Zonal Model for Natural Ventilation of Light Well in High-rise Apartment Building

AIVC 12104

H. Kotani[1], R. Sato[1], T. Yamanaka[1]

[1] Department of Architectural Engineering, Graduate School of Engineering, Osaka University, Osaka, JAPAN

ABSTRACT

The light well located in the center of high-rise apartment building in Japan is called "Void". Gas water-heaters settled in Void discharge the exhaust gas into Void so that the enough opening area has to be designed at the bottom of Void to keep the IAQ in Void. In order to secure the IAQ in Void, a simple zonal model to calculate the ventilation rate induced by the wind force and the thermal buoyancy through openings at the bottom of Void with heat sources like water heaters is presented. And the accuracy of this calculation method is examined by wind tunnel test. As a result, it is turned out that the calculation methods introduced in this study are valid for predicting the vertical temperature distribution and ventilation rate of Void.

KEYWORDS

Residential buildings, Natural ventilation, Model experiments, Zonal model

INTRODUCTION

There have been built many high-rise apartment buildings recently in Japan. These buildings often have a light well that is an empty space without ceilings or floors from bottom to top. Therefore, the center of the plan is void and this light well is usually called "Void" in Japan. The common corridor open to Void is arranged in the inner circumference of Void. The gas water-heaters are sometimes installed in the open corridors and the exhaust gas is discharged into Void. In order to maintain the IAQ in Void, natural ventilation, i.e. wind-forced ventilation and stack effect are usually depended on.

Generally, ventilation rate due to wind force and stack effect vary with time, and especially the wind-forced ventilation rate is unstable. Therefore, the contaminant concentration will vary with time similarly. To know the necessary opening area, the frequency distribution of contaminant concentration should be examined. As the concentration of contaminant emitted in Void is not linear to the ventilation rate of Void, the varying contaminant concentration should be calculated from the varying ventilation rate with the differential equation of mass balance of contaminant. Such calculation need varying ventilation data, so that the ventilation rate has to be calculated from the wind data previous to the calculation of concentration. The simple method to calculate the ventilation rate is desired, because much computing is needed to have the data of ventilation rate ready for the calculation of contaminant concentration.

As a simple method to calculate the natural ventilation rate, the method based on the modified Bernoulli's equation is valid. And it is useful to calculate the temperature distribution for the large space that the space is divided into the multiple stratified zones. Therefore the zonal model with the modified Bernoulli's equation is used.

Today, many studies on ventilation in large spaces have been conducted such as an excellent zonal model for air-conditioned large space by Togari et al. (1993) and many works of IEA Annex 26 (1996). But there are few studies for natural ventilated space, especially the simplified ones useful for clarification of the unstable natural ventilation characteristics such as a frequency distribution of contaminant concentration. Furthermore, the ventilation about the above-mentioned Void has not studied so much. The authors made model experiments and calculation studies and proved the validity of this method for the wind-forced ventilation (Nakamura et al. 1996) and the ventilation caused by thermal buoyancy (Kotani et al. 1996) respectively. Ohira and Omori (1996) made a model experiment and the CFD simulation for the ventilation by thermal buoyancy.

In this study, to clarify the natural ventilation characteristics caused by both wind force and thermal buoyancy, the ventilation rate and the temperature distribution in Void are tried to predict and the applicability of the method based on the modified Bernoulli's equation will be examined. For this purpose, the scaled model of high-rise apartment building with Void is set on the floor of wind tunnel with atmospheric boundary layer and the heat is generated from coiled Nichrome wires stretched in Void. The ventilation rate of Void on various conditions is measured by the tracer gas technique and the temperature distribution is measured by thermocouples. The measured ventilation rate and temperature distribution in Void will be compared with the calculated ones.

EXPERIMENTAL METHODS

The profiles of velocity and turbulent intensity in wind tunnel are shown in Figure 1. The profile of the wind velocity can be expressed by the power law of 1/4 except for the case with the velocity of 0.5m/s. This corresponds to the wind above the towns.

