NATURAL VENTILATION CAUSED BY STACK EFFECT IN LARGE COURTYARD OF HIGH-RISE BUILDING

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ABSTRACT

In the large courtyard of high-rise residential buildings, the exhaust from the kitchen, and the gas water heater, is sometimes discharged into the public corridors, which can pollute the air. The exhaust heat causes the stack effect, so the outdoor air flows through the openings at the bottom of the courtyard to the top.

The purpose of this study is to describe these ventilation characteristics and to predict the airflow rate for removing the pollutants.

Firstly, model experiments were conducted to know the temperature distribution and airflow rates. The result showed that the characteristics are influenced by the size of the bottom opening area and the position of heat sources.

Secondly, the comparison between mathematical calculation and experimental data were nearly in agreement, except for some inconsistencies at the top of the courtyard. This was due to the air down flow, when the bottom opening area was not large enough.

KEYWORDS

Large Courtyard, Stack Effect, Temperature Distribution, Airflow Rate

INTRODUCTION

Lately in Japan, a large courtyard is often designed in a high-rise residential building. This courtyard has a empty space without ceilings or floors from bottom to top, and the space is very narrow like a well. The example of this large courtyard is shown in Figure 1 (looking down on courtyard from the top). The reasons for this design are as follows (Takai 1993) .

1. Japan has a climate of such high temperature and humidity that the residence needs many openings for natural ventilation. Therefore the residential buildings tend to have interior courtyards that are open to outdoor air.
2. As Japan is a country with frequent earthquakes, the structural design is considered very important. The plan with a courtyard in center of the building has the advantage that it has larger base areas. Therefore the residential buildings tend to have courtyards inside.

For this courtyard is regarded as the outdoor space, there is the possibility that the exhaust gas from residences is discharged into a courtyard via a public corridor around the empty courtyard space. The main exhaust gas is discharged from a kitchen or a gas water heater which is set on a public corridor in front of each residence. This exhaust gas is hot, and the air inside the courtyard is heated. On the other hand, the courtyard generally has openings in the bottom of it, and there is a large opening in the top of it. Therefore the stack effect is caused due to indoor-outdoor temperature differences, and the air flows from bottom to top.

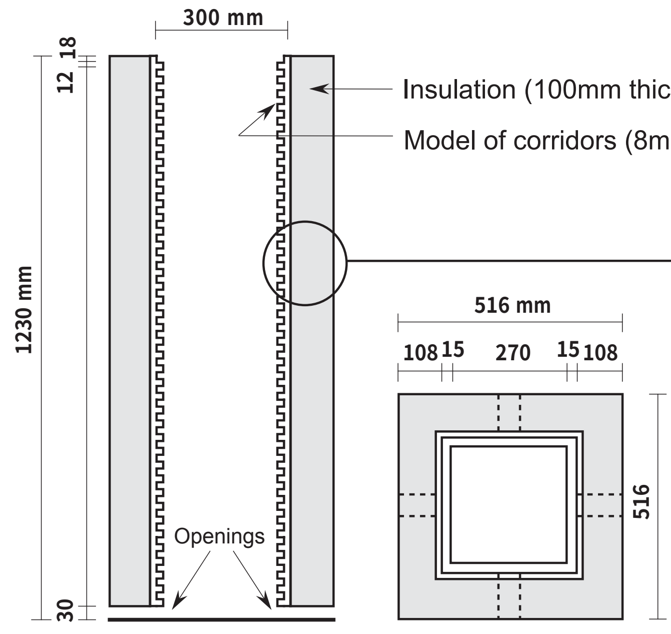
Today, many studies on ventilation in large spaces have been conducted such as works of IEA Annex 26. But there are few studies on ventilation of the above-mentioned large courtyard.

Therefore firstly in this paper, a model experiment is conducted to describe these ventilation characteristics. In this experiment, the effect of the size of the bottom opening areas and the heating positions on the air temperature and the airflow rate are investigated. Secondly, the air temperature and the airflow rate is calculated by the simplified ventilation model. Experimental data and predicted data are compared to evaluate the prediction accuracy of the mathematical model.

Figure 1 Example of large courtyard (looking down on courtyard from the top).

