A TWO-NODE HEAT AND MASS TRANSFER NETWORK MODEL FOR LONG-TERM SIMULATION OF VOID SPACE OF HIGH-RISE APARTMENT HOUSES EQUIPPED WITH GAS-FIRED BOILERS

Tatsuo Nagai and Takashi Kurabuchi
Tokyo University of Science

ABSTRACT

A simplified model was developed by use of thermal-ventilation network with the purpose of studying air environment in void space at the central portion of high-rise apartment houses when gas-fired boilers were installed in the void. First, a one-node model was studied assuming uniform temperature distribution in the void space, resulting mismatching between calculated and measured values for building surface temperature. Then, a two-node model was prepared by separating corridor region from void region. The changes of values by the two-node model were confirmed to be closer to the measured values for the building surface temperature. Finally, by using the two-node model, long-term simulation study was performed for 9 years on high-rise apartment houses in suburban area of Tokyo, Japan, and the conditions to produce high CO_2 concentration that relates closely to residents' health and normal burning conditions for the boilers were extracted.

INTRODUCTION

In recent years, high-rise apartment houses with void (space with open ceiling) in central portion of the building have been increasingly constructed in Japan, and there are many cases where corridors are provided for the purpose of installing gas-fired boilers and of providing convenience for free passing of the residents. In such case, it is necessary to install a ventilation opening on lower portion of the building to connect the void space with the outside space and to maintain air quality in the void, typically represented by CO_2 concentration, for both of the residents and for the gas-fired boilers at adequate level. However, the ventilation rate between the void and the outside space, which gives influence on CO_2 inside, is influenced by various factors such as exhaust heat from boilers, changes of outside air temperature, temperature of building surface, etc. Also, the volume of the exhausted gas to the void shows extensive changes in a year or in one day, depending on the conditions used. Because extremely high CO_2 concentration within the void may be caused by combination of probabilities of these factors, it is desirable that a long-term simulation study is performed in advance when the size of the ventilation opening is designed for void space.

In previous papers, CFD (Computational Fluid Dynamics) was used as a method to evaluate air environment within the void or recessed space (Ohira et al., 1996, Chow et al., 2002). However, it is practically impossible to calculate the changes of temperature or ventilation rate from moment to moment throughout the year. Kotani et al., 2003, proposed simplified model, dividing void space into several vertical zones to reflect vertical air temperature distribution. However, a real void has corridor spaces that might have different temperature distribution from the void, and the influence has not been studied in previous papers.

The primary purpose of this paper is to develop a simplified model reflecting a real building geometry such as corridor for the purpose of evaluating temperature and CO_2 concentration variations within the void throughout the year or for even longer period. The simplified model is based on thermal and ventilation network on a system, which is made up with the void, the building envelope, and the outside space. Using the simplified model, long-term simulation study was performed for 9 years, and weather and time-related conditions to cause high CO_2 concentration were extracted.

ONE-NODE MODEL

Description of the model

Evaluation was made on a one-node model prepared under the assumption that the temperature in void space is uniform regardless of the position of the void space (Figure 1). Outside temperature, excluding the void area, is also assumed to be uniform regardless of the height and the horizontal position. Supposing that TRNSYS 15 with modular structure is used as a simulation tool, a model was constructed by coupling two modules, i.e. a heat balance module and a ventilation rate calculation module. Although the ventilation rate and air temperature in the void depend on each other, the calculation modules of these two factors were calculated iteratively until convergence occurs.

With regard to the heat balance module, it was assumed that the void space was a room, and the existing room temperature calculation module "Type 56" was used. Corridors are modelled as internal walls, and outer walls of dwelling units as boundary walls. Ventilation rate calculated from ventilation rate calculation module was used as input, and air temperature in the void was output. With regard to the ventilation rate calculation module, air temperature of void region as obtained from the heat balance module was used as input, and the ventilation rate between the void and the outside space, $\dot{m}_o$, was calculated from the equation (1).

$$\dot{m}_o = \alpha A_{all} \sqrt{2\rho_o |\Delta p_g + \Delta p_w|} \cdot \mathrm{sgn}\,(\Delta p_g + \Delta p_w) \quad (1)$$

Here, $\dot{m}_o$ is regarded as a positive value when it is on the ascending flow side, i.e. when the outside air flows from the ventilation opening on lower portion of the void and flows out from the ventilation opening on upper portion of the void. Δp_g represents driving force (pressure difference) of gravitational ventilation caused by temperature difference between the void space and the outside space, and the value was regarded as positive on the side where the ascending flow occurs, and it is expressed by the equation (2):

$$\Delta p_g = gL\rho_o \frac{\theta_v - \theta_o}{T_o} \quad (2)$$

Also, Δp_w represents a driving force of wind ventilation between the void space and the outside space. It takes a positive value on the ascending flow side and is given by:

$$\Delta p_w = \frac{\Delta C \rho_o U^2}{2} \quad (3)$$

where ΔC, difference of wind pressure coefficients (lower – upper openings), is assumed to be constant value of 0.3 in this paper. That means upward pressure occurs constantly whichever direction the wind blows.