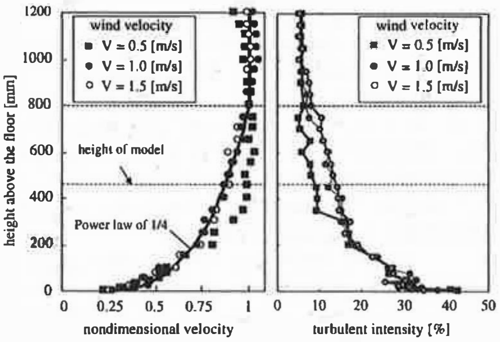


Figure 1 Profiles of velocity and turbulent intensity in wind tunnel.

A scaled model of high-rise apartment building is used as shown in Figure 2. The scale is 1/250. The height of the building model corresponds to about 40 stories.

The conditions of the experimental parameters are listed in Table 1. The thermal buoyancy is changed by the heat generation rate and the wind force is changed by the wind velocity in the wind tunnel. 16 combinations of the thermal buoyancy and the wind force are used.

It must be noted that the similarity requirements are not satisfied in this experiments, so that the results could not be applied to the full scale building necessarily. Another examination would be needed in the future.

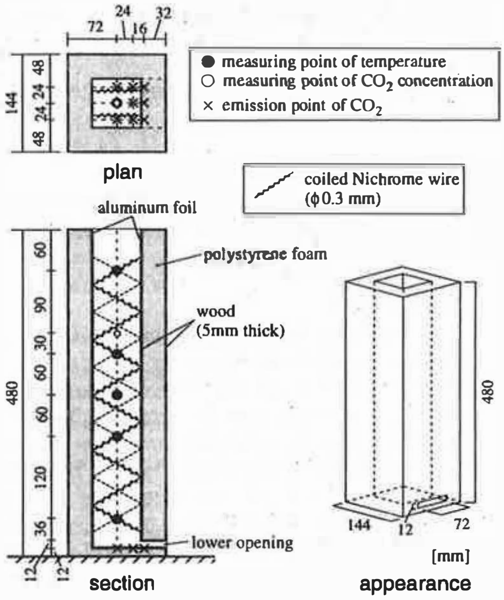


Figure 2 Experimental model with Void.

Table 1 Conditions of experimental parameters

heat generation rate*1	q [W]	10, 20, 30, 40
wind velocity*2	V [m/s]	0, 0.5, 1.0, 1.5
wind direction	θ [°]	0 (wind → opening, Void)

*1 total electric power consumed by nichrome wires
*2 at the height of 80 cm above the wind tunnel floor

Visualization of air flow pattern

The air flow patterns in Void was visualized by laser light sheet and tobacco smoke using another model made of acrylic boards with the same size as the measurement model.

Measuring methods of temperature distributions and ventilation rates

Heat is generated from the Nichrome wires stretched in Void. Five thermocouples are equipped in Void to measure the vertical temperature distributions (see Figure 2). The thermocouples are located in the center of Void horizontally.

In order to measure the ventilation rate through the lower opening of Void, CO_2 gas is emitted continuously from 8 points near the lower opening and the concentration of CO_2 is measured at the upper part of Void where the distribution of CO_2 concentration becomes uniform enough (see Figure 2).

CALCULATION METHODS

Void is separated into several smaller zones stratified vertically to take account of the vertical temperature distribution as shown in Figure 3.

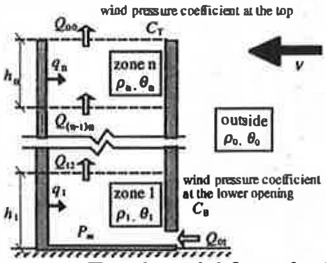


Figure 3 Zonal model for calculation.

