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A STUDY ON AN ESTIMATION METHOD OF THE EFFECTIVE OPENING AREA OF ENTRANCE DOORS AND WINTER AIRFLOW RATE INTO ATRIUM BUILDINGS

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ABSTRACT

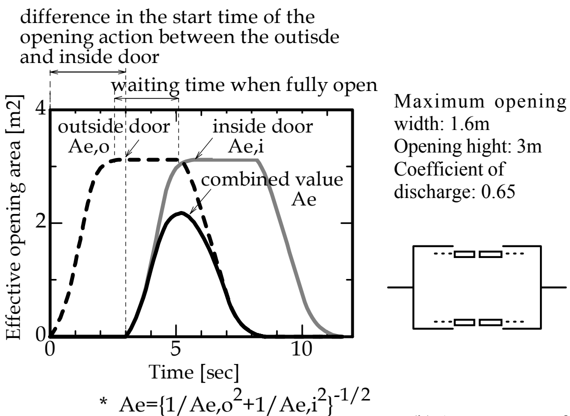
This study develops a simplified estimation method for calculating the effective opening area of automatically operated entrance doors and the winter airflow rate into entrance halls due to the stack effect. The relationships between the number of people passing through the doors and the average opening area ratio were obtained from detailed simulations of a variety of different types of doors, and were approximated by equations. The relationships between the effective entrance door opening areas and the outdoor airflow rates were determined by solving air balance equations for each of the six types of buildings. These relationships were also approximated by equations. The proposed estimation method, utilizing these two kinds of approximation equations, was used to examine the changes in the winter outdoor airflow rate through the entrance doors on a weekday for six different buildings. This method helps designers plan entrances and determine the proper heating equipment capacity.

INTRODUCTION

Automatically operated sliding doors with a vestibule are common entrances in Japan. In the winter, frequent use of this type of entrance door allows for a large amount of outdoor airflow to enter high-rise buildings. This may cause serious problems, especially in buildings with tall atriums, because the atrium is often an easy route for the airflow due to the stack effect. A simplified estimation method for the winter airflow rate through entrance doors caused by the stack effect would help designers plan entrances and determine the proper heating equipment capacity. Previously, a simplified estimation method for the calculation of the effective entrance door opening area and the winter outdoor airflow rate due to the stack effect had been proposed (Kohri, 2001). In this study, the method has been expanded and improved to include various door specifications for several types of atriums.

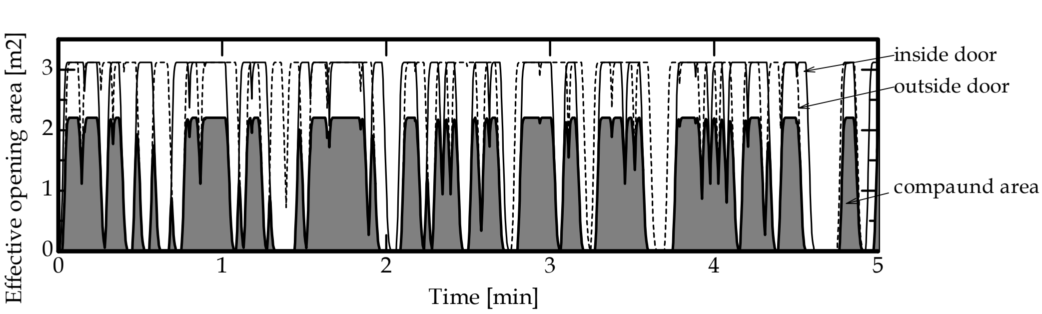
ESTIMATION OF THE DOOR OPENING AREA

This method was developed to estimate the effective opening area of automatically operated sliding double doors with a vestibule under a given amount of entrance traffic. **Figure 1** shows the opening and closing



(a) Opening and closing action of the doors (b) Arrangement of the doors

Figure 1 Standard entrance doors



* Number of people passing through the doors: 100 people every 5 minutes

Figure 2 Changes in effective opening area of the standard doors at time intervals of 0.2 sec due to occurrence of persons passing through them

actions of a typical entrance door when a person enters a building. These doors are used as the standard doors for the simulations in this study. **Figure 2** presents the results of a detailed simulation in which 100 people pass through the doors every 5 minutes. The effective opening area was calculated every 0.2 seconds and the pattern of people passing through the entrance doors was assumed to be a Poisson distribution. The average effective opening area for a given entrance frequency depends on an averaging period unless the averaging period is enough long. The previous study found that 150 minutes of averaging is necessary for obtaining the average effective opening area that is independent of averaging periods. The effective opening area averaged over 150 minutes for the entrance traffic using the standard doors was obtained from the detailed simulation. The results are shown in **Figure 3**. The average opening area ratio is defined as the ratio of the average effective opening area to the maximum effective opening area. The curve shown in **Figure 3** can be approximated as an exponential polynomial expression and the effective opening area of the doors A_e (in square meters) can be estimated using the following equations.

