheme to other terms. The boundary conditions are summarized in Table 2. The mesh has approximately 300,000 grid points.

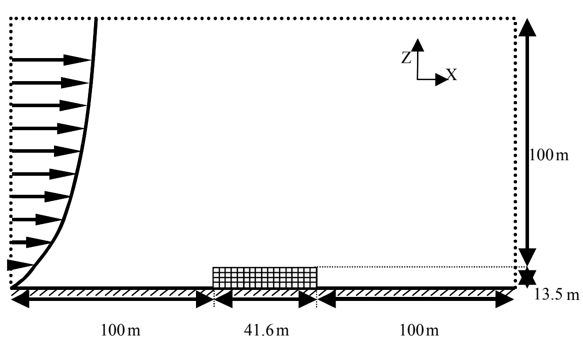


Figure 7. Dimensions of analyzed area

Table 2. Boundary conditions

Inlet	$U(Z)/U_D = (Z/D)^{1/4}, V = 0, W = 0, \varepsilon(Z) = C_\mu k(Z)^{3/2}/l(Z),$ $l(Z) = 4(C_\mu k(Z))^{1/2} D^{1/4} Z^{3/4} / U_D, D = 13.5, U_D = 1.0$
Outlet	Mass balanced
Side and upper planes	Symmetrical planes
Ground plane	Generalized log law
Building surface	Generalized log law

Note: *k* is from experimental data (Murakami et al 1988)

NOMENCLATURE

A	: area of opening [m^2]	C_μ	: constant = 0.09
D	: height of building model [m]	k	: turbulent kinetic energy [m^2/s^2]
L	: length between windward opening and leeward opening [m]	LP	: lost power [W]
l	: turbulence length scale [m]	P	: pressure [Pa]
PW	: rate of energy transport (PW = Pd·Q + Ps·Q) [W]		
U, V, W	: velocity components in the X, Y, Z directions [m/s]	Q	: airflow rate [m^3/s]
ε	: turbulent energy dissipation rate [m^2/s^3]	ρ	: fluid density [kg/m^3]
θ	: angle between windward opening and leeward opening [rad]	ξ	: conventional pressure loss coefficient [-]
ζ	: total pressure loss coefficient [-]		

SUBSCRIPTS

0	: reference value	s	: static pressure
t	: total pressure	*m*	: m^{th} control volume surface
i	: i^{th} windward opening	*j*	: j^{th} leeward opening
new	: result from developed flow network model analysis	cfd	: result from CFD analysis

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