Influence of Doorway Opening Conditions on Vestibule Pressurization Smoke Control in Office Buildings

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ABSTRACT

A practical calculation method for the vestibule pressurization smoke control systems was provided in previous papers[1][2]. This method covers fire scenarios corresponding to every stage of building evacuation in fire, namely, fire room evacuation, fire floor evacuation and whole building evacuation, and consists of a series of equations which can be successively calculated by a hand calculator to obtain required air supply rates to vestibules and elevator shafts. The required air supply rates may be calculated under the condition that all the doors are open in order to cope with the worst scenario. However, such an opening condition of the doors may not be the worst for the required air supply rates, since the pressures of the corridors and the elevator shafts are affected by the opening conditions in a complex manner. In this study, the effects of opening conditions of fire room doors on the corridor pressure and the required air supply rates at the stage of whole building evacuation are examined. In addition, the influence of closure of staircase doors on the required air supply rates is investigated.

Keywords: smoke control, vestibule pressurization, pressure difference, smoke stop, pressure relief, opening condition

INTRODUCTION

A vestibule pressurization smoke control, which directly pressurizes vestibules of staircases, is an effective method to prevent smoke infiltration into the staircases thereby assuring smoke free means of escape for building occupants and means of access for fire brigade, particularly in high-rise office buildings. Since, this smoke control system produces a corridor pressure rise, it is often accompanied by pressurization of the elevator shafts to prevent smoke spread from the corridor.

A simple hand calculation method was proposed in previous papers for determining required air supply rates to vestibules and elevator shafts in this smoke control system [1][2]. This calculation method covers fire scenarios corresponding to three stages of evacuation, i.e: fire room evacuation, fire floor evacuation and whole building evacuation. In addition, it is worth mentioning that this method consists of a series of simple formulas, which can be followed by use of a hand calculator, so that the verification of safety requirements can be carried out by not only a limited number of fire experts but also for a large number of ordinary engineers.

However, as easily presumed, the required air supply rates in the smoke control method heavily depend on conditions of openings around the corridor and vestibule. In general, one may assume that the condition that all the doors are fully open is the worst scenario for the air supply rates, because the required flow rates for smoke stop and the rates of air leakage from pressurized zones to the other spaces usually increase with the opening area.

Nevertheless, the required air supply rates are not always the largest when the opening areas are the largest, because different opening conditions of doors induce a different pressure field among the spaces involved. The opening conditions of doors on the required air supply rates should be considered carefully. Also, the effect of the opening condition of the doorway of a vestibule into a staircase on the corridor pressure has to be examined. When the door happens to be closed the air which is expected to leak into the staircase in the design will be diverted into the corridor to raise its pressure and may break the smoke seal of the elevator shaft therein.

1 SIMPLE HAND CALCULATION METHOD

In the beginning, the calculation method for the required air supply rate for fully developed fire scenario proposed in the previous paper is summarized as follows:

1.1 Layout of Floor of Office Building

A typical layout of floor plan of office buildings, which has two staircases connected by one corridor as shown in **Figure 1** is considered in the investigation of this method. Needless to say there is a wide range of possible layouts of floor plans of office buildings, the plan of this type can be often found in real office buildings and is one of the most simple and popular floor plan to consider pressurization smoke control system.

Figure 1 also illustrates a typical flow pattern at the openings. The spaces on the floor, i.e, the fire room, corridor, vestibule, elevator shaft and staircase, are identified by letters *R*, *C*, *L*, *E* and *S*, respectively. The multiple spaces of identical use are distinguished by adding numerals to the characters. A doorway connecting two spaces is identified by a pair of letters corresponding to the spaces.