$$A_e = rA_{e,max} \qquad (1)$$

$$r = 1 + A_1 exp(-a_1 X) + A_2 exp(-a_2 X) \qquad (2)$$

where r is the average opening area ratio of the doors, $A_{e,max}$ is maximum effective opening area in square meters, X is the number of people passing through the doors every 5 minutes, and A_1, A_2, a_1, and a_2, are the coefficients of r.

The average opening area ratio is affected by variety of factors, such as the maximum opening width of the door, the waiting time when the door is fully open, and the time from when the first door starts to open until the second door starts to open. Approximation equations for each of these factors were generated. The

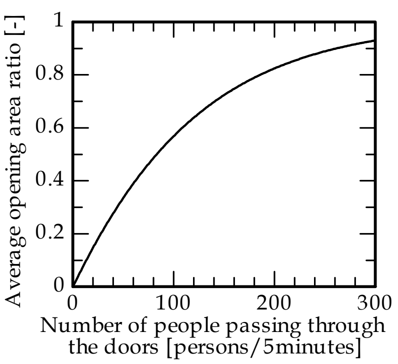


Figure 3 Relationship between average opening area ratio and number of people passing through the standard doors

coefficients for the approximation equations are summarized in **Table 1**. Using the coefficients in **Table 1**, the effective opening area can be easily estimated for 36 different types of doors. The effects of the three door factors on the effective opening area are shown in **Figure 4**. Although the waiting time when the doors are fully open and maximum opening width significantly affect the effective opening area, the difference between the outside and inside door opening start times has only a slight effect.

ANALYSIS OF AIR MOVEMENT IN SIX OFFICE BUILDINGS

Besides entrance door conditions, other factors such as the building height, the indoor/outdoor temperature difference, the presence of elevator shafts, stairwells, and spaces with open ceilings, and the air tightness of the building also affect the outdoor airflow rate due to stack effect. This study focuses on the effect of

Table 1 Coefficients in approximation equations of effective opening area for different types of doors

Tw: waiting time when fully open [sec]
ΔT: difference in the start time of the opening action between the outside and inside door
$A1$ 、$A2$ 、$a1$ 、$a2$: Coefficients for calculation of Ae
Approximation equations of the average opening area Ae [m2]
$Ae = r \cdot Aemax$
$r = 1 + A1 \cdot exp(-a1 \cdot x) + A2 \cdot exp(-a2 \cdot x)$
r : Average opening area ratio of the doors [-]
$Aemax$: Maximum effective area of the opening [m2]
x : The number of people passing through the doors [person/5minutes]

Tw	ΔT	Wmax	Coefficients			
			A1	A2	α 1	α 2
1.5	1.5	1.2	-1.08	0.08	0.006	0.007
		1.6	-0.95	-0.05	0.006	0.015
		2.0	-0.89	-0.11	0.007	0.033
	3.0	1.2	-1.13	0.13	0.006	0.022
		1.6	-1.09	0.09	0.007	0.016
		2.0	-1.08	0.08	0.007	0.011
	6.0	1.2	-1.14	0.14	0.006	0.035
		1.6	-1.11	0.11	0.007	0.057
		2.0	-1.11	0.11	0.007	0.051
2.5*	1.5	1.2	-1.22	0.22	0.009	0.008
		1.6	-1.11	0.11	0.010	0.009
		2.0	-1.08	0.08	0.010	0.008
	3.0*	1.2	-1.20	0.20	0.009	0.019
		1.6*	-1.15	0.15	0.009	0.019
		2.0	-1.17	0.17	0.010	0.016
	6.0	1.2	-1.19	0.19	0.009	0.058
		1.6	-1.17	0.17	0.009	0.057
		2.0	-1.23	0.23	0.010	0.037
3.5	1.5	1.2	-1.06	0.06	0.012	0.007
		1.6	-1.08	0.08	0.013	0.010
		2.0	-1.10	0.10	0.013	0.015
	3.0	1.2	-1.22	0.22	0.012	0.023
		1.6	-1.23	0.23	0.013	0.021
		2.0	-1.14	0.14	0.013	0.022
	6.0	1.2	-1.23	0.23	0.011	0.057
		1.6	-1.21	0.21	0.012	0.061
		2.0	-1.20	0.20	0.013	0.059
5.0	1.5	1.2	-1.08	0.08	0.017	0.015
		1.6	-0.96	-0.04	0.017	0.037
		2.0	-0.93	-0.07	0.017	0.050
	3.0	1.2	-1.22	0.22	0.017	0.030
		1.6	-1.11	0.11	0.017	0.030
		2.0	-1.08	0.08	0.017	0.033
	6.0	1.2	-1.26	0.26	0.016	0.072
		1.6	-1.56	0.56	0.018	0.036
		2.0	-1.31	0.31	0.018	0.047