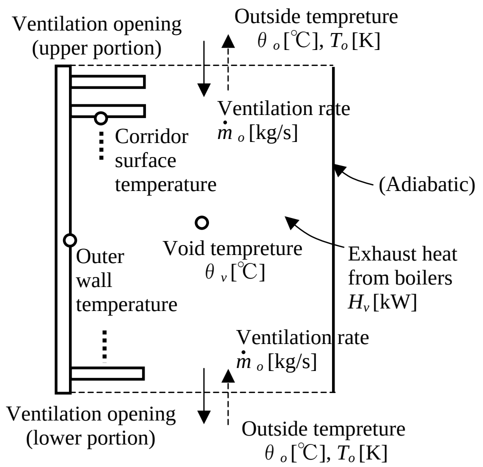


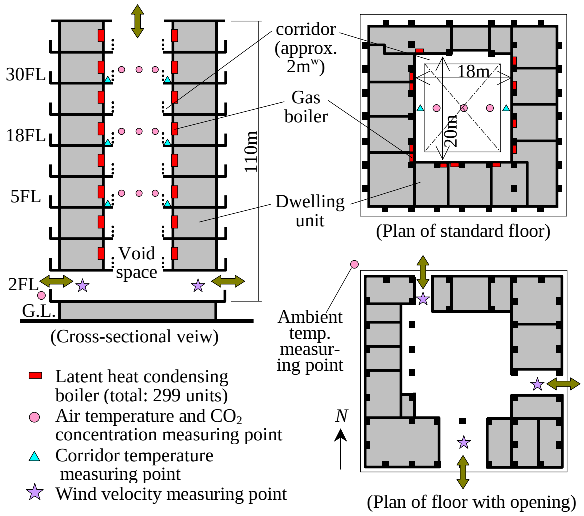
Figure 1 one-node model for void space (cross-sectional view)

Comparison with the measured values

To verify the validity of the model, the measured values in the high-rise apartment houses with void space was compared with the calculated values obtained in the one-node model. The building where the measurement was made was the apartment houses built in suburban area of Tokyo, Japan, and had a void space of about 110 m in height. Under the condition that the residents were living there, air temperature in the void, corridor floor surface temperature, and external air temperature were continuously measured. General features of the

Table 1 general feature of the studied building and the calculation conditions

Location: Saitama (suburb of Tokyo), Japan
Floors: 34 floors, Dwellings: 421 units
Void dimensions: $^{W}18\text{m} \times {}^{D}20\text{m}, \times {}^{H}110\text{m}$
Ventilation openings: 2nd floor: 85 m^2, top floor: 157m^2
Measured periods: Autumn in 2006, spring, summer, autumn, and winter in 2007

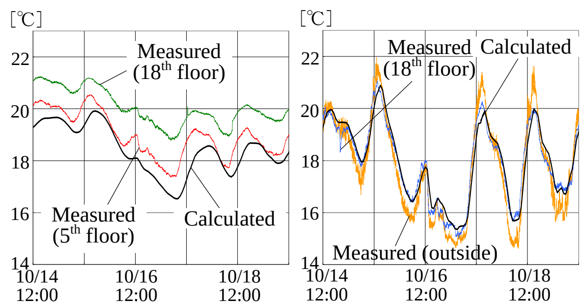


Calculation parameters:
- Discharge coefficient of ventilation openings: 0.7
- Difference of wind pressure coefficients (lower – upper openings): ΔC=0.3 (constantly upward force)
- Outer wall of dwellings: ALC 100[mm] with polyurethane foam insulation (25mm)
- Gas boiler usage:

Utilization factor※1 [%]	7 a.m. - 9 a.m.	8 p.m. - 12 a.m.	The rest hours
MAR - JUN	1.7	2.7	1.0
JULY - SEPT	0.8	1.0	0.4
OCT - NOV	1.2	2.1	0.4
DEC - FEB	2.1	3.1	1.5

(Fully generated contaminant quantity of CO_2 : 0.11 m^3/s)

※1: ratio of total gas consumption rate to total rated gas consumption rate



(a) Corridor surface temperature (b) Void air temperature

Figure 2 comparisons between measurement and calculation with one-node model (Oct., 2007) building and the condition of calculation are summarized in Table 1.

