A Proposal of Hybrid Ventilation System Using Stack Effect in High-rise Buildings

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Abstract

This study proposes the hybrid ventilation system and its design methods for high-rise buildings. The proposed hybrid ventilation system uses natural driving power for ventilation based on air flow in the whole building and indoor and outdoor pressure distributions. Furthermore, it solves the troubles of the conventional natural or mechanical ventilation systems. This paper presents theories and a process for duct design for natural ventilation which forms the basis of a hybrid ventilation system in high-rise buildings. Also, the validity of the proposed design method will be analyzed by simulations.

1. Introduction

Recently with rising demands for environmentally friendly building and increasing interest in indoor air quality, interest in hybrid ventilation that combines natural and mechanical ventilation is also increasing. Hybrid ventilation can overcome the problems of conventional ventilation systems and guarantee proper ventilation rate in each target space while saving

energy consumption for ventilation. In this respect, hybrid ventilation is being actively

applied and researched.

Meanwhile, as high-rise buildings increase domestically and internationally, stack effect has

become a remarkable and is greatly influencing the ventilation performance of each floor. In

spite of this fact, stack effect is generally not considered during the design phase of

ventilation systems, and many problems of mechanical ventilation system caused by stack

effect are being reported.

This study proposes a hybrid ventilation system in high-rise residential buildings that takes

into consideration the pressure distribution and air flow in and outside the building, and

attempts to establish a method of duct design which forms the basis of this system.

Accordingly, this paper discusses the theory and process of duct design to maximize the

performance of natural ventilation. Furthermore, the validity of the proposed duct design

method will be verified through the network simulation technique.

2. Outline of hybrid ventilation system

The proposed hybrid ventilation system sets the supply/exhaust paths by taking into

consideration the pressure distribution and air flow in a high-rise building by stack effect and
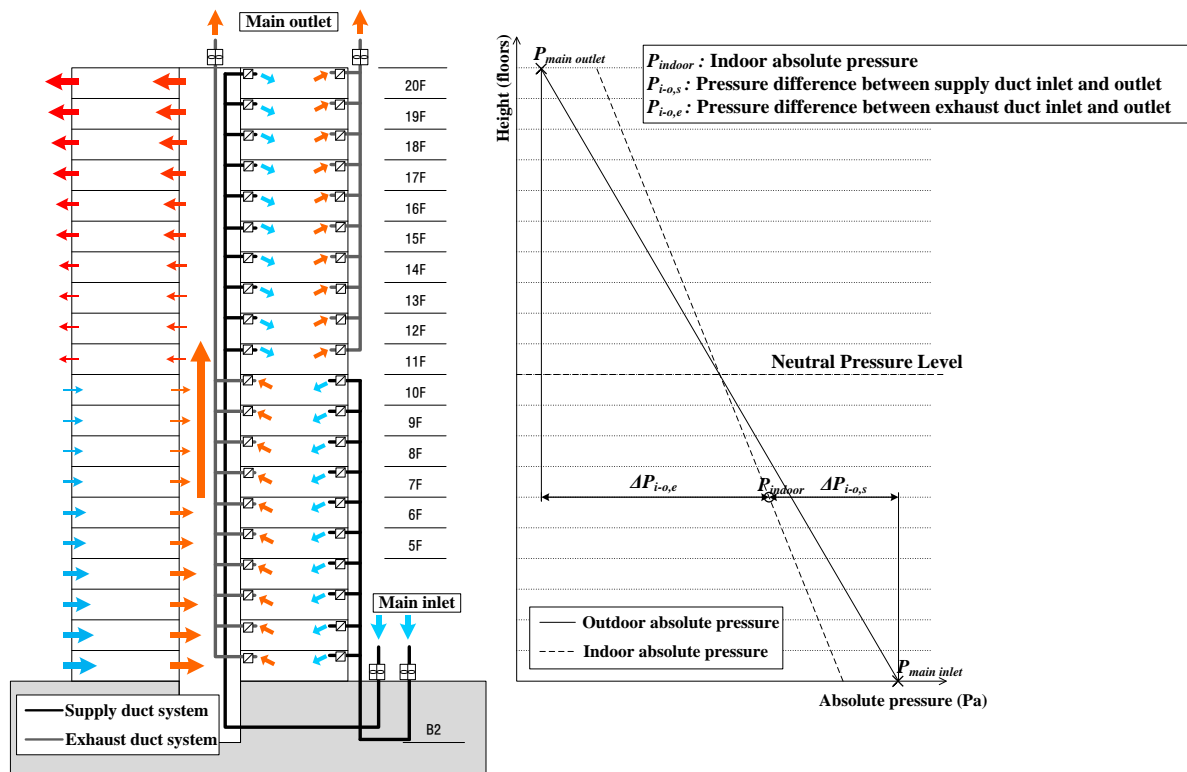
Fig. 1 Outline of the Hybrid ventilation system using stack effect in high-rise building