* standard condition

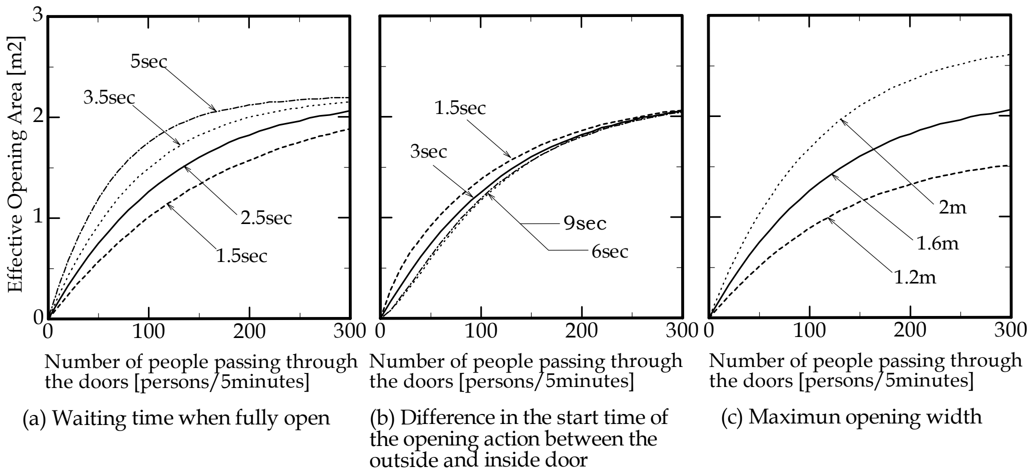


Figure 4 Relationship between effective opening area and number of people passing through the doors for various doors

the atrium. In most buildings with atriums, the outdoor airflow rate entering the building is substantially larger than in buildings with no atrium. Atria are often used as entrance halls, thereby providing an easy route for upward airflow due to the winter stack effect.

Airflow balance for a whole building was solved in order to clear the characteristics of winter air movement through each of several atrium buildings. Air pressures at floor level in rooms on each floor and in elevator shafts and stairwells were treated as unknown values. Airflow balance equations for all the spaces in a building were solved simultaneously. In calculation of air leakage rate through exterior walls and interior walls between rooms and an atrium, a flow exponent of 2/3 was assumed and the value of flow coefficient was assumed according to the air tightness of walls. These flow coefficients were presented for Japanese buildings by M. Hayakawa and T. Togari (1989). Crack sizes of doors like room doors, elevator doors and stairwell doors were assumed to be the value obtained from the measurements in an existing office building (Kohri, 2001).

In this study, six different types of 30-story office buildings were used in the simulations, five of them with atriums and one without. All six building types have two entrances on the first floor. A detailed description of each of the building types is provided below.

1) Type S1
Building type S1 has an atrium that is partially open to the adjacent rooms. The atrium is used as an entrance hall and its ceiling is open up to the 30th story. Every floor has a corridor that surrounds the atrium. Both the corridor and the hall to the elevator on each floor are open to the atrium, with a balustrade on the atrium side. Internal walls separate the offices from the corridor.

Table 2 Building schematics and the airflow balance conditions for 6 types of buildings

(Building)
Number of story above ground: 30
Building use: office
Total occupants: about 2,000 persons
(Office floor)
Floor area: 1,600m2/floor
Space volume: 4800m3/floor
Area of building envelope: 720m2/floor
(Atrium)
Ceiling height: 120m for building type S1, O1 and C
60m for building type S2 and O2
Space volume: 52,800m3 for building type S1, O1
28,800m3 for building type S2 and O2
35,400m3 for type C
(Air temperature and outside wind)
Air temperature: outdoor 0 ^{o}C atrium 20^{o}C
office room 22^{o}C
elevator shafts and stairwells 18^{o}C
Outside wind: absent
(HVAC system)
The effects of HVAC systems are ignored.