EXPERIMENTAL DESIGN

Figure 2 shows the experimental apparatus as a 1/100 scale model of a 41-



(a) Section (b) Plan

Figure 2 Experimental appatatus.

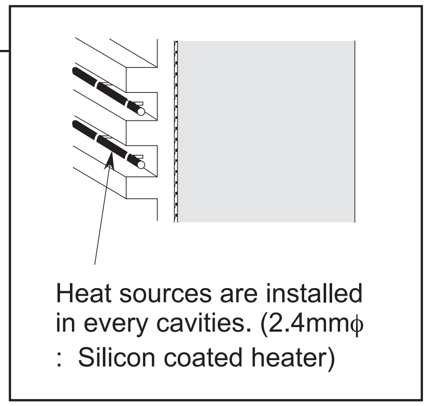


Figure 3 Installtion of heat source.

Table 1 Experimental conditions

Heating			Opening		
Rate [W]	Position		Area [cm^2] (Ratio to top opening area)	Position	
	Horizontal	Vertical		Horizontal	Vertical
125.2	All sides	All	0 (0 %)	All sides	Bottom (the grand floor of 41 stories)
		Lower (25% of all parts)	36 (4 %)		
			120 (13%)		
		Upper (25% of all parts)	324 (36%)		

storied apartment building in existence. In this model, the heat sources were installed in the cavities of the inside wall as models of the public corridors (see Figure 3). The heat sources were simulated the exhaust heat from a gas water heater, and the heat was generated with following assumptions in the actual building :

(1) the heat generation rate from each gas water heater is 9,280 W,
(2) the total number of gas water heaters is 480,
(3) the simultaneous usage percentage of heaters is 25%.

The heat was assumed to be removed only by convection through the openings, therefore the model was well insulated. In this condition, the Archimedes number of the model, defined as the ratio of the buoyancy force to the inertial force, coincided with that of the actual building and the similarity condition was satisfied (Kato et al. 1988). Thus, the scale factor of physical parameter was chosen freely.

In this model, its heating positions and the size of bottom opening areas are variable for investigating their effects on the ventilation characteristics. The experimental conditions are shown in Table 1. Especially, the schematic of heating positions are shown in Figure 4.

The air temperature was measured by C-C thermocouples. Data was taken from 18 separate vertical points and 49 separate horizontal points, as a result, the total number of measuring points in one experiment is 882. To investigate the airflow rates, the wind velocity through the bottom openings was measured by an omnidirectional temperature-compensated anemometer, then the velocity was multiplied by the opening area.

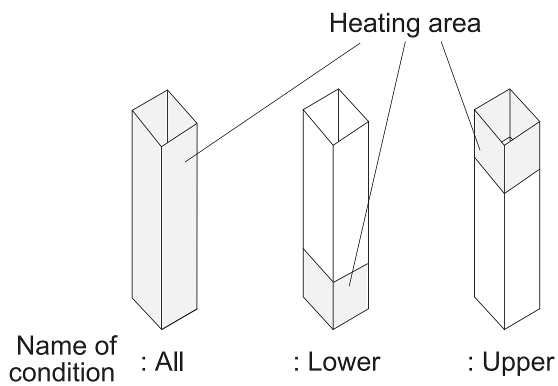


Figure 4 Schematic of heating positions.

EXPERIMENTAL RESULTS

Isotherm of Air Temperature

Figure 5 shows the isotherms of measured air temperature in all conditions. The values of temperature are not described as ones of the actual building scale but of the model scale. Generally the stack effect makes such a temperature distribution as the highest temperature at the top. But it is sometimes seen that the temperature near the top opening is lower than the other spaces, such as the case when the bottom opening area is small (bottom opening area is 0 and 36 cm^2) in the condition of "All" heating position. It is due to the air down flow from the top opening that is observed by a preparatory experiment using a flow visualization technique. When the bottom opening area becomes large (bottom opening area is 324 cm^2), this down flow is not observed and the temperature distribution of the whole space becomes uniform. This down flow is observed in other conditions of the heating position ("Lower" and "Upper"), when its bottom opening area is not large enough. The example of this down flow is shown in Figure 6.