reverse stack effect. This enables natural driving power (stack effect) to be used for

ventilation as much as possible to reduce energy consumption. When natural driving power is

insufficient, the supply and exhaust fans are operated as auxiliary means so that constant

ventilation will be always guaranteed for each household.

In high-rise buildings, such pressure distribution and airflow as shown in Fig. 2 are generated

by the stack effect due to temperature difference between the inside and outside of the

building. Therefore, if we construct the ventilation system based on the pressure distribution

and airflow in Fig. 2, it is possible to supply fresh air to every room with minimum energy

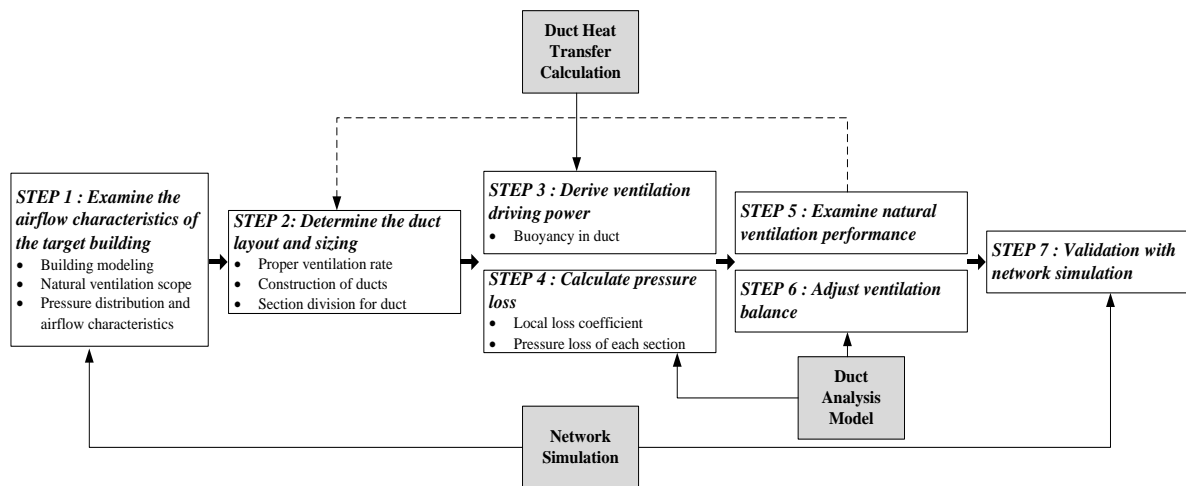consumption. Meanwhile, to maximize the ventilation driving power by

Fig. 2 Design process of duct in hybrid ventilation system

stack effect, "the construction of supply/exhaust ducts that reflect air flow and minimize

pressure loss" is most important.

3. Duct design process

This chapter describes the process of duct design which forms the basis of the hybrid

ventilation system design. Fig. 2 shows the duct design process along with review contents

and method for each step.

3.1 STEP 1: Examine the air flow characteristics of the target building

3.1.1 Building modeling

Examine the pressure distribution and airflow characteristics in the target building by stack effect through building modelling.

3.1.2 Determination of natural ventilation scope

Through climate analysis, determine the temperature difference between inside and outside (ΔT) which the cause of the stack effect in the building. Based on this, examine the possibility of natural ventilation of each floor of the target building and determine the natural ventilation scope. Within this scope, set as the design temperature condition that is minimum temperature difference (ΔT) to arouse the driving force for ventilation.