2) Type S2
Building type S2's atrium is similar to that of building type S1. The difference between the two is that the ceiling of the atrium in building type S2 is only open up to the 15th story.
3) Type O1
Buildings type O1 has an open atrium, meaning that there is no partition between the offices on each floor and the atrium. The atrium is used as an entrance hall and its ceiling is open up to the 30th story.
4) Type O2
Building type O2 has two open atria. The atrium that begins on the first floor and is open up to the 15th story is used as an entrance hall. The other atrium begins on the 16th floor and is open up to the 30th story

5) Type C
Building type C has a closed atrium, meaning that there are partitions between the atrium and the offices on every floor. The atrium is used as an entrance hall and its ceiling is open up to the 30th story.
6) Type N
Building type N has neither an atrium nor any room with an open ceiling.

Table 2 details the building schematics and the airflow balance conditions that will be used in the simulations. The intended use of the proposed estimation method is for determining the heating equipment's load requirements. In this paper, the building is assumed to be located in Tokyo and, therefore, the indoor and outdoor temperatures are typical heating design values used in the Tokyo area. For the purposes of this simulation, the outside wind is assumed to be absent and the effects of heating, ventilation and air-conditioning (HVAC) systems are ignored. Data for the air leakage through the doors and walls are given in **Table 3**. Before the relationship between the door effective opening area and the outdoor airflow rate was obtained, the air movement characteristics in the building due to the stack effect were analyzed using simulations. In this analysis, the total effective opening area of the two entrance doors is assumed to be 2 square meters. This opening area is the value based upon 140 people passing through two standard doors.

Figure 5 shows the floor plan and the airflow circuit network of building type S1. 38 unknown pressure locations are identified, including three in the elevator shafts and two in the stairwells. Airflow balance equations were used to determine the pressure values for these 38 spaces. **Figure 6** presents the airflow balance in both the atrium and the offices on each floor. In this study, the airflow rate in and out of a space is expressed as an air exchange rate in terms of air changes per hour (ACH). This value that defines the airflow rate relative to the volume of the offices on a typical floor. In building type S1, the main route of the upward airflow is through the atrium. The outdoor air enters the atrium through the entrance doors, and then the atrium air moves to the rooms above the 9th floor. The elevator shaft and stairwell air temperatures are assumed to be slightly lower than that of the atrium. The atrium air moves into the shafts through doors on the higher floors. The shaft air moves into the atrium through doors on the lower floors.

Figure 7 shows the results of the simulation for building type N. The airflow moves out of the lower elevator shafts and into the higher elevator shafts on the 15th floor. The results of the simulations for building types O1, O2, C, and S2 are shown in **Figures 8-1**, **8-2**, **8-3** and **8-4**, respectively. The air movement characteristics of building type O1 are similar to those for building type S1, with the main upward airflow route through the atrium. In building type O2, the air flows out of the lower atrium and flows into the higher atrium via the elevator and stairwell shafts. In building type C, the upward airflow through the atrium and the upward airflow through the shafts run parallel to each other. In building type S2, the air flows from atrium into the shafts and into the rooms above the 15th floor.

Table 3 Data for air leakage

(a) Effective opening area of doors
Ae: effective opening area of each door [m2]

Door	Ae	Number of door
Elevator door	0.035	9 on 1F and 15F 1 on B1F 5 on each of the other floors
Stairwell door	0.010	2 on each floor
Room door	0.056	4 on each floor

(b) walls

Wall	Tightness	Wall area [m2/floor]
Exterior walls in the room	Average	440 for building type C 400 for the other type
Exterior walls in the atrium	Tight	80 for building type S1, O1 and O2 240 for building type S2
Interior walls between the rooms and the arium	Average	280 for building type C

Note) Air leakage rate through walls Q [lit/s·m2] was obtained from the following equation.
$Q=K\cdot\Delta P^{(1/1.5)}$
Where, K: flow coefficient [lit/(s·m2·Pa^(1/1.5))] K=0.043, 0.086, 0.173 for tight, average, leaky walls, respectively.

In these simulations, the air leakage characteristics of walls and doors were assumed to be the reasonable value based on the results of the previous studies. It is difficult to directly verify the simulated value of airflow rate with measured value because of difficulty of measurement of airflow rate such as outdoor airflow rate entering through large openings at entrances and airflow balance in a whole building. Further study is necessary in order to clear the detail of air leakage characteristics of building component, especially inner walls and partitions.