In the condition of "Lower" heating position, the temperature of the lower part is the greatest, and there is the lower part of the temperature near the

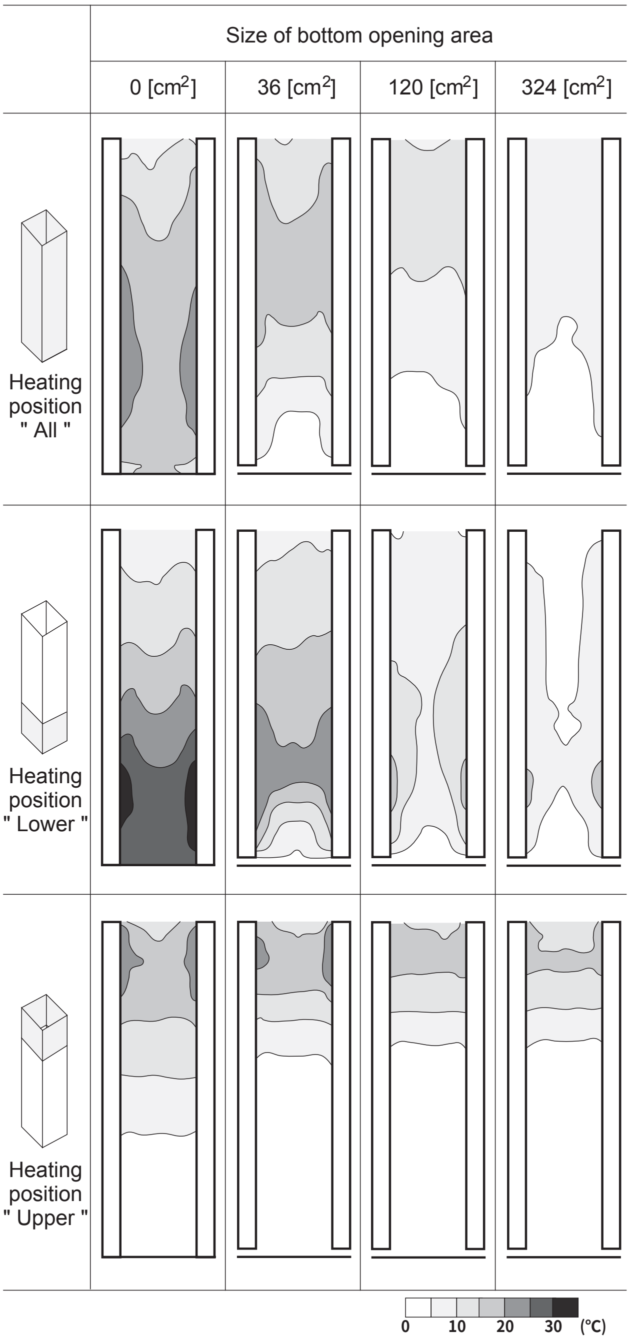


Figure 5 Isotherms of measured air temperature in vertical sections. The sections are located in the center of horizontal planes. The values of temperature are described by differences between inside and ambient air temperature.

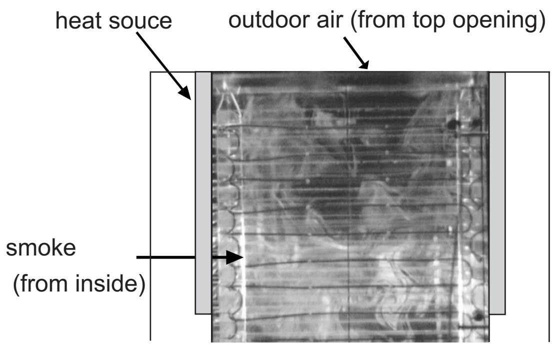
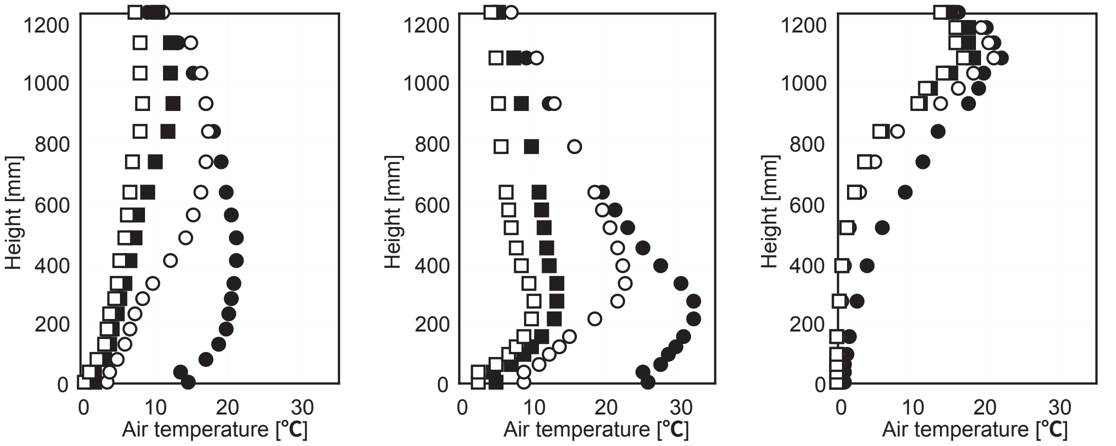