3.2 STEP 2: Determine the duct layout and sizing

3.2.1 Determination of the proper ventilation rate

Determine the ventilation rate based on the ventilation code by country or the air pollutant concentration of the target space. The determined ventilation rate is set as the design air flow rate in the duct design step.

3.2.2 Construction of the duct layout

As shown in Figure 1, determine the duct layout to achieve maximum ventilation driving power in consideration of the air flow and pressure distribution in the building by stack effect.

Decide the duct size according to the ventilation demand. In order to achieve the maximum ventilation driving power for the supply/exhaust ducts, the ducts must be constructed in such a manner to maximize the pressure difference between duct inlet and outlet ($\Delta P_{i\text{-}o}$) and the buoyancy in the duct (ΔP_{se}). Thus, in order to achieve the maximum pressure difference between duct inlet and outlet ($\Delta P_{i\text{-}o}$), based on the indoor and outdoor pressure distributions, the outside air inlet must be placed at the point of the maximum absolute pressure of outside air and place the outlet of the indoor air in the exhaust duct at the point of minimum absolute pressure of outside air. In addition, to achieve buoyancy (ΔP_{se}) in the duct through heat exchange on the path, the supply duct must be placed in the vertical space of the building from the outside air inlet through underground, and the exhaust duct must be also placed in the vertical space of the building. The supply inlet and exhaust outlet for each room must be installed on the basis of the air flow direction by stack effect so as to improve ventilation efficiency.

3.2.3 Section division for duct

To calculate the buoyancy and pressure loss of the duct for each household, the air flow rate in the duct, cross sectional area, and shape changing are main factors to consider how to divide sections of the duct.

3.3 STEP 3: Derive ventilation driving power

To achieve a certain ventilation rate for each household using natural power, we must consider the pressure difference (ΔP) which provides the ventilation driving force for the duct construction proposed in this study. Assuming that the temperature inside the duct is constant and the air is stationary state and non-compressive, the pressure difference based on the Bernoulli's equation is defined as the following expression (Eq. 1). This can be used to derive the ventilation driving power for supply/exhaust ducts in each household.

$$\Delta P = P_i - P_o + \rho g (H_i - H_o)$$
$$\Delta P = \Delta P_{i-o} + \Delta P_{se}$$
(Eq. 1)

where P_i is the absolute pressure at duct inlet, P_o is the absolute pressure at duct outlet, ρ is the density of air within duct, g is the acceleration due to gravity, H is the elevation, ΔP is the pressure difference that lead to air movement, ΔP_{i-o} is the pressure difference between duct inlet and outlet, and ΔP_{se} is the thermal gravity effect.

$$\Delta P_{se} = \sum_{i=1} \Delta p_{se_i}$$
(Eq. 2)

where Δp_{se} is the thermal gravity effect of location i.

The pressure difference between duct inlet and outlet for the supply/exhaust ducts in each household (ΔP_{i-o}) can be derived from the difference of absolute pressures between the inlet and outlet of the duct on the pressure distribution in and outside the building which was

investigated in STEP 1. The buoyancy in the supply/exhaust duct (ΔP_{se}) can be obtained by the sum of the buoyancy values for the vertical section which corresponds to the supply/exhaust path of each household as shown in expression (Eq. 2). To determine the buoyancy in each vertical section of the duct, this study used the calculation module for the duct heat transfer presented in ASHRAE for duct design as shown in expressions (Eq. 3) and (Eq. 4) [1]. From the average outlet and inlet air temperatures of each section of the duct that have been calculated through these expressions, we can derive the buoyancy for each section.

$$t_l = \frac{t_e(y-1) + 2t_a}{(y+1)} \qquad \text{(Eq. 3)}$$

$$y = \frac{0.5DV\rho c_p}{UL} \qquad \text{(Eq. 4)}$$

where t_l is the temperature of air leaving duct, t_e is the temperature of air entering duct, t_a is the temperature of air surrounding duct, and D is the diameter of duct, L is the duct length, U is the overall heat transfer coefficient of duct wall, and c_p is the specific heat of air.

3.4 STEP 4: Calculate pressure loss

This step determines the pressure loss of the supply/exhaust ducts for each household. The calculation of pressure loss uses the analysis model created on the basis of the basic equation for air flow in the duct.