ESTIMATION OF THE OUTDOOR AIRFLOW RATE THROUGH ENTRANCE DOORS

These simulations were performed in order to obtain the relationship between the effective opening area of the entrance doors and the airflow rate through them. The results are shown in **Figure 9**. When the effective opening area is equal to 2 square meters, the outdoor airflow rate for building types O1 and S1 was found to be about five times higher than in building type N. For

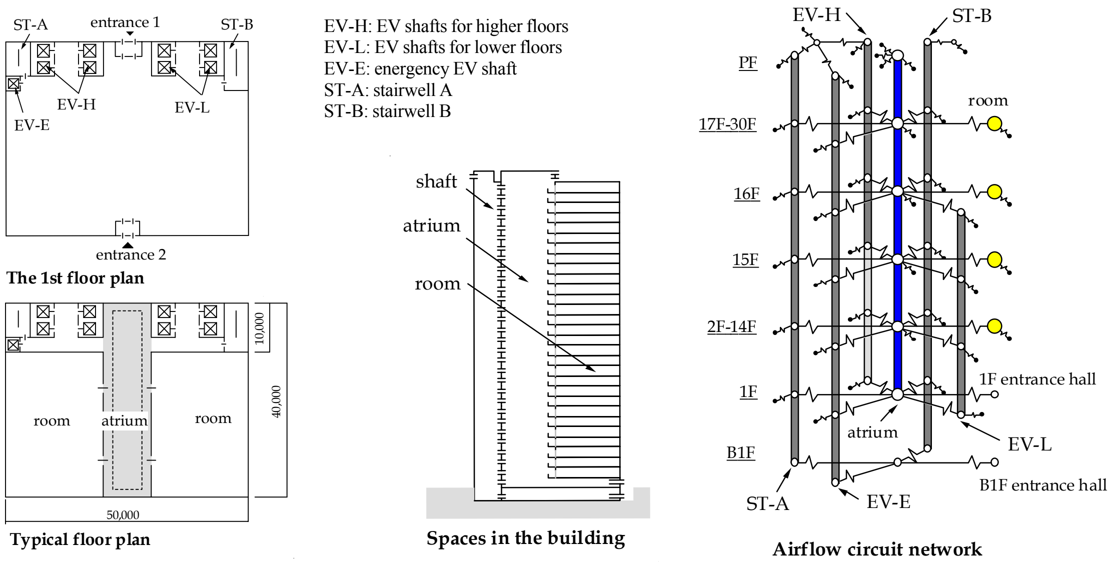
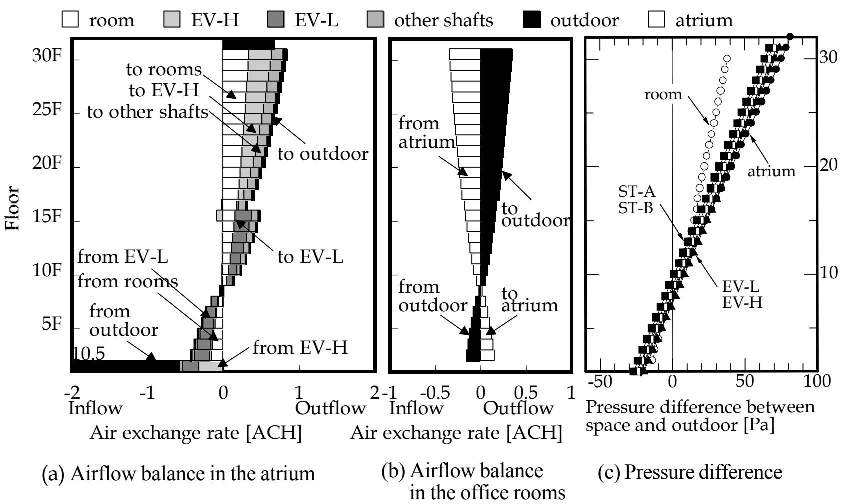


Figure 5 Floor plan and airflow circuit network of building typ S1



* all the air exchange rates in this paper is defined as the airflow rates relative to the space volume on a typical floor.