The method to calculate the ventilation rate and the temperature distribution of Void is based on the basic equations of mass balance, heat balance and modified Bernoulli's equations as follows;

Mass balance

$$\rho_{n-1} Q_{(n-1)n} = \rho_n Q_{n(n+1)} \tag{1}$$

Heat balance

$$c\rho_{n-1} Q_{(n-1)n} \theta_{n-1} + q_n = c\rho_n Q_{n(n+1)} \theta_n \tag{2}$$

Modified Bernoulli's equations for bottom and top opening of Void

$$Q_{01} = \alpha_B A_B \left\{ \frac{2}{\rho_0} \left(C_B \frac{\rho_0}{2} V^2 - P_m \right) \right\}^{1/2} \tag{3}$$

$$Q_{n0} = \alpha_T A_T \left\{ \frac{2}{\rho_0} \left(-C_T \frac{\rho_0}{2} V^2 + P_m + \rho_0 g \sum_{j=1}^{n} h_j - \sum_{j=1}^{n} \rho_j g h_j \right) \right\}^{1/2} \tag{4}$$

where ρ : air density [kg / m³] $\rho = \dfrac{353.25}{273+\theta}$

Q : ventilation rate [m³ / s]
c : specific heat of air [J / kg degC]
θ : temperature [degC]
q : heat generation rate [W]
α : discharge coefficient [-]
A : opening area [m²]
C : wind pressure coefficient [-]
V : wind velocity [m / s]
P_m : pressure at the floor level of Void [Pa]
g : gravity acceleration [m / s²]
h : height of each zone [m]

subscripts
n : zone number (1 for the lowest zone in Void)
T : upper part of Void
B : lower part of Void
0 : outside (in wind tunnel)

The calculations of temperature distribution and ventilation rate in Void for the conditions in Table 2 are conducted with the various values shown in Table 3. The number of zones were fixed at 1 and 8. The wind pressure coefficients in Table 3 were measured in the same wind tunnel using another model without Void.

Table 2 Conditions of calculation parameters.

experimental parameter		condition
heat generation rate*1	q [W]	10, 20, 30, 40
wind velocity *2	V [m/s]	0, 0.5, 1.0, 1.5
wind direction*3	θ [°]	0
number of zones	n	1 (single zone model) 8 (8 zone model)

*1 conduction heat loss rate through the wall is subtracted from this rate
*2 velocity at the height of 80cm above the wind tunnel floor
*3 incident angle of approach flow to the lower opening

Table 3 Constants for calculation.

geometric mean wind pressure coefficient at the top of Void	C_T	- 0.58
geometric mean wind pressure coefficient at the lower opening	C_B	0.40
height of zone (single zone model)	h [m]	0.468
height of zone j (8 zone model)	h_j [m]	0.0585
specific heat of air at constant pressure	c_p [J/kg℃]	1008
air temperature inside the wind tunnel	θ_0 [℃]	12.0

Discharge coefficient of upper part of Void and lower part of Void are defined as shown in Figure 4 and Table 4. In Figure 4, the modification of the stream tube in Void into duct system is shown. In Table 4, the discharge coefficient of each part of Void is listed.

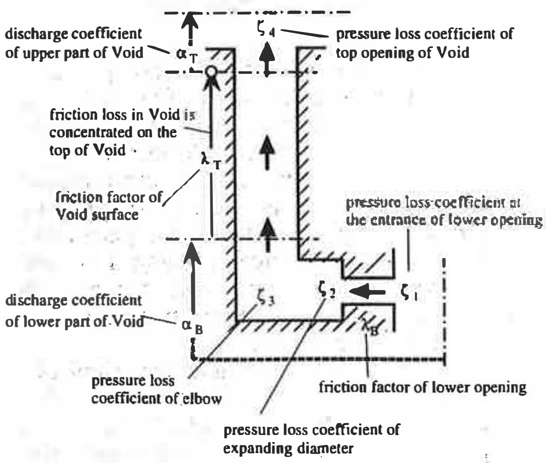


Figure 4 Modification of the stream tube into duct system.