Figure 2 shows the results of comparison of the calculated values with the measured values on air temperature in the void and corridor surface temperature. The calculated values of air temperature in the void agreed with the measured values relatively well. However, calculated corridor surface temperature showed higher variations and its values are lower compared with the measured values especially when ambient temperature goes down rapidly as on October 17. The cause of this unconformity may lie in the assumption of the one-node model that air temperature in corridor space was equal to the air temperature in the void space inside. It is suggested that actual air temperature around the corridor may be different from that of the void space inside because of the influence of heat capacity of corridors and of outer walls of dwelling unit. When it is tried to evaluate the influence of the heat flow from building surface on ventilation rate between the void and the outside space, the reproducibility of building surface temperature is an important factor. In the one-node model based on uniform temperature distribution, the calculated heat and airflow rate may not be accurately reproduced.

TWO-NODE MODEL

General features of the model

Based on the results in the preceding section, a two-node model was developed by separating the corridor region from the void region (Figure 3). Supposing that the corridor and the building walls belong to the corridor region, heat balance was obtained by using the room temperature calculation module "Type 56" for the corridor region. If walls separating corridor from void zone exist, they should be modelled. But, it is assumed that lightweight fence is installed between the corridor and the void space, and its thermal effect is neglected. For the void region, a calculation module (named as "Type 110") was

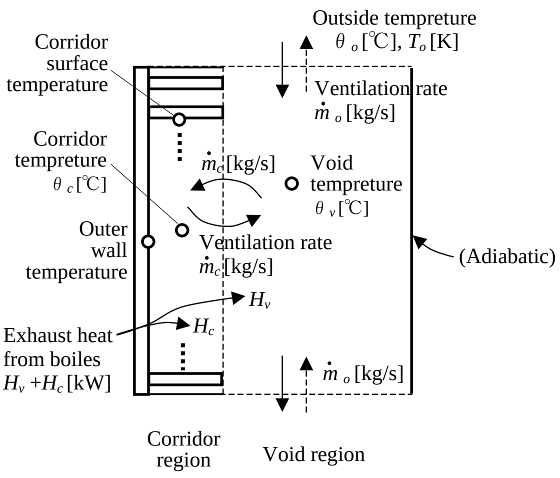


Figure 3 two-node model for void space (cross-sectional view)

newly prepared, which may give solution to heat balance and airflow balance. By coupling the two regions (corridor and void) together, total heat and airflow rate balance was obtained. The rate of air circulation (the number of air changes) between the void and the corridor were regarded as a pre-conditioned input. The calculation module "Type 56" of the corridor region calculates and outputs air temperature of the corridor region according to the ventilation rate between the void and the corridor and air temperature in the void region as outputted from the module "Type 110". On the other hand, in the calculation module "Type 110" of the void region, the corridor air temperature as outputted from the calculation model "Type 56" was made as input, and ventilation rate between the void and the outside space and the air temperature in the void were calculated and outputted. Because both modules depend on each other, convergence calculation was performed in the step of the same moment. Among the simultaneous equations in Type110, supposing that void air temperature θ_v and ventilation rate $\dot{m}_o$ were unknown, the one relating to heat balance was given in the equation (4). For the ventilation rate between the void and the outside space, the equation (1) was used without change.

$$H_v + C_p\dot{m}_o\left(\theta_o - \theta_v\right) + C_p\dot{m}_c\left(\theta_c - \theta_v\right) = 0 \qquad (4)$$

For the calculation of CO_2 concentration, the corridor region was not discriminated from the void region, and was assumed that the concentration distribution was even and uniform in order to calculate space average concentration. Ordinary differential equation of the equation (5) was applied for the calculation.

$$V\frac{dC}{dt} = M - (C - C_0)Q \qquad (5)$$

In the equation (5), time-averaged concentration in each time step was calculated by using numerical integration routine incorporated in TRNSYS.

Setting of parameters based on the comparison with calculation results of CFD

In case of the two-node model, the ventilation rate between the corridor and the void is regarded as an input, thus, a problem arises as to how the values is to be set. Also, by dividing to the two regions, an additional calculation parameter arises as to at what ratio the exhaust heat from the boilers was distributed to each of the regions. Further, the values of convective heat transfer coefficient on building surface and corridor surface may exert strong influence on heat balance and airflow rate balance in the void. For the purpose of adequately setting these calculation parameters, space average temperature was obtained from each of the two regions by using CFD, and it was tried to adjust that the calculation parameters of the two-node model would be consistent with the results.