Figure 6 Airflow balance due to stack effect for building type S1

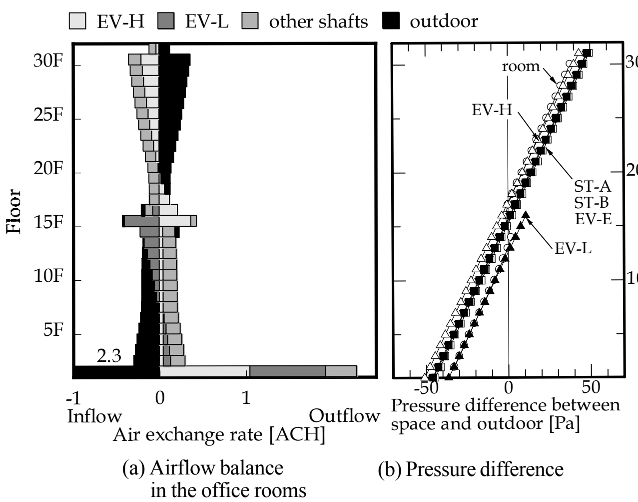
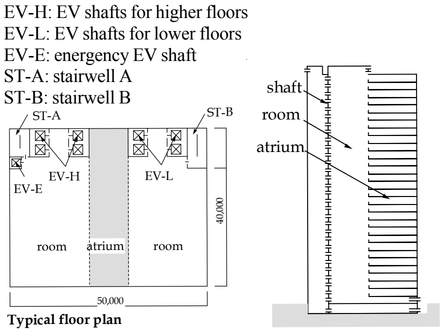


Figure 7 Airflow balance due to stack effect for building type N



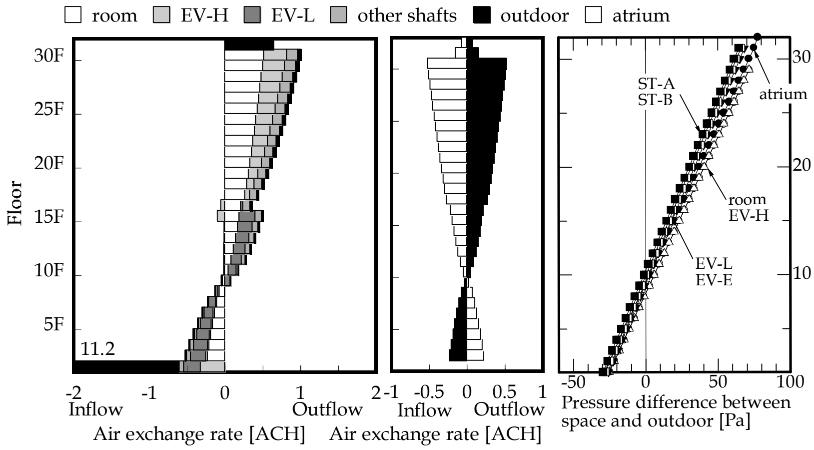
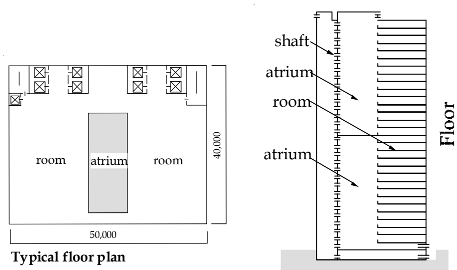


Figure 8-1 Airflow balance due to stack effect for building type O1

(a) Airflow balance in the atrium (b) Airflow balance in the office rooms (c) Pressure difference



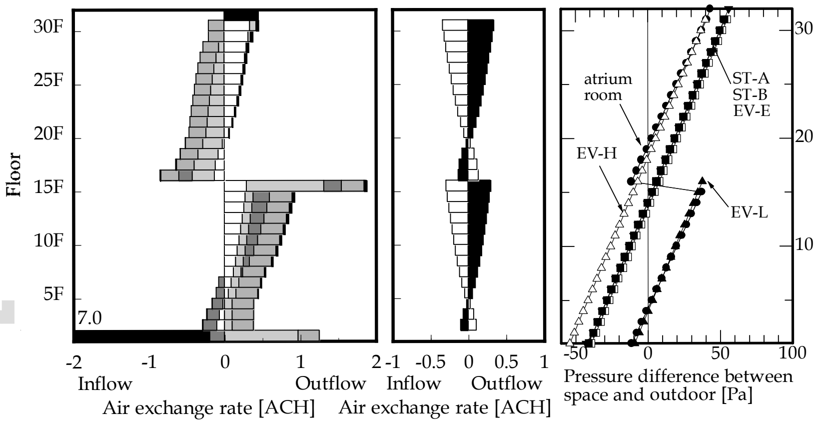
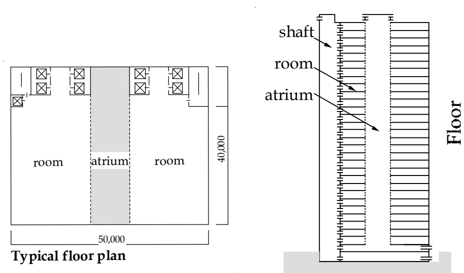