Table 4 Discharge coefficients for calculation

discharge coefficient of upper part of Void : $\alpha_T = 2.187$

$$\alpha_T = \left(\lambda_T \frac{l_T}{d_T} + \zeta_4 - 1 \right)^{-1/2}$$

friction factor of Void surface	λ_T	0.033
pressure loss coefficient of top opening of Void	ζ_4	1.0
length of Void	l_T [m]	0.456
equivalent diameter of Void	d_T [m]	0.072

discharge coefficient of lower part of Void : $\alpha_B = 0.855$

$$\alpha_B = \left\{ \left(\frac{A_B}{A_T}\right)^2 + \zeta_1 + \lambda_B \frac{l_B}{d_B} + \zeta_2 + \zeta_3 \left(\frac{A_B}{A_T}\right)^2 \right\}^{-1/2}$$

pressure loss coefficient at the entrance of lower opening	ζ_1	0.50
pressure loss coefficient of expanding diameter	ζ_2	0.75
pressure loss coefficient of elbow	ζ_3	1.19
friction factor of lower opening surface	λ_B	0.033
length of lower opening	l_B [m]	0.036
equivalent diameter of lower opening	d_B [m]	0.0206
area of lower opening	A_B [m²]	0.072×0.012
area of Void	A_T [m²]	0.072×0.072

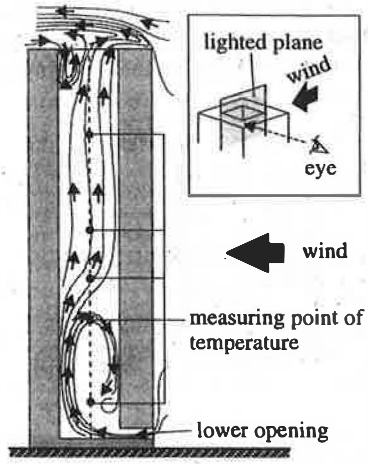
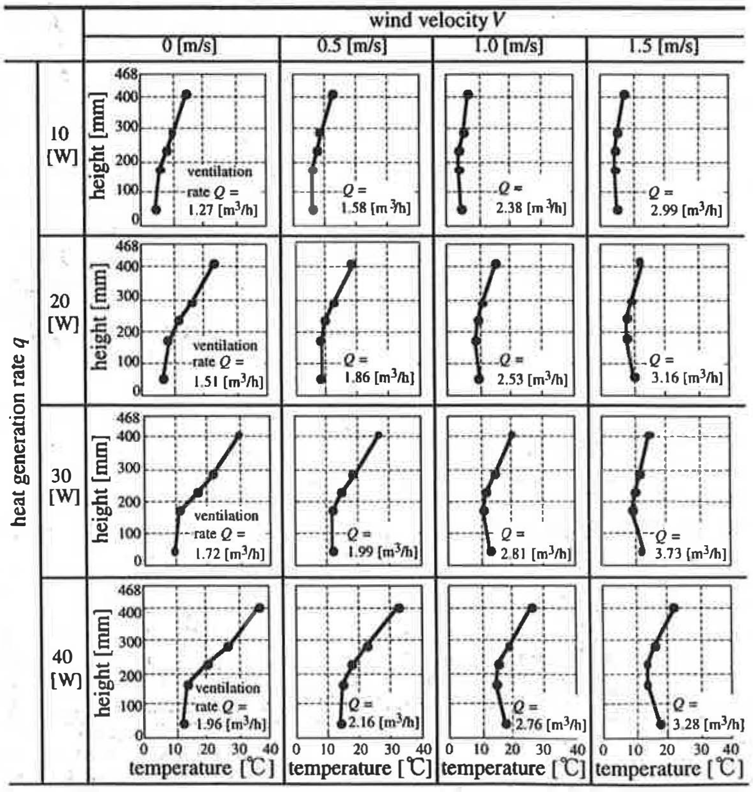


Figure 5 Basic air flow pattern in Void visualized by a laser light sheet.