3.4.1 Basic equation for air flow in the duct

With the Darcy-Weisbach Equation, we can express the pressure loss in the duct as expression (5):

$$\Delta p_t = \left(f \frac{L}{D} + \sum C \right) \frac{\rho V^2}{2} \tag{Eq. 5}$$

where Δp_t is the total pressure loss due to friction and dynamic losses, f is the friction factor and C is the local loss coefficient.

The air flow rate can be represented by expression (Eq. 6) based on the cross sectional area of the duct and expression (Eq. 5). Here, the friction coefficient was determined with the Colebrook's equation.

$$Q = VA$$
$$Q = \sqrt{\frac{2A^2 \Delta p_t}{\left(fL/D + \sum C \right) \rho}} \tag{Eq. 6}$$

where Q is the air flow rate and A is the cross-sectional area of duct.

3.4.2 Calculation of pressure loss

The total pressure loss of the supply/exhaust ducts for each household is determined by first calculating the pressure losses in each section of the duct divided in STEP 2 using the basic equation for air flow of the duct as shown in expression (Eq. 7) and adding to them the pressure loss of the sections corresponding to the supply/exhaust paths of each household.

Because the duct air flow equation is nonlinear, this study used the MATLAB fsolve function

for solving nonlinear equation to obtain the numerical answer.

$$\Delta p_{t_i} = \Delta p_{f_i} + \sum_{j=1}^{m} \Delta p_{ij} + \sum_{k=1}^{n} \Delta p_{ik}$$

$$\Delta P_t = \sum_i \Delta p_{t_i}$$

(Eq. 7)

where Δp_{ti} is the net total pressure loss for i-section, Δp_{fi} is the pressure loss due to friction for

i-section, Δp_{ij} is the total pressure loss due to j-fittings for i-section, Δp_{ik} is the pressure loss

due to k-equipment for i-section, and ΔP_t is the total pressure loss between duct inlet and

outlet.

3.5 STEP 5: Examine natural ventilation performance

Examine whether the design air flow rate can be achieved from the ducts constructed in such

a manner to attain maximum ventilation driving power for each household. If the pressure

loss in the duct determined above is equal to the natural ventilation driving power of each

household, the design air flow rate for this target space can be attained by natural driving

power only. Therefore, the criterion for the supply/exhaust ducts of each household was

defined as the difference between the ventilation driving power and the pressure loss as

shown in expression (Eq. 8). If this is not satisfied, the duct specification in STEP 2 must be

changed to satisfy this criterion

$$\Delta P - \Delta P_t \geq 0 \qquad\qquad (Eq.\ 8)$$

3.6 STEP 6: Adjust ventilation balance

Even if the expression (Eq. 8) is satisfied in the previous step, the proposed ventilation

system causes ventilation imbalance by the location (height) of each household and the

supply and exhaust air flow rates differ by household because it uses stack effect and

buoyancy in the duct as ventilation driving power. Thus, this step solves the ventilation

imbalance between households and between supply and exhaust through adjustment of the

ducts by installing a damper. As shown in expression (Eq. 9), the opening rate of the damper

is adjusted to make the total pressure loss become equal to the ventilation driving power for

the supply/exhaust ducts of each household so as to achieve the same air flow rate (design air

flow rate) for the supply/exhaust ducts of all households. Expression (Eq. 9) is a function of

the damper's local loss coefficient. The solution is derived through numerical analysis. The

derived solution is the local loss coefficient of the damper. Determine the opening rate of the

damper based on this.

$$\Delta P = \Delta P_t (C_d) \qquad\qquad (Eq.\ 9)$$

where C_d is the damper loss coefficient based on opening rate.

3.7 STEP 7: Validation with network simulation

In order to determine whether the proposed ventilation system achieves the proper ventilation rate meeting the design conditions and whether the ventilation rate is identical between supply and exhaust and between different households, add ducts to the building model used in STEP 2 and check the results.

4. Case study

This chapter verifies the validity of the design method presented in chapter 3. For this validity verification, the pressure distribution in the whole building, air flow characteristics, the duct construction (layout, dimension) determined in chapter 3, heat exchange characteristics, and pressure loss have been simulated, and the duct for natural ventilation was designed in accordance with the design method presented above. Then, it is determined whether the proper ventilation rates of the analyzed households are achieved as designed.