Figure 8-2 Airflow balance due to stack effect for building type O2

(a) Airflow balance in the atrium (b) Airflow balance in the office rooms (c) Pressure difference



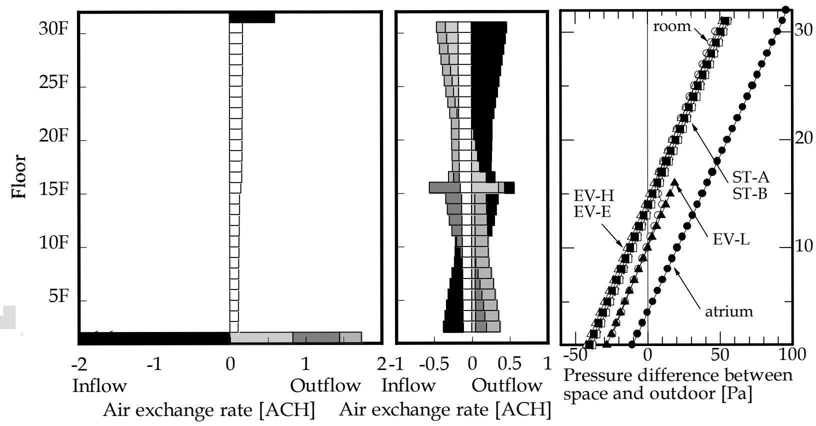
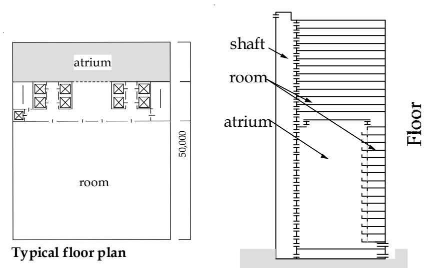


Figure 8-3 Airflow balance due to stack effect for building type C

(a) Airflow balance in the atrium (b) Airflow balance in the office rooms (c) Pressure difference



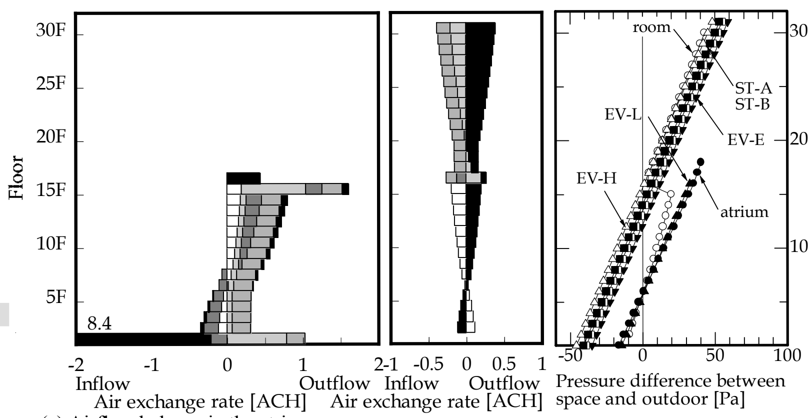


Figure 8-4 Airflow balance due to stack effect for building type S2

(a) Airflow balance in the atrium (b) Airflow balance in the office rooms (c) Pressure difference

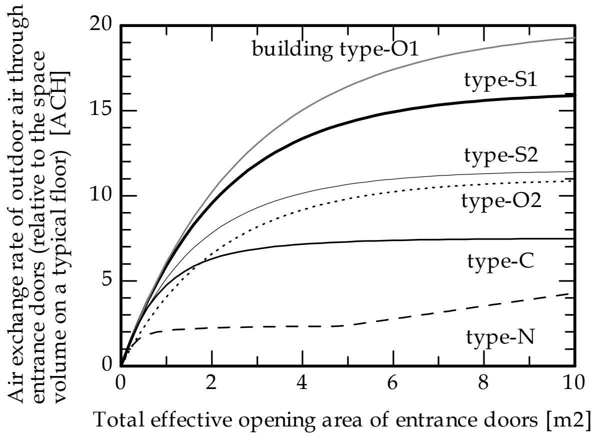


Figure 9 Relationship between effective opening area of entrance doors and winter outdoor airflow rate through them for 6 types of building