Figure 6 Example of the air down flow (Heating position: "Upper", Bottom opening area: "0"). Showing part is upper 25% of whole space. White part is smoke generated from inside. Black part means outdoor air.



(a) Heating position: "All" (b) Heating position: "Lower" (c) Heating position: "Upper"

Figure 7 Vertical temperature distribution. The values are the average of 49 points in each horizontal plane.

Bottom opening area ● — 0 [cm²]
○ — 36 [cm²]
■ — 120 [cm²]
□ — 324 [cm²]

center of the courtyard. It is assumed that the air from the bottom openings flows in the center of space.

The temperature distributions in the condition of "Upper" heating position are different from ones of the above-mentioned two cases. The part of high temperature is seen near the top opening, and the shape of the distribution seems to be in a layer. The effect of the bottom opening area on the temperature distribution and the value of the temperature is smaller than those of the other two cases.

In most conditions, the vertical temperature differences are larger than the horizontal ones. Therefore in the following paragraphs, the temperature distribution is described as a vertical distribution of the mean value over the data of 49 measuring points in each horizontal plane.

Vertical Temperature Distribution

The vertical temperature distributions in each condition of heating position are shown in Figure 7. The values are the average of the 49 points in each horizontal plane. When

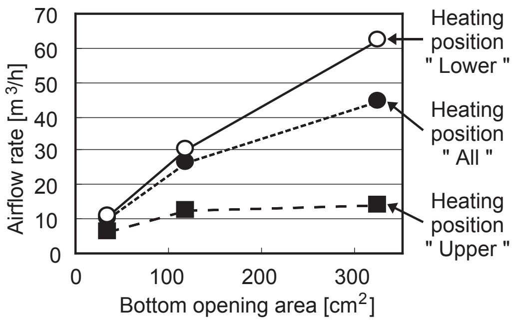


Figure 8 Measured airflow rate through the bottom opening.

the heating positions are "All" and "Lower", the enlargement of the bottom opening area definitely causes the decline of the temperature at all heights. In the condition of "Upper" heating position, the effect of the bottom opening area is small. On the other hand, the effect of the heating position is large from a point of view which the shape of a profile itself is different in each condition. The declines of the temperature near the top opening in some conditions are also recognized in these vertical profiles. These seem to be influenced by the above-mentioned air down flow.

Airflow Rate

The measured airflow rates through the bottom openings are shown in Figure 8. The airflow rate is impossible to measure in the condition that the bottom opening area is 0 cm^2. Except for the condition of "Upper" heating position, the enlargement of the bottom opening area causes the increase of the airflow rate. Obviously, this relation seems to be proportional. However, in the condition of "Upper" heating position, there is only a little change of the airflow rate. When the bottom opening area is large, the difference by the condition of heating positions is very large. In all condition of the bottom opening area, the airflow rate in the condition of "Lower" heating position is largest. This can be explained that the "Lower" heating makes the strongest buoyancy force, because the overall temperature differences of space become large when the air flows from bottom to top.

VENTILATION MODEL

The basic ventilation model is used to predict the air temperature and the airflow rate of the courtyard. It is useful to calculate the temperature and the airflow rate of the large space that the space is divided into the multiple stratified zones.

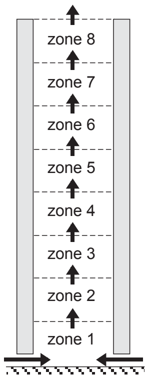


Figure 9 Ventilation model.