"temperature" means the difference between the temperature inside Void and the temperature in the wind tunnel. "height" means the height above the floor of Void (wind tunnel floor level +12mm).

Figure 6 Vertical temperature distributions and ventilation rates in Void.

EXPERIMENTAL RESULTS

Basic air flow patterns in Void are illustrated in Figure 5. The circulating flow at the lower part of Void and the some reverse flows from outside into Void at the top of Void are observed.

The vertical temperature distribution and the ventilation rate in Void in each case are listed in Figure 6. The temperature in the higher part of Void is the higher in most cases. In the case with high ventilation rate and big heat generation, the temperature in the vicinity of the Void floor is relatively higher than the temperature at the middle height. It is supposed to be induced by the circulating flow observed in Figure 5. The temperature at the top of Void (temperature of the air flowing out of Void) has negative correlation with the wind velocity and positive correlation with heat generation rate. On the other hand, ventilation rate Q has almost positive correlation with wind velocity and heat generation rate respectively. These tendencies can be understood easily from the thermal buoyancy generated by the heat generation and the wind pressure difference between the lower opening plane and the top plane of Void.

CALCULATION RESULTS AND DISCUSSION

Calculated temperature distribution and ventilation rate in Void are shown in Figure 7 in comparison with measured ones.

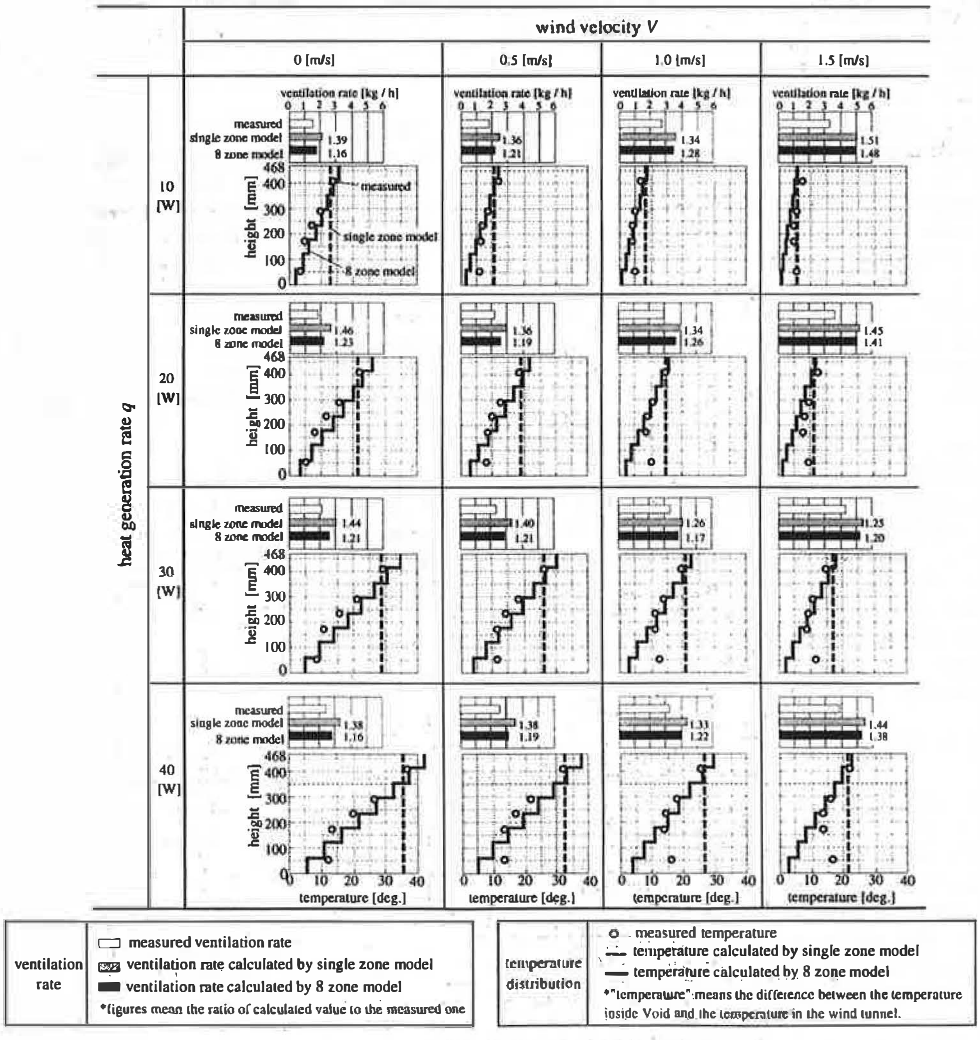


Figure 7 Comparison between measured temperature distributions and calculated ones, measured ventilation rates and calculated ones.

It can be seen from Figure 7 that the measured temperatures almost agree with the calculated temperatures in most cases. But the calculation can not predict the high temperature in the vicinity of Void floor shown in some cases. The reason is the air is assumed to flow in one direction in the calculation and the circulating air flow in Figure 5 is not taken into account. Nevertheless, both temperatures at the top of Void calculated by two models (n=1 and 8) are in good agreement with the measured temperature. As the temperature is highest at the top of Void, this agreement guarantees the validity of these calculations for predicting the highest temperature in Void.