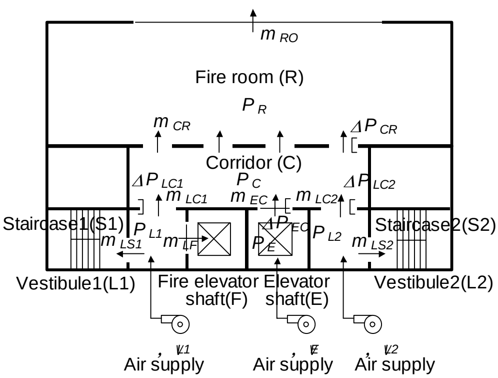


Figure 1 Assumed plan and flow

1.2 Scenario Corresponding to the Stage of Whole Building Evacuation

The scenario adopted for fire at whole building evacuation stage is as follows:

1) The fire is fully developed so the windows in the fire room have been broken.
2) The smoke extraction in the fire room has been shut down due to closure of the fuse damper to avoid fire spread through the duct.
3) Some of the doors between 'the fire room and corridor' are left open so the corridor is contaminated with smoke.
4) After all the occupants from the fire floor have escaped to the staircases, it is sufficient to stop smoke between 'the corridor and vestibule', to support fire brigade operation and occupants evacuation in the staircase. At the same time, it is necessary to prevent smoke to spread from the corridor to the elevator shaft.

1.3 Relationships which Hold for the Pressures and the Opening Flow Rate

The relationships which hold for the room pressures and the flow rates are as follows:

Pressures

$$P_C = P_R + \Delta P_{CR} \quad (1)$$

$$P_{L1} = P_C + \Delta P_{LC1} \ , \ P_{L2} = P_C + \Delta P_{LC2} \quad (2)$$

$$P_E = P_C + \Delta P_{EC} \quad (3)$$

Flow rates

Fire room (R): $m_{CR} = m_{RO}$ (4)

Corridor (C): $m_{LC1} + m_{LC2} + m_{EC} = m_{CR} + m_{CO} + u_C$ (5)

Vestibule (L1): $W_{L1} = m_{LC1} + m_{LS1} + m_{LF}$ (6)

Vestibule (L2): $W_{L2} = m_{LC2} + m_{LS2}$ (7)

Elevator shaft (E): $W_E = m_{EC} + m_{EO}$ (8)

1.4 Smoke Stop Criteria

Once the corridor temperature is given, the average pressure differences and doorway mass flow rates corresponding to smoke stop criteria between 'the vestibules and corridor' ΔP_{LC} and m_{LC}, and 'the elevator shaft and corridor' ΔP_{EC} and m_{EC} are given as follows:

$$\Delta P_{LC} = \frac{4}{9}(\rho_L - \rho_C) g\, h_{LC} \quad \text{and} \quad m_{LC} = \frac{2}{3}(\alpha A)_{LC}\sqrt{2\rho_L(\rho_L - \rho_C) g\, h_{LC}} \quad (9)$$

$$\Delta P_{EC} = \frac{4}{9}(\rho_E - \rho_C) g\, h_{EC} \quad \text{and} \quad m_{EC} = \frac{2}{3}(\alpha A)_{EC}\sqrt{2\rho_E(\rho_E - \rho_C) g\, h_{EC}} \quad (10)$$

where, ρ_L and ρ_E are the initial air density of the vestibule and elevator shaft, and ρ_C is an air density of the corridor. h_{LC} and h_{EC} are the heights of the openings between 'the vestibule and corridor', and between 'the elevator shaft and corridor', respectively.

1.5 Calculation Procedure for Air Supply Rates

Based on the above relationship, the air supply rates required to realize the smoke stop criterion given by Eqns.(9) and (10) can be calculated by the following procedure as follows:

[Step 1] Determine temperatures of the fire room ΔT_R and corridor ΔT_C, which can be obtained using some appropriate means such as the simple formulas proposed by Tanaka et al. [3].