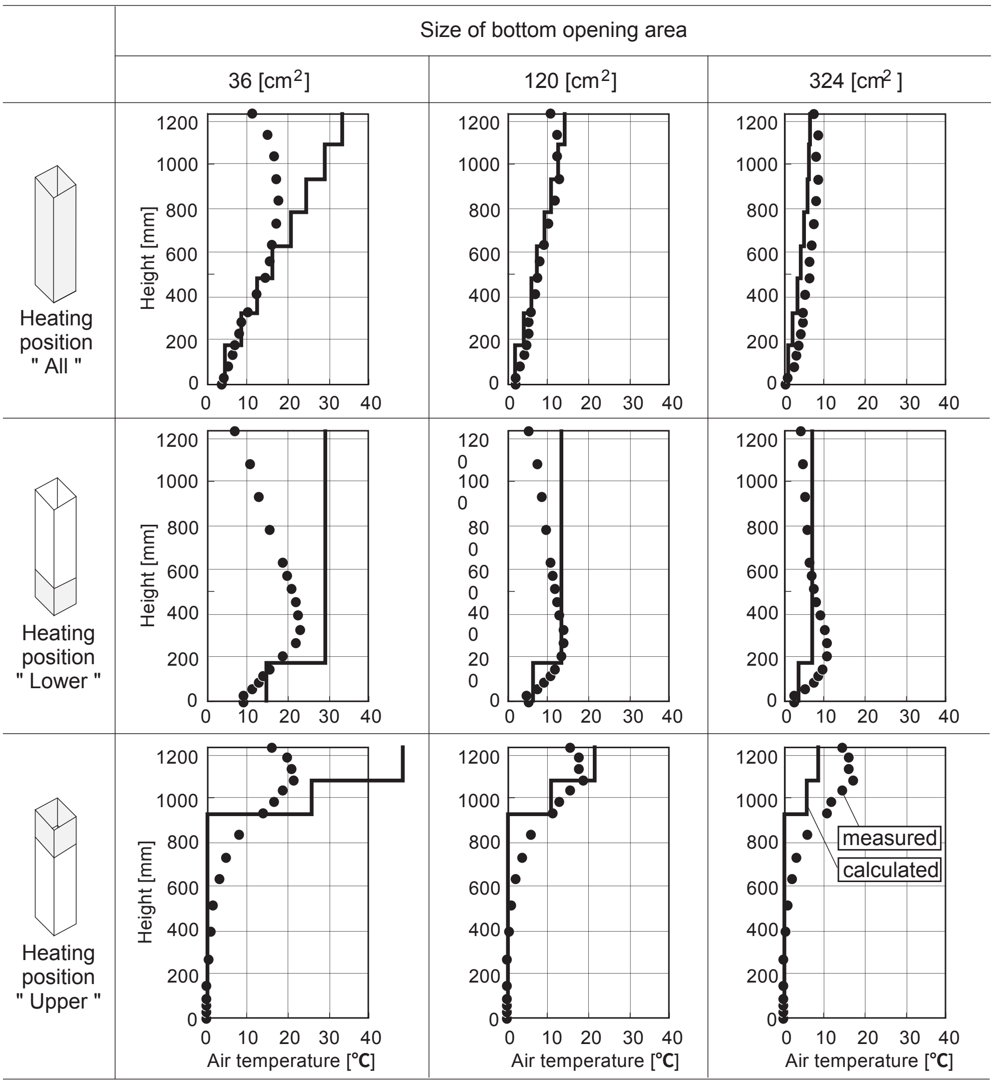


Figure 10 Comparison between measured air temperature and calculationed one.

There is an excellent work for the air-conditioned large space (Togari et al. 1991). But there are few studies for natural ventilated space. On the other hand, in future of this study, the calculation in the condition of natural ventilation must be made in consideration of such fluctuating outside conditions as outdoor wind velocities and outdoor air temperatures. Therefore, the ventilation model in this paper is very simplified one.