4.1 STEP 1

The building to which the design method of this study was applied was a typical flat type apartment building in Korea with 2 floors underground and 20 floors above ground. The underground part is used for parking lots and the above ground part is used for residences. There are two households with the size of around 100m^2 on each floor. The elevator shaft is located between the two households and the stairwell is interfacing with the outer wall of the corridor.

According to the proposed design process, the natural ventilation scope based on stack effect was determined. Natural ventilation was made possible in every household for the ducts of the appropriate sizes determined in consideration of the allowable indoor wind velocity and the heat exchange efficiency of the ducts. To enable ventilation driving power in this case, the indoor and outdoor temperature difference (ΔT) must be at least 17℃. In other words, if the indoor temperature is set to 22℃[2], the outside air temperature must be 5℃ or lower to give ventilation driving power. Thus, in Suwon City which was analyzed in this study, the percentage of the area that allowed natural ventilation through stack effect was approximately 30%.

Natural ventilation performance was analyzed for three households on the 11th to 13th floors which are roughly located at the neutral zone of the building and the pressure difference by stack effect is relatively small. The air flow characteristics in the building and the pressure distributions in and outside the building were derived using CONTAMW which is a network simulation tool. As shown in Fig. 3, each floor of the analysis model consists of the inside space of the household, corridor, and elevator. Each space was modeled as one zone without any internal sections. For the stairwell and elevator shaft space, the nodes are vertically connected. The interior temperature was set to 22.0℃, and the exterior temperature was set to 5℃ as described above. Although wind velocity and direction affect the indoor and outdoor

pressure distributions, they were not considered in this case study. The air leakage data for

each component used the results of a previous study, which are shown in Table 1.

The analysis results in Fig. 4 show the pressure differences which form the basis of air flow

in each section. In the lower floor part below the 9th floor which is the neutral zone, air flows

from the outside into the interior space of each household, and air moves upward through the

stairwell, and the elevator shaft. In the higher floor part, on the contrary, the air rising from

the lower floor part moves into the inside of each household due to the high pressure of the

stairwell and the elevator shaft. In this case study, on the 11th to 13th floors which are the

target area for the analysis of natural ventilation performance, because they are located at

upper part of the neutral zone, the air rising through the stairwell and the elevator shaft flows

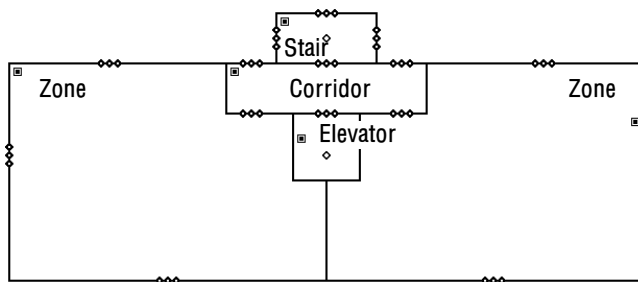into the households through the corridor and flows out through the exterior walls.

Fig. 3 Analysis model plan

Table 1 Air leakage data

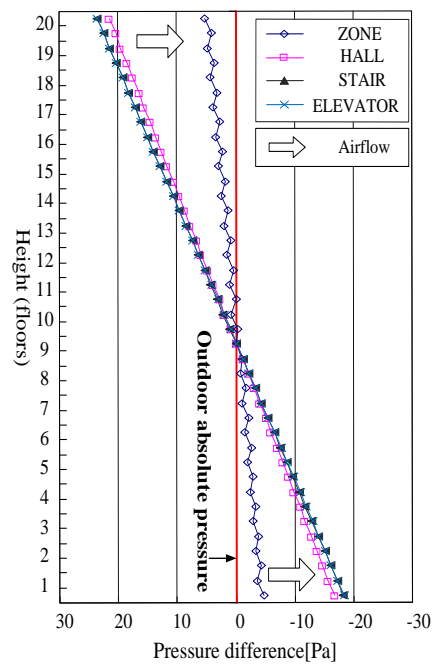| Building component	Air leakage data	Source
Exterior wall	EqLA$_{10}$[a]1.21 cm^2/m^2	[3]
Residential entrance door	EqLA$_{10}$ 70 cm^2/item	
Elevator door	EqLA$_{10}$ 325 cm^2/item	
Stairwell door	EqLA$_{10}$ 120 cm^2/item	
Swing door located on lobby and basement floors	430 CMH at 50 Pa	[4]