Table 2 results of stationary CFD calculation

	Temperature [K]	Temperature [℃]	Normalized temperature [-]※1
Outside air	273.0	-0.1	1.00
Void air	271.9	-1.2	0.78
Corridor air	270.0	-3.1	0.40
Corridor surface	268.0	-5.1	0.00

※1 Outside air temperature:1, corridor surface temperature:0

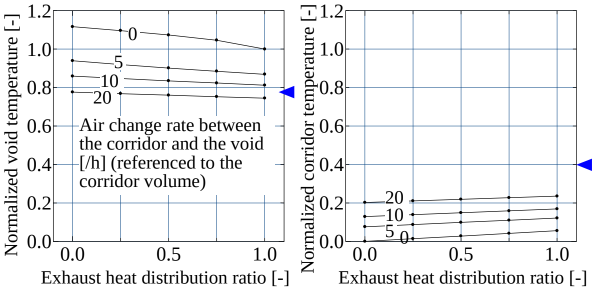


Figure 4 air temperature by two-node model (α_c = 15[W/m^2/K], arrows: CFD results)

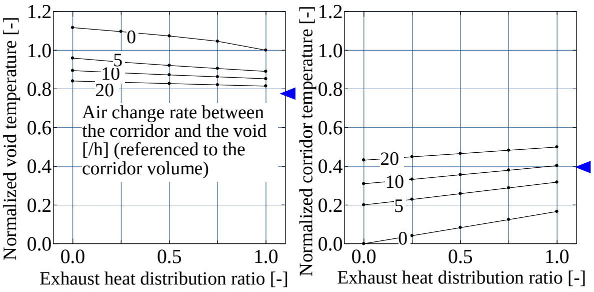


Figure 5 air temperature by two-node model (α_c = 5[W/m^2/K], arrows: CFD results)

In the CFD calculation, it was supposed that a large space including the void and the building under study (128m × 128m × 157m(height)) was regarded as calculation area. Further, for the area outside, it was supposed that the temperature was at a constant level: 273 K (-0.1 ℃). The convective heat transfer coefficient, α_c, on building surface and corridor surface was constant at 15W/m^{2}K and surface temperature was 268K (-5.1℃) and at constant level. The exhaust heat from the boilers was 80.6 kW in total, and it was assumed that the exhaust heat was generated in the upper portion of the corridor. From the result of steady flow computation of CFD, average temperature values of each of the regions were summarized, as shown in Table 2. Also, exchange airflow rate between the void and the corridor was 20.94 m^3/s in average (and 4.95 times/h with the value of corridor region volume as reference).

Comparison between the results of CFD (Table 2) and those of the two-node model were made (Figure 4). Compared with the calculation results of CFD, air temperature in the void region was calculated higher value (closer to outside air temperature), and air temperature of corridor region was calculated lower (closer to surface temperature). In particular, the air temperature in the corridor region was considerably different from the results of CFD. In both CFD and the two-node model, it was supposed that wall surface convective heat transfer coefficient α_c = 15 W/m^2/K, while the definition of "air temperature" to calculate the convective heat flow was different from each other in these two cases. In CFD, air temperature nearer to the surface was referred. In this respect, in the two-node model, it may be preferable to set up a smaller convective heat transfer coefficient. Thus, evaluation was made on a case where the value α_c in the two-node model was set to a smaller value, i.e. 5 W/m^{2}K (Figure 5). In the two-node model, it was evident that the results were well-coordinated with the results of CFD when the value of α_c was set to a smaller value, e.g. about 5 W/m^{2}K.

With regard to the number of air changes between the corridor and the void, when a value of 5 times/h, which is the results of calculation of CFD, was applied to the two-node mode, the discrepancies from CFD was observed. Also, as to boiler exhaust heat distribution ratio (i.e. ratio of heat release passively transferred with forced air movement to corridor region among the total exhaust heat from the boilers installed in the corridor; $H_c/(H_c+H_v)$ in Figure 3), no substantial influence was given to the calculated values of air temperature in the two regions.

Considering on these facts, calculation parameters in the two-node model were set as given below in order that the results would be well-coordinated with the results of calculation by CFD, and this value will be used hereinafter.