As for the ventilation rate, the calculation tends to overestimate the ventilation rate. The ratio of calculated value to the measured one range from 1.26 to 1.51 for single zone model (n=1) and range from 1.16 to 1.48 for 8 zone model. 8 zone model is superior to single zone model for predicting ventilation rate of Void. Considering the good agreement of the temperature at the top of Void, there might be some error in heat generation rate used in calculation, because the overestimation of ventilation rate leads to the difference between the heat flow rate through the Void obtained by calculation and that obtained by experiment. This should be investigated more.

Generally, it would be concluded that the vertical temperature distribution and ventilation rate can be predicted by the calculation with the multizone model using modified Bernoulli's equations that the wind force and the thermal buoyancy are combined as the pressure differences, although there left are some problems that the similarity requirements are not examined and there might be some error in heat generation rate used in calculations.

CONCLUSIONS

The results obtained in this study are following.

1. The calculation methods introduced in this study are valid for predicting the vertical temperature distribution in Void and ventilation rate of Void.
2. The multizone model is superior to the single zone model.
3. The calculation method tends to overestimate the ventilation rate, but this could be caused by some error in heat generation rate.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support by Takenaka Corporation, and would like to thank Dr. N. Takahashi, Dr. M. Higuchi, Mr. M. Nakamura, Mr. K. Yamamoto, Mr. Y. Nakajima and Mr. K. Igarashi for many useful advice and discussions.

REFERENCES

IEA ANNEX 26 (1996) Outcome of IEA Annex 26; Energy efficient-ventilation of large enclosures. *ROOMVENT'96 Workshop*, Yokohama, Japan

Kotani, H., Narasaki, M., Sato, R. and Yamanaka, T. (1996) Natural Ventilation Caused by Stack Effect in Large Courtyard of High-Rise Building. *Proceedings of ROOMVENT'96*, Yokohama, Japan, Vol. 2, pp. 299-306.

Nakamura, M., Sato, R., Yamanaka, T. Kotani, H., Takahashi, N. and Higuchi, M. (1996) Predicting Method of Wind-Forced Ventilation in a Void of High-Rise Building. *Proceedings of ROOMVENT'96*, Yokohama, Japan, Vol. 2, pp. 343-350.

Ohira, N. and Omori, T. (1996) Ventilation Behavior in a Void Space Furnished with Gas Water-heaters. *Proceedings of ROOMVENT'96*, Yokohama, Japan, Vol. 3, pp. 255-262.

Togari, S., Arai, Y. and Miura, K. (1993) A Simplified model for predicting vertical temperature distribution in a large space. *ASHRAE Transactions*, Vol. 99, Part. 1, pp. 84-99.