Fig. 4 Pressure distribution

4.2 STEP 2

In accordance with the ventilation standards for domestic residential buildings, the target ventilation rate for each target space was set to 0.7 times/h. Since the volume of each household is 360m^3, the target ventilation rate is 252CMH. The ducts were constructed as shown in Fig. 5 to raise ventilation efficiency depending on the pressure distribution and indoor air flow of the target building. The outside air inlet was located on the ground, and the outlet of the indoor air through the exhaust duct was located at the top of the building. The depth of the underground duct was decided as 5m in consideration of the point where underground temperature is stabilized[5]. The elevator shaft was decided as the vertical space in the building for the passage of the supply/exhaust ducts because it can minimize the length of the supply inlet and exhaust outlet to the households and the temperature is relatively high because it does not interface with the outside air. The locations of the supply inlet and exhaust outlet for each room were decided on the basis of the air flow direction for the households on the 11th to 13th floors as described above. The supply inlet was installed at the doorway of each household, and the exhaust outlet was installed at the exterior wall to improve the ventilation efficiency in the household. Fig. 5 shows the indoor and outdoor pressure distributions in the whole building, and indicates on the absolute pressure line the pressure differences (ΔP_{i-o}) between the inlet and outlet of the supply/exhaust ducts for each

household on the 11th to 13th floors. Fig. 6 shows the determined sections of ducts and the calculation results for each section in the following step.

4.3 STEP 3

As input conditions for outlet temperature calculation for each section of the duct, the underground temperature was set to 12℃[5], and the temperature of the shaft for heat exchange of the duct was set to 22℃. For the heat transfer coefficient, the value of ASHRAE was used. From these outlet and inlet temperatures for each section, the buoyancy of each section of the duct was derived. The ventilation driving power calculated using them are summarized in Fig. 6 and Table 4. In this case study, the temperature for all sections of the exhaust duct was set to 22℃ because the temperature of the air discharged from the room is equal to the temperature of the elevator shaft which is the path of the exhaust duct. Table 2 shows the input conditions for heat exchange for each section of the supply duct and the calculated outlet temperatures.

Table 2 Heat transfer calculations for supply duct

Duct Section	Airflow, CMH	Duct Size, mm φ	Duct length, m	Velocity, m/s	[a]heat transfer coefficient, $W/m^2 \cdot K$	Inlet Temperature, ℃	Outlet Temperature, ℃
1	756	500	53	1.1	3.5	5	14.7
3	504	500	3	0.7	3.4	14.7	15.3
5	252	250	3	1.4	3.5	15.3	15.6

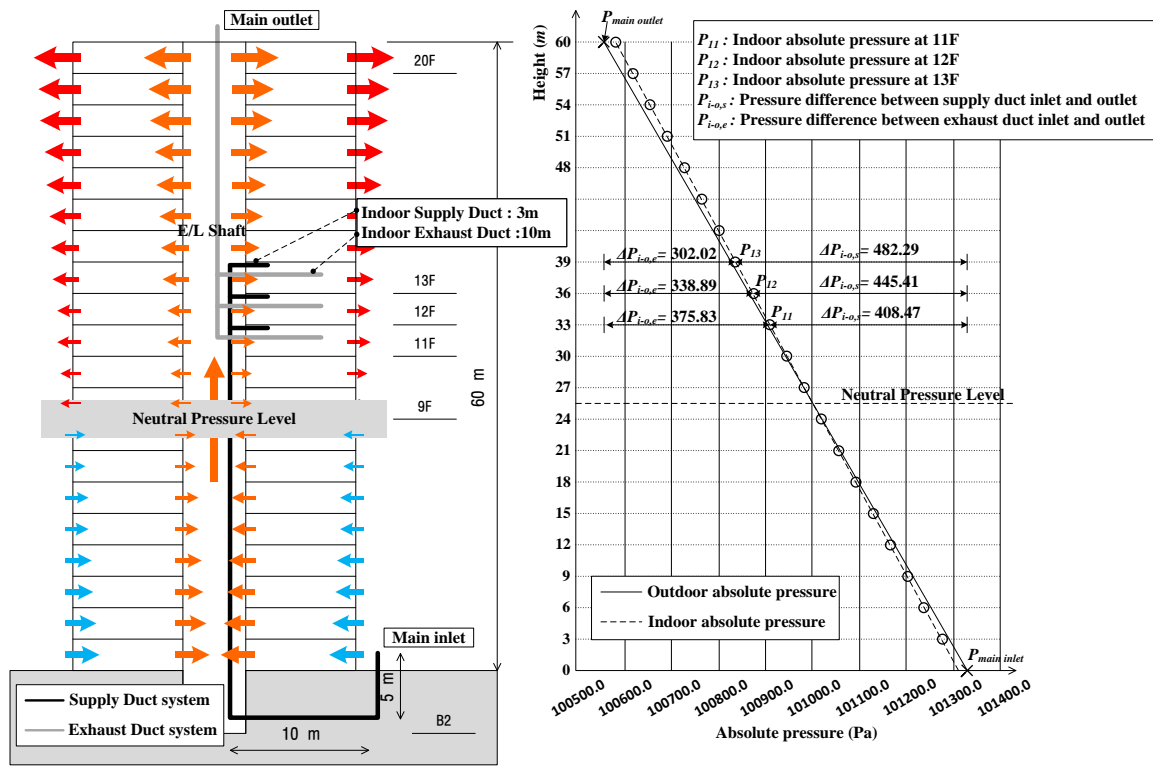Note) [a]Uninsulated sheet metal (1997 ASHRAE handbook—fundamentals. Chapter 32.)

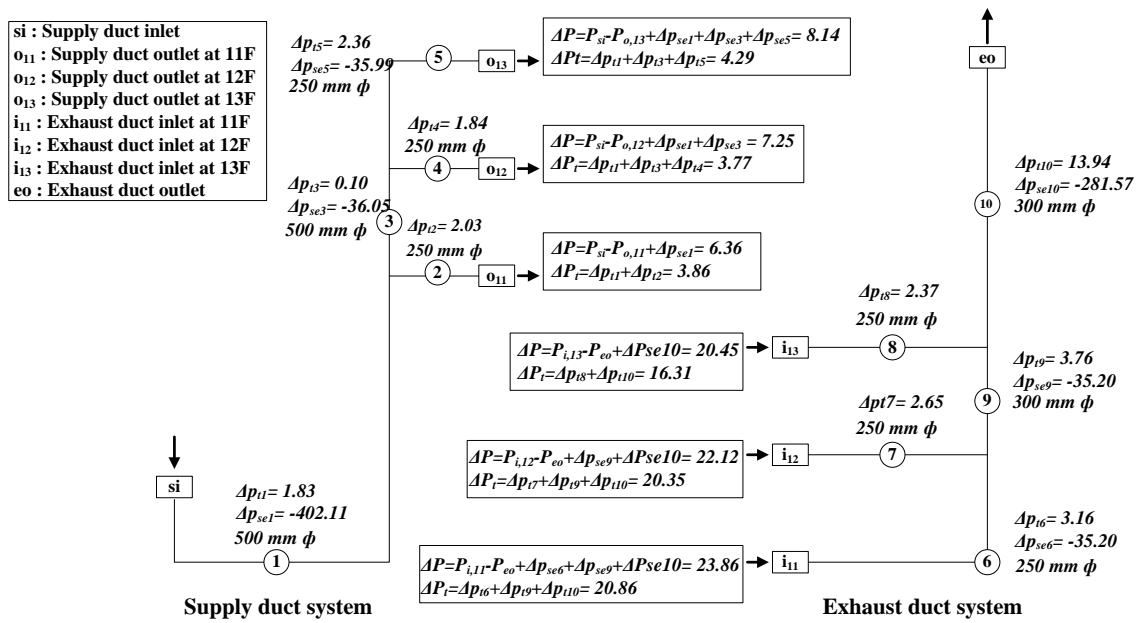**Fig. 5** Air flow and construction of ducts in the target building

Fig. 6 Sections for calculation of pressure losses in the duct and the calculation results for each section

4.4 STEP 4

Table 3 shows the input conditions for pressure loss calculations for each section of the duct

and the calculation results. The total pressure loss for the supply/exhaust ducts of each

household are summarized in Fig. 6 and Table 4.

Table 3 Pressure loss calculations

^{a}Duct Section, i	Airflow, CMH	Duct Size, mm ϕ	Duct length, m	Summary of Local Loss Coefficients	Friction Factor, dimensionless	Section Pressure Loss(Δp_{t_i}), Pa
1	756	500	53	0.13	0.023	1.83
2	252	250	3	1.33	0.025	2.03
3	504	500	3	0.16	0.025	0.10
4	252	250	3	1.18	0.025	1.84
5	252	250	6	1.29	0.025	2.36
6	252	250	13	1.29	0.025	3.16
7	252	250	10	1.17	0.025	2.65
8	252	250	10	0.94	0.025	2.37
9	504	300	3	1.38	0.022	3.76
10	756	300	24	1	0.021	13.94

Note) ^{a}See figure 6

4.5 STEPS 5 and 6

We examined on the basis of expression (Eq. 8) whether the design air flow rate can be

satisfied for the ducts using the natural ventilation driving power and the total pressure loss

for the supply/exhaust ducts of each household. It was found that the proper ventilation rate

for each household analyzed could be achieved. However, the ventilation rate varied by

household due to the pressure difference by stack effect and the difference in buoyancy inside

the duct by height. Therefore, a damper was installed at the end of the duct to each household

(sections 2, 4, 5, 6, 7, and 8 in Fig. 6) so that the air inflow rate could be adjusted by the

opening rate of the damper. The local loss coefficient according to the opening rate of the

damper was determined using expression (Eq. 9), which is shown in Table 4. Table 4 shows

the values calculated in each step of the case study.

Table 4 Step results

Floor	STEP 3			STEP 4	STEP 5	STEP 6
	Pressure difference between i and o ($\Delta P_{i\text{-}o}$), Pa	Thermal gravity effect (ΔP_{se}), Pa	Pressure difference (ΔP), Pa	Total pressure loss (ΔP_t), Pa	$\Delta P\text{-}\Delta P_t$, Pa	Local loss coefficient
11F S	408.47	-402.11	6.36	3.86	2.50	2.01
11F E	375.83	-351.97	23.86	20.86	3.00	2.47
12F S	445.41	-438.16	7.25	3.77	3.48	2.80
12F E	338.89	-316.77	22.12	20.35	1.77	1.46
13F S	482.29	-474.15	8.14	4.29	3.85	3.09
13F E	302.02	-281.57	20.45	16.31	4.14	3.40

4.6 STEP 7: result

This step examines whether the ducts determined above achieves the proper ventilation rate

for each household as designed, and can solve the ventilation imbalance between households

through dampers. For this purpose, the duct was additionally modeled in the network model

in Fig. 3. The basic input conditions for the network model were set to the same values as

those in STEP 2. For the boundary conditions of the ducts, the temperature of each duct

section and the local loss coefficient of the damper which were determined above were used.

Table 5 shows the input conditions for the duct model. The calculations of the ventilation rate

of the supply/exhaust ducts for each household are shown in Fig. 7. The error range

compared to the design air flow rate 252CMH was around 1%. The ventilation rates of the

households and the supply/exhaust ducts were almost identical to the design air flow rate.

Thus, the ducts designed by the proposed design method achieved the proper ventilation rate

of each household by natural driving power and solved the ventilation imbalance of the

conventional ventilation systems.

Table 5 Summary of duct model parameters (CONTAMW)

Duct Flow Element Model : Darcy-Collebrook resistance		
Model Parameters	Roughness	0.03 *mm*
	Shape	Circle
	Diameter	Figure 6
Segment Data	Duct segment length	Figure 5
	Sum of loss coefficients	Tables 3 and 4
Junction Data	Relative elevation	Elevation of Duct Section
	Tmperature	Outlet Temperature
		in Table 2

Fig. 7 Comparison of design air flow rate and simulation results.

Acknowledgments

References

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