- Convective heat transfer coefficient: α_c = 5.0 W/m^{2}K
- Number of air changes between corridor and void: 15 times/h (reference volume: corridor region volume)
- Boiler exhaust heat distribution ratio: Corridor: Void = 0.5: 0.5

Comparison with the measured values

The results of calculation in the two-node model were compared with the results of actual measurement. For corridor surface temperature (Figure 6(a)), the calculated values were at the closest to the results of actual measurement on 5th floor. The difference was about 1 K at maximum. When compared with the results of the one-node model (Figure 2), daily variation was small, and variations closer to the measured values were reproduced. For the air temperature in the void region (Figure 6(b)), the accuracy of calculation was high.

The comparison of CO_2 concentration and the number of air changes is shown in Figure 6(c) and 6(d), respectively. To determine the measured values on the number of air changes, wind velocity

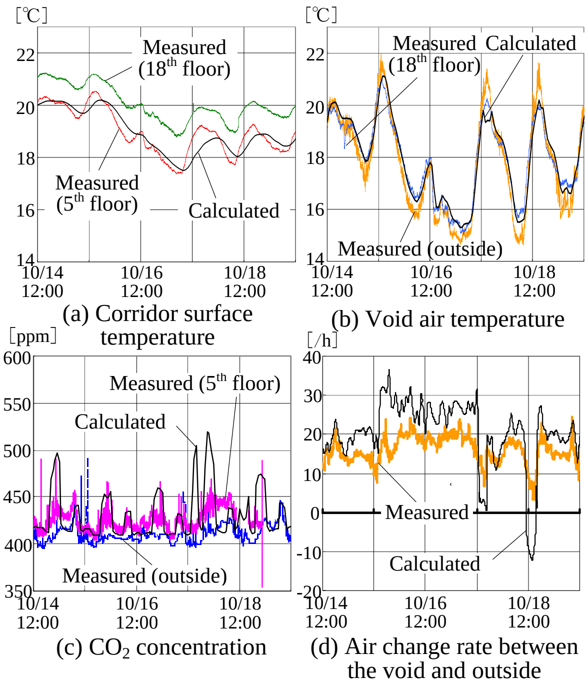


Figure 6 comparison between measurement and calculation by two-node model (Oct., 2007)

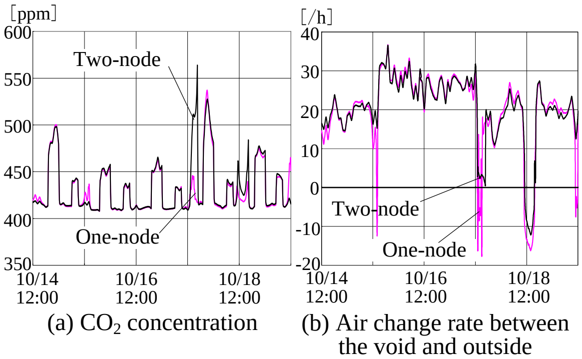


Figure 7 comparison between one-node model and two-node model (Oct., 2007)

measured with ultrasonic anemometer at the ventilation opening on lower portion of the void was multiplied by cross-sectional area of the ventilation opening. CO_2 concentration may be difficult to strictly evaluate the coordination with the measured values because accurate gas consumption quantity could not be determined, but it was certain that variation pattern relatively closer to the measured values was obtained. For air change rate, variation pattern of the calculated values was considerably closer to that of the measured values. However, in the calculated values, the number of air changes was turned to negative in daytime, and airflow was in the descending flow, while no remarkable reverse flow was observed in the actual measurement. When wind pressure coefficient difference ΔC was set to a higher value, upward wind ventilation driving force increased, and this may have resulted in lower frequency of the descending flow. However, in the evaluation by changing the setting value of ΔC, no considerable change was noted in the frequency of the occurrence of the descending flow.

Figure 7 shows comparison between one-node and two-node model in terms of calculated CO_2 concentration and ventilation rate. During the period illustrated, descending flow was suggested three times by one-node model, even though descending flow actually had not been observed as shown in Figure 6(d). In one-node model, when ambient temperature rises rapidly, heat absorption into the walls and corridor floors might be overestimated, void air temperature underestimated, thus lead to the descending flow due to the gravitational ventilation effect caused by the temperature difference between the void and the outside. Compared to one-node model, two-node model presents stable ventilation variation that is nearer to the observed one.

LONG-TERM SIMULATION STUDY

Using the two-node model as described in the preceding section, the void temperature and ventilation rate between the void and the outside space were calculated for 9 years, and the frequency distribution of void average CO_2 concentration was evaluated. Also, the season or the time zone when CO_2 concentration tended to be higher was determined.