Table 4 Coefficients in approximation equations of outdoor airflow rate through entrance doors

$$Q = B_0 - B_1 e^{-\beta_1 R} - B_2 e^{-\beta_2 R} [R < R_0]$$

$$Q = C_1 R + C_2 [R \geq R_0]$$

Q : Air exchange rate of outdoor air through entrance
doors (relative to the space volume on typical floor [ACH]
R : Total opening area of the entrance doors [m2]
B0,B1,B2,β1,β2,R0,C1,C2 : Coefficients in the approximation equations

	B_0	B_1	B_2	β_1	β_2	R_0	C_1	C_2
Type-S1	16.10	13.90	2.20	0.42	0.77	-	-	-
Type-O1	20.00	16.40	3.55	0.31	0.63	-	-	-
Type-C	7.50	2.38	5.12	0.50	1.37	-	-	-
Type-O2	11.00	9.90	1.10	0.43	0.81	-	-	-
Type-S2	11.50	8.29	3.21	0.46	1.04	-	-	-
Type-N	2.35	0.51	1.84	0.77	4.00	5.00	0.38	0.45

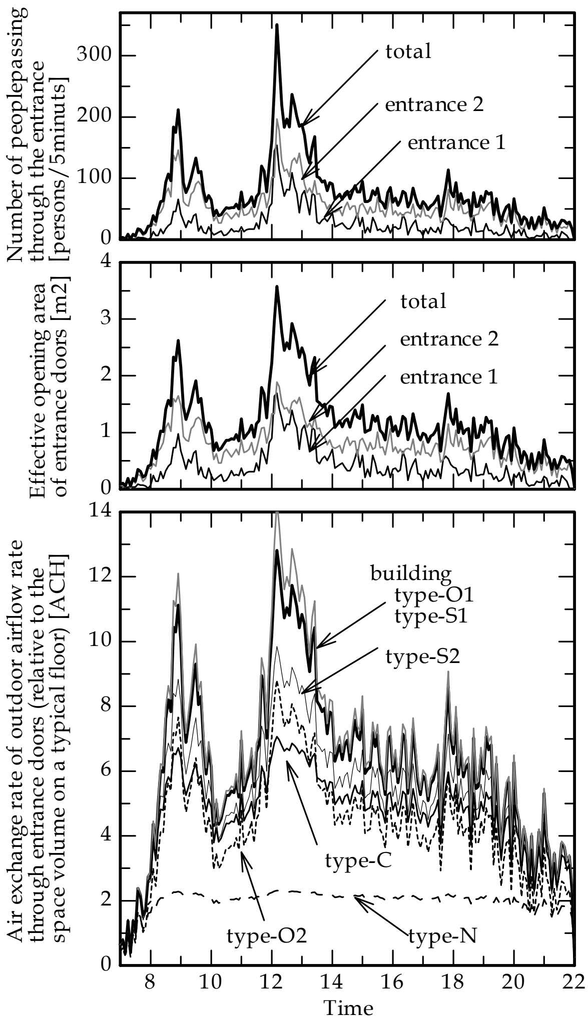


Figure 10 Changes in effective opening area of entrance doors and outdoor airflow rate through them on a winter day

building type S2, the outdoor airflow rate was found to be about four times higher, and for building types C and O2 about three times higher. When the effective opening area is larger than 5 square meters for building type N, the height of the atrium's neutral pressure level is lower than the height of the entrance door, causing the outdoor flow rate into the entrance hall to increase. The relationship between the entrance door effective opening area and the outdoor airflow rate was approximated using the equations shown in **Table 4**. The outdoor airflow rate through the entrance doors can be easily estimated using the approximation equations for the six types of buildings.

EXAMINATION WITH PROPOSED METHOD

Using the data obtained by observing the entrance traffic in an existing office building, the proposed method was used to make changes to the effective opening area and the outdoor airflow on a winter weekday. The results of these calculations are shown in **Figure 10**. Throughout the day, the effective opening area of the entrance doors fluctuates between 1 and 3.5 square meters. Although the outdoor airflow rate for building type N is almost a constant 2 ACH, the rates for the other building types widely fluctuate. These values can reach three to six times as high as those for building type N. In fact, the outdoor airflow rate for building types O1 and S1 just before work and during lunchtime is over 10 ACH

CONCLUSION

1) The effective opening area estimation method for entrance doors at a given traffic level was expanded to be applicable to 36 different types of doors.
2) An estimation method for calculating the winter outdoor airflow rate through entrance doors was presented for six different types of buildings.
3) An example calculated the changes in the outdoor flow rate through the entrance doors on a winter day using the proposed method. Although the

outdoor airflow rate is an almost constant low value for building type N, the rates for atrium buildings wildly fluctuate and reach values three to six times as high as those for building type N.

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