The space is divided into 8 stratified zones with the same volume. It is assumed that the outdoor air flows only from the bottom openings to the top opening, and there is no down flow between each zone (see Figure 9). In each zone, the perfect mixing and the uniform temperature are assumed, and the equations based on the mass balance and the heat balance are described. At the bottom and top opening, the airflow rate is expressed by a simplified equation based on Bernoulli's equation. The equation is expressed by the pressure differences caused by the indoor-outdoor temperature differences (ASHRAE 1993). They are solved as simultaneous equations of many unknowns. Because of the characteristics of this model, it is impossible to calculate in the condition that the bottom opening area is 0 cm^2.

The values of the discharge coefficient is 0.64 for the bottom opening and 0.84 for the top opening.

COMPARISON WITH EXPERIMENTAL DATA

Vertical Temperature Distribution

Figure 10 shows the comparison between measured air temperature and calculated one by the ventilation model. The plot of ● is the measured one, the line means the calculated one. The result of calculations can be anticipated as follows: (1) the increase of the bottom opening area causes the declines of temperature values of the whole space, (2) the effect of the heating position on the distribution itself is large.

In the condition of "All" heating position, the calculation is nearly in agreement with the measured data, except for inconsistencies at the higher part of the courtyard due to the declines of temperature in the condition that the bottom opening area is 36 cm^2 . This is due to the above-mentioned air down flow from the top opening.

In the condition of "Lower" heating position, the temperature distribution itself is different. When the bottom opening area is large, the rough values of temperature are in agreement, but the shape of the temperature distribution can't be expressed.

In the condition of "Upper" heating position, the effect of the bottom opening area on the calculated data is very large. Therefore, when it is compared with the

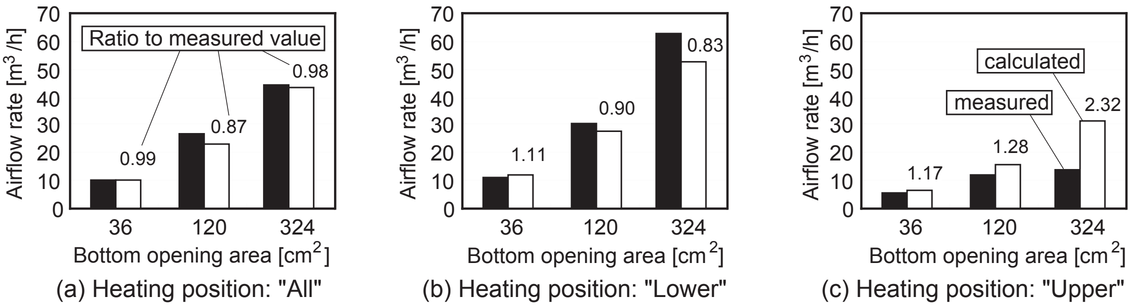


Figure 11 Comparison between measured airflow rate and calculationed one.

measured data on which the effect of the bottom opening area is small, the difference between the measured data and the calculated one is very large.

Airflow Rate

The comparison between the measured airflow rate and the calculated one is shown in Figure 11 (■ is measured value and □ is calculated one). The values upper the white bar of the calculated one show the ratio of calculated values to the measured ones. In the condition of "All" heating position, the calculated values are in good agreement with the measured ones. The calculation has enough accuracy, because it is considered that the error of about 10% is very small.

In the temperature distribution, there are some differences in some conditions. But in the airflow rate, the differences are less than those in the temperature, because it is calculated by total effect of the temperature differences of the whole space. However the inconsistency is seen in the condition of "Upper" heating position. The error of the calculation in this condition is very large as over 100%.

In the conditions of "Lower" and "Upper" heating position, the accuracy of the calculation decreases when the bottom opening area is large.

CONCLUSION

The air temperature distribution in the courtyard of the high-rise residential building becomes in a layer in general. The enlargement of the bottom opening area causes the decline of the temperature at all heights and the increase of the airflow rate through the bottom openings. The effect of the heating position is strong on the shape of the temperature distribution.

In the condition of "Upper" heating position, it is shown the different characteristics from the other two conditions both in the air temperature and in the airflow rate.

The ventilation model that have been used in this paper is very simple. Although it should be improved for the wide using, it is useful to predict the air temperature and the airflow rate in some conditions. In the condition of "All" heating position which must be considered as the condition of the actual buildings, the error of the calculation is practically permissible both in the temperature and in the airflow rate.

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