Evaluation of calculation time interval

Before the long-term simulation, evaluation was made on the influence of the time interval of calculation on the calculated values of CO_2 concentration. As the meteorological data, one-minute data of wind velocity and air temperature, measured in Otemachi, Tokyo, was used. Here, the one-minute value of wind velocity is the averaged value in the preceding 10 minutes. As the calculation time interval, two cases were set up: every 10 minutes and every one hour. As the data to be used in case of the calculation time interval of 10 minutes, one-minute data for every 10 minutes were used for wind velocity, and time average of one-minute data for the preceding 10 minutes were used for air temperature. For time interval of one hour, time average of one-minute value data for the preceding 60 minutes were used for both wind velocity and air temperature.

The changes of CO_2 concentration are given in Figure 8. Compared with the case where the calculation time interval was 10 minutes, smooth concentration variation was shown in the time interval of one hour. However, maximum CO_2 concentration, found on May 11, is higher in the case of time interval of one hour. This may be attributed to the fact that, when calculation time interval was set to one hour, high CO_2 concentration may have been calculated according to the equation (5) as if the number of air changes continued for one hour in the time step where the number of air changes is accidentally calculated to a very low value. Actually, however, it is not considered that the conditions, where the number of air changes is extremely low, would continue for one hour because of ventilation fluctuation for shorter period. For this reason, 10 minutes will be adopted as the calculation time interval in the evaluation described hereinafter.

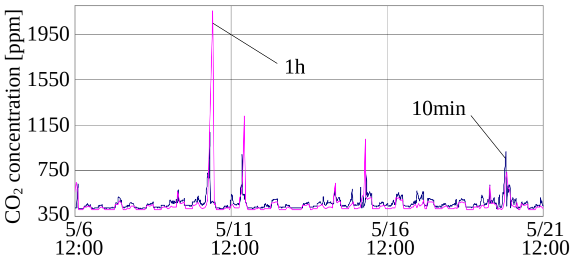


Figure 8 influence of calculation time interval on calculated CO_2 concentration

Frequency distribution of the number of air changes and CO_2 concentration and the maximal value

Figure 9 shows frequency distribution of the number of air changes between the void and the outside space for 9 years. It is evident from the figure that the upward air ventilation occurred in most part of time, but it was also found that air ventilation in downward direction had occurred in about 20% of the time zones. The frequency of the occurrence where the number of air changes had been turned to about 0 was very low. Frequency distribution of absolute values of the number of air changes and its accumulation are shown in Fig. 10. Median value was 19.17 times/h, and the proportion of time when ventilation rate was 5 times/h or less to all period is 3.88%.

Accumulation frequency of CO_2 concentration in void space is shown in Table 3. In most of the cases, CO_2 concentration was within the range of 600 ppm or less, and only 0.02% or less of all cases exceeded the level of 1000 ppm. Average CO_2 concentration in the past 9 years was 453 ppm, and the maximum CO_2 concentration was 1532 ppm.

The conditions when high CO_2 concentration occurred

From the results as described in the preceding paragraph, it was confirmed that CO_2 concentration in the void space was not turned to an extremely high value. However, evaluation will be made in detail now on the variations of concentration on the day when the value reached high concentration in the simulation study for the 9 years. Figure 11 shows the variations on December 23, 2000. For reference, monthly average temperature per hour in December 2000 are summarized in Figure 12 on the measured values of outdoor air temperature, calculated air temperature in the void, and calculated corridor surface temperature. In Figure 11, outside air

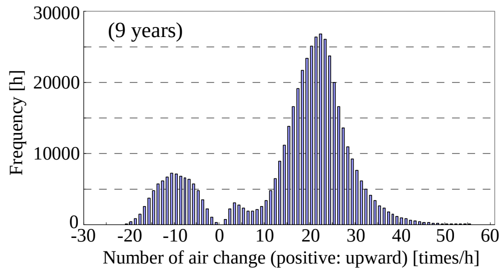


Figure 9 Frequency distribution of ventilation rate between the void and the outside space

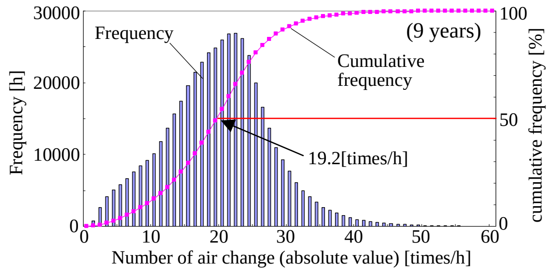


Figure 10 Frequency distribution of ventilation rate between the void and the outside (absolute value)