$$\Delta T_R = 3.0 K_R^{\ 2/3} F_{OR}^{\ 1/3} \tau^{1/6} T_a \quad (11)$$

$$\Delta T_C = 1.35 F_{OC}^{\ 1/3} K_R^{\ 4/9} F_{OR}^{\ 2/9} \tau^{5/18} T_a \quad (12)$$

where T_a is the ambient air temperature. The four parameters in the above formulas, K_R, F_{OR}, F_{OC}, and τ, are given by the following Eqns.(13)-(16).

$$K_R = \frac{A_{RO}\sqrt{h_{RO}}}{A_{RO}\sqrt{h_{RO}} + A_{RC}\sqrt{h_{RC}}} \quad (13)$$

$$F_{OR} = \frac{A_{RO}\sqrt{h_{RO}} + A_{RC}\sqrt{h_{RC}}}{A_{RW}} \quad (14)$$

$$F_{OC} = \frac{A_{RC}\sqrt{h_{RC}} + A_{CO}\sqrt{h_{CO}}}{A_{CW}} \quad (15)$$

$$\tau = t_{dev} / k\rho c = 0.3 t_{dev} \quad (16)$$

Where, $A_{RO}\sqrt{h_{RO}}$, $A_{CR}\sqrt{h_{CR}}$, $A_{CO}\sqrt{h_{CO}}$ are the ventilation factors of the openings between 'the fire room and outdoors', between 'the corridor and fire room' and between 'the corridor and outdoors', respectively. A_{RW} is the total surface area of the fire room, A_{CW} is the total surface area of the corridor, k is heat conductivity, ρ is density and c is specific heat. t_{dev} is safety goal time, such as the evacuation time.

[Step 2] Calculate the flow rates and the average pressure differences for smoke stop criteria between 'the vestibule and corridor' m_{LC} and ΔP_{LC}, and 'the elevator shaft and corridor' m_{EC} and ΔP_{EC} by Eqns.(9) and (10).

[Step 3] Calculate the corridor pressure P_C by

$$P_C = \frac{\left(m_{LC1} + m_{LC2} + m_{EC} - u_C\right)^2}{2\rho_C (\alpha A)_{CO}^{\ 2}} \tag{17}$$

where $(\alpha A)_{CO}$ is the effective opening area calculated by combining the series or parallel openings which connect the corridor to outdoors.

[Step 4] Calculate the average pressures of the vestibule P_{L1} and P_{L2} using Eqn.(17) to Eqn.(2).

[Step 5] Calculate the air leaks from the vestibule to the staircase m_{LS1} and m_{LS2} by, [1]

$$m_{LS} = (\alpha A)_{ELSO}\sqrt{2\rho_L\left(P_L + |\rho_O - \rho_S| g H_{LSO}\right)} \tag{18}$$

where, H_{LSO} is the vertical distance of these openings from the vestibule doorway into two staircases and $(\alpha A)_{ELSO}$ is the effective opening area of the flow path from the vestibule to outdoors via the staircase, which can be calculated from

$$\sqrt{\rho_L}(\alpha A)_{ELSO} = \frac{1}{\sqrt{\dfrac{1}{\rho_L (\alpha A)_{LS}^{\ 2}} + \dfrac{1}{\rho_S (\alpha A)_{SO}^{\ 2}}}} \tag{19}$$

Likewise, the air leak from the vestibule to the fire elevator shaft m_{LF} can be calculated as Eqns.(18) and (19).

[Step 6] Calculate the air supply rates to the vestibule W_L by Eqns.(6) and (7).

[Step 7] Calculate the average pressure of the elevator shaft at the level of the fire floor P_E by Eqn.(3).

[Step 8] Calculate the air leak from the elevator shaft to outdoors m_{EO} by

$$m_{EO} = (\alpha A)_{EO}\sqrt{2\rho_E\left(P_C + \frac{4}{9}\Delta\rho_{EC} g h_{EC} + \Delta\rho_{EO} g H_{CE}\right)} \tag{20}$$

[Step 9] Calculate the air supply rate to the elevator shaft W_E by Eqn.(8).

2 OUTLINE OF EXAMINATION

2.1 Objecitves of Examination in This Study

The objectives of the investigation here is two fold as follows:

(1) The effect of doorway width on required air supply rate to vestibule

The smaller width of the fire room doors means the higher pressure of the corridor, which results in corresponding rise of the pressures of the vestibule and elevator shaft, and the air leakage from these spaces to the outdoors increases. It may be a difficult to determine how large width of the fire room doors to be assumed as the design scenario. In this paper, the investigation is made on how large effect the opening condition of the fire room doors has on the required air supply rates to the vestibule and elevator shaft.

(2) The effect of closure of the door between 'vestibule and staircase' on elevator shaft

When the door of the staircase happens to be closed by some reason due to evacuation or fire brigade operation, the air flow rates that were supposed to leak into the staircase will turn into the corridor, which results in the rise of pressure therein. This may cause a risk of loss of the smoke stop at the opening to the elevator shaft. In this paper, a method to maintain the smoke stop condition leak in such a circumstance is explored.

2.2 Conditions for the Calculation

For the case study to investigate the effects of opening conditions on the required air supply rate and corridor pressures, the dimensions and initial temperatures of the spaces are set as in **Table 1**. The height of staircases and elevator shafts roughly correspond to a building having seventeen stories. Winter period is assumed to set the temperature conditions in each spaces and the second floor was selected as the fire floor to take into account the stack effect. The dimensions and the effective flow coefficients of the openings are listed in **Table 2**.

Table 1 Calculation condition for the case study (Spaces)

	W x D x H (m)	Floor Area (m^2)	Total surface area (m^2)	Initial temperature ( )
Fire Room (R)	30 x 18 x 2.7	540.0	1339.0	22
Corridor (C)	19.5 x 3 x 2.7	58.5	238.5	22
Vestibule1, 2 (L1,L2)	3.5 x 3 x 2.7	10.5		22
Staircase1, 2 (S1,S2)	5.25 x 3 x 70	15.75		10
Elevator Shaft (E)	10 x 3 x 70	30.0		10
Fire Elevator shaft (F)	3 x 2.5 x 70	7.5		10
Outdoors (O)				5

Table 2 Calculation condition for the case study (Openings)

	Nominal Opening Dimension (m) (x number)	Area (m^2)	Effective flow coefficient
Corridor - Fire Room (CR)	1.7 x 2.2 (x 4)	14.96	open 0.7 close 0 *
Vetibule–Corridor (LC1, LC2)	0.9 x 2.1	1.89	open 0.7
Elevator shaft – Corridor (EC)	1.0 x 2.2 (x 4)	8.8	close 0.01
Vestibule1–Fire Elevator Shaft (LF)	1.1 x 2.2	2.42	close 0.01
Vestibule–Staircase (LS1,LS2)	0.9 x 2.1	1.89	open 0.35 close0 *
Fire room–Outdoors (RO)	33.0 x 2.0	66.0	open 0.7

* A little air leakage which may exist even when the doors are closed in real situation is ignored for simplicity.

3 OPEN RATE OF FIRE ROOM DOORS AND REQUIRED AIR SUPPLY RATES

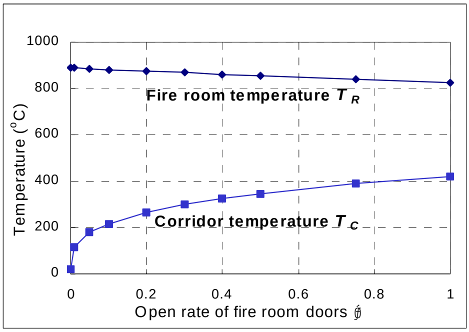
3.1 The First Results of the Case Study

Figures 2 shows the results of the calculation to investigate the effect of the fire room doorway width on the required air supply rates. The open rate ϕ in the abscissa is defined as the proportion of opening area to the total of opening area of the fire room doors, that is

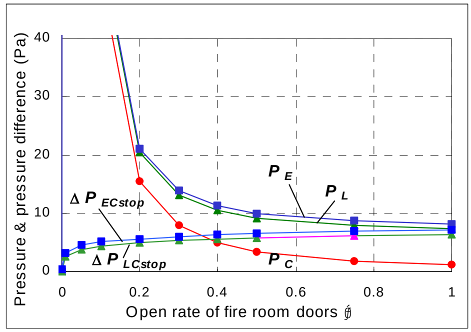
$$\phi \equiv \frac{\text{width of fire room doorway assumed to be open}}{\text{nominal width of fire room doorway}} \qquad (21)$$

Figure 2a shows the results of the temperatures of the fire room T_R and corridor T_C, calculated for different open rate ϕ using simple Eqns.(11)-(16) for fully developed fire temperature. Note that the decrease of the gas flows from the fire room into the corridor due to the rise of the corridor pressure is not considered in the simple formula Eqn.(12). **Figure 2b** indicates the required pressure differences between 'the vestibule and corridor' ΔP_{LC}, and 'the elevator shaft and corridor' ΔP_{EC}, and the pressures in the corridor P_C, vestibule P_L and elevator shaft P_E. **Figure 2c** indicates the flow rate m_{LCstop} corresponding to the smoke stop pressure difference, the air leak from the vestibule to the staircase m_{LS} and the fire elevator shaft m_{LF}, and the required air supply rates for the vestibule W_L. **Figure 2d** indicates flow rate m_{ECstop} corresponding to the smoke stop pressure difference, the air leakage from the elevator shaft to the outdoors m_{EO}, and the required air supply rates to the elevator shaft W_E.

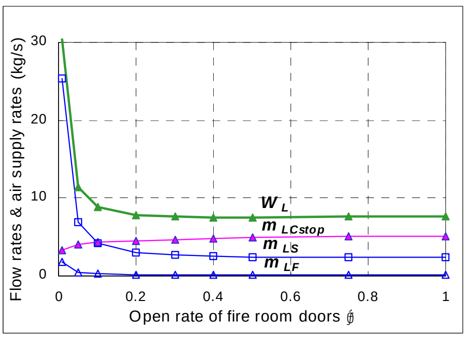
As shown in **Figures 2c** and 2**d**, the required air supply rates to the vestibule W_L and to elevator



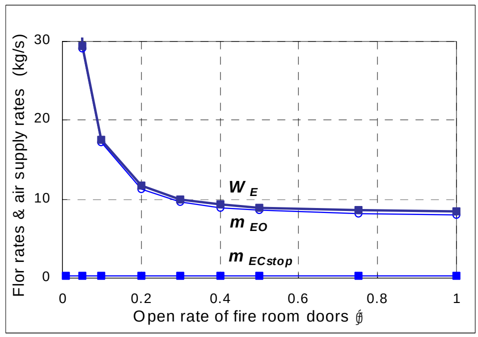
a. Temperatures of fire room and corridor



b. Required pressure differences for smoke stop and pressures of each space



c. Flow rates between 'vestibule and adjacent spaces', and required air supply rates to vestibule



d. Flow rates between 'elevator shaft and adjacent spaces', and required air supply rates to elevator shaft

Figure 2 Influence by open rate of fire room doors (Reduction of flow rates from fire room into corridor due to rise of corridor pressure is not reflected on corridor temperature.)

shaft W_E are approximately constant where the open rate ϕ is large, but increase sharply as the open rate ϕ becomes small. The reasons of this result seem to be as follows:

The pressure differences corresponding to the smoke stop criteria ΔP_{LC} and ΔP_{EC} are relatively insensitive to the open rate ϕ (**Figure 2b**), although the temperature of the corridor T_C becomes lower as the open rate ϕ decreases (**Figure 2a**). On the other hand, a small open rate ϕ means a narrow air flow path to the outdoors. So the corridor pressure P_C has to rise high as the open rate ϕ becomes small to let the air supply to the corridor, which is roughly constant in a wide range of ϕ, out to outdoors (**Figure 2b**). The rise of the corridor pressure P_C implies the corresponding rise of pressures of the vestibule P_L and elevator shaft P_E (**Figure 2b**), which then increase the air leaks from the vestibule and elevator shaft. As a result, the required air supply rates to the vestibule and elevator shaft W_L and W_E become larger with the decrease of ϕ (**Figures 2c**, **2d**)).

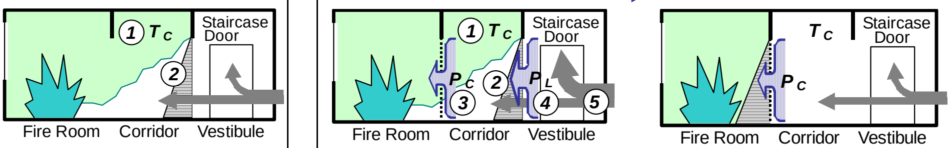
However, it should be born in mind that these are the results obtained using the simple formulas which does not take into account the effect of pressure build up on the corridor temperature. The actual corridor temperature will be lower than that indicated in **Figure 2a**, particularly when the open rate is small. So the rise of the corridor pressure P_C implies the increase of the pressure difference at the doorways between 'the fire room and corridor' ΔP_{CR}, which may shut smoke out of the corridor.

In summary, there can be two situations, one that corridor is contaminated by smoke and the other that the corridor is free from smoke, depending the opening condition of the fire room doors, even at the stage of fully developed fire.

i) When all the fire room doors are open…

ii) When some of the fire room doors are closed…

(in calculation) (in real situation)



i)

1. The Corridor temperature T_C is calculated, and
2. flow rates for smoke stop between 'the vestibule and corridor' is obtained.

ii) (in calculation)

1. T_C is calculated, and
2. the flow rates for smoke stop between 'the vestibule and corridor' is obtained.
3. However, the corridor pressure P_C rises higher than that of **i)**,
4. so the vestibule pressure P_L also rises much higher than that of **i)**.
5. As a result, air leaks to the staircase becomes so large that the required air supply rates is calculated large.

ii) (in real situation)

When the corridor pressure P_C is large, smoke in the fire room may be stopped at the doorway between 'the corridor and fire room' and the corridor is free from smoke.

Figure 3 Effect of opening condition of fire room doors

3.2 Revision of Pressure and Required Air Supply Rates at Non Smoke Leak Situation

Let's call the situation that the corridor is free from smoke as "Non Smoke Leak Situation (NSLS)" and the situation that corridor is contaminated with smoke as "Smoke Leak Situation (SLS)". It is thought that there is the threshold open rate on the doorway width that divides the two situations, which we call "Smoke Stop Threshold (SST)." How to find SST is examined and the lines in the range of NSLS are revised as in **Figure 2**.

(1) Procedure to find the Smoke Stop Threshold (SST)

If the smoke stop is achieved at the doorways between 'the fire room and corridor', the temperature of the corridor is supposed to be normal. SST is given by the value of the open rate ϕ at which the lines for ΔP_{CRstop} and $\Delta P_{CRnormal}$ meet, where ΔP_{CRstop} is the required pressure difference to stop smoke between 'the corridor and fire room', and $\Delta P_{CRnormal}$ is the pressure difference between 'the corridor and fire room' which enable to pass the total air flow entering from the vestibule and elevator shaft into the corridor.

The open rate that corresponds to SST ϕ_{stop} can be found with a procedure as follows:

[Step 1] Calculate the required pressure difference corresponding to the smoke stop criterion between 'the corridor and fire room' ΔP_{CRstop} by

$$\Delta P_{CR\,stop} = \frac{4}{9}\left(\rho_C(0) - \rho_R(0)\right) g\, h_{CR} \tag{22}$$

where $\rho_C(0)