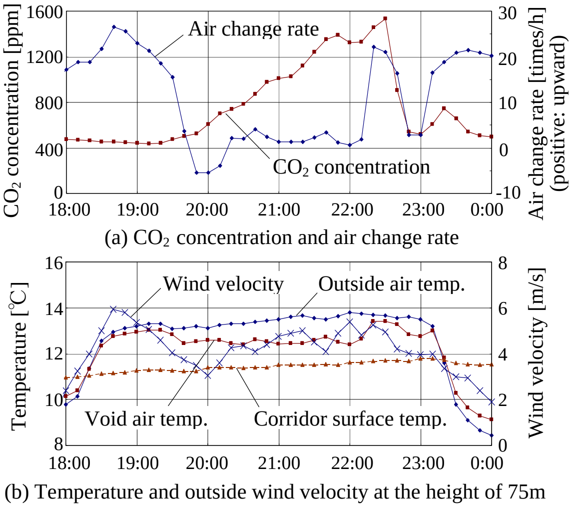
Table 3 Cumulative frequency of CO_2 concentration in the void

CO_2 concentration [ppm]		600	1,000	1,400
Cumulative frequency	[h]	467,670	473,245	473,334
	[%]	98.80%	99.98%	99.99%

temperature rapidly increased from about 18:00, while the change of the outside temperature subsided from 19:00 to 23:00. In this time zone, outdoor air temperature was higher than the air temperature in the void, and downward gravitational ventilation driving force may have occurred. On the other hand, wind velocity in this time zone was 3 m/s or more, and upward ventilation driving force was caused by wind force. As the result of competition between these two factors, ventilation rate of 5 times/h or less may have continued for nearly 2 hours and CO_2 concentration may have increased. Also, according to Figure 12, at nighttime during this season, air temperature in the void was higher in average than the outside temperature, and upward air ventilation should have occurred. From these facts, rapid increase of external temperature in the evening and subsequent stabilization of the external temperature and wind velocity may have resulted in high CO_2 concentration.

Months and seasons when CO_2 concentration may increase

Figure 13 and Figure 14 each represents the number of days when CO_2 concentration exceeded the level of 1000 ppm for every month and for every hour, respectively. From Figure 13, it is seen that there were more days when CO_2 concentration in the void exceeded the level of 1000 ppm in March – June, and



(a) CO_2 concentration and air change rate

(b) Temperature and outside wind velocity at the height of 75m

Figure 11 Time variations when CO_2 concentration increased (Dec. 23, 2000)

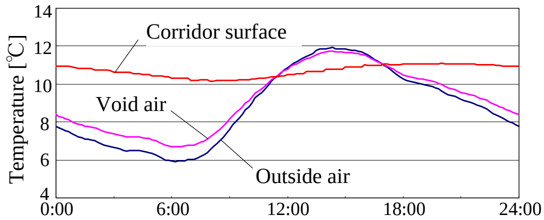


Figure 12 concurrently measured average value of temperatures (Dec., 2000)

there was no such day in July, August, September and November. This frequency was higher in spring season rather than winter season when gas consumption increased. This may be caused from the reason that the downward ventilation driving force caused by temperature difference and the upward air ventilation driving force caused by wind force may have been brought to an equilibrium because external air temperature was higher than void air temperature in spring season, and that ventilation rate was more likely to decrease. Because gas consumption quantity seems to be almost the same in October and November, there may be possibility that it exceeded the level of 1000 ppm even in November. As seen in Figure 14, the level of 1000 ppm was exceeded mostly in the peak consumption time zone at nighttime (21:00 – 24:00) when gas consumption increased. The next higher level was observed in the afternoon, and no such exceeding had occurred in the morning time zone.

CONCLUSION

For high-rise apartment houses with void space within the building, a simplified model was developed using thermal ventilation network for the purpose of evaluating the air environment in the void space for long period. First, study was performed on a one-node model, which was based on the assumption that temperature distribution in void and

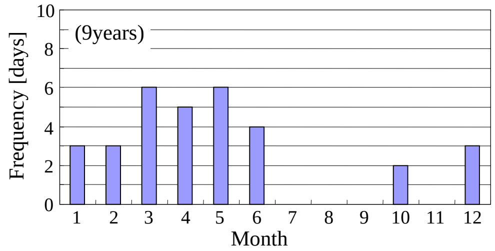


Figure 13 Number of days when CO_2 concentration exceeded 1000[ppm]

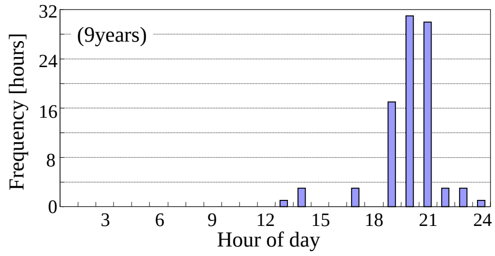


Figure 14 Number of hours when CO_2 concentration exceeded 1000[ppm]

corridor region was uniform. As the result of the study, the calculated values of the temperature in the void agreed relatively well with the measured values, while the calculated values on corridor surface temperature showed higher variations compared with the measured values, and unconformity was found.

Next, a two-node model was prepared, in which corridor region and void region were separated from each other. The calculated air temperature in the void region showed a prediction accuracy approximately equal to the case of the one-node model. On the corridor surface temperature, it was confirmed that the variations were closer to the measured values compared to the case of one-node model. Also, it was found that the calculated values of CO_2 concentration within the void were extensively influenced by the calculation time interval. In the present article, the study was performed by using 10-minute average data with minimum time interval as obtained from the meteorological observatory. Further study should be performed on the influence of the variations of wind velocity of shorter cycle.

Finally, by using the two-node model thus prepared, long-term simulation study was performed for 9 years on high-rise apartment houses in suburban area of Tokyo, Japan. The ventilation between the void and the outside space was mostly ascending ventilation throughout the year, while descending ventilation was observed in about 20% of the time during the period of the study. CO_2 concentration showed a tendency to increase under the conditions where outside air temperature was increased in comparison with the building temperature during peak consumption time zone at nighttime when gas consumption increases. Such conditions occur when gravitation ventilation driving force in downward direction occurs and when the upward ventilation driving force caused by wind force competes with the above driving force. CO_2 concentration in the void exceeded the level of 1000 ppm mostly in spring seasons, and it was not observed in summer season almost at all.

The results of the study as described above suggest that the temperature in each of the void region and the corridor region can be reproduced with comparatively high accuracy by the two-node model, in which the corridor region and the void region are separated from each other. One-node model possibly suggests descending flow in the void more often than real condition due to overestimation of heat absorption to the building walls or corridors. Compared to the one-node model, two-node model presents ventilation rate variation between the void and outside nearer to the observed one. However, the ventilation rate between corridor and void region is assumed fixed during simulation in this paper. Implementation of calculating variable ventilation rate that depends on temperature difference between the two regions is preferable. As for CO_2 concentration, it seems that further study on local concentration distribution should be performed, and it would be necessary to continue to study on a method to analyze by simultaneously applying CFD.

NOMENCLATURE

$\dot{m}_o$: ventiration rate between void and outside space [kg/s]

αA_{all}: effective opening area [m^2]

ρ_o : density of outside air [kg/m^3]

Δp_g : pressure difference due to gravitational ventiration effect [Pa]

Δp_w : pressure difference due to wind ventiration effect [Pa]

$\mathrm{sgn}(\bullet)$: =1 if ・ is positve, =－1 if ・ is negative

g : gravitational acceleration [m/s^2]

L : height of void [m]

θ_v : temperature of void region [℃]

θ_o : temperature of outside space [℃]

T_o : temperature of outside space [K]

ΔC : difference of wind pressure coefficients between lower and upper openings, reffered to the wind velocity of the eave height of the building (positive when uppward ventilation occurs) [-]

U : wind velocity at the eave hight of building [m/s]

H_v : exhausted heat from boilers to void region [kW]

H_c : exhausted heat from boilers to corridor region [kW]

θ_c : temperature of corridor region [℃]

C_p : specific heat of air [kJ/kgK]

$\dot{m}_c$: ventiration rate between void and corridor space [kg/s]

V : Void volume including corridor space [m^3]

C : CO_2 concentration in void [m^3/m^3]

C_o : CO_2 concentration of outside space [m^3/m^3]

Q : ventiration rate between void and outside space [m^3/s]

M : CO_2 rejection rate from boilers [m^3/s]

t : time [s]

REFERENCES

Ohira, N., Omori, T. 1996. Ventilation Behavior in a Void Space furnished with Gas Water-heaters, Proceedings of ROOMVENT ‘96, vol.3, pp.255-262, Yokohama, Japan.

Chow, T.T., Lin, Z., Liu, J.P. 2002. Effect of condensing unit layout at building re-entrant on split-type air-conditioner performance, Energy and Buildings, vol.34, pp.237-244.

Kotani, H., Satoh, R., Yamanaka, T. 2003. Natural ventilation of light well in high-rise apartment building, Energy and Buildings, vol.35, pp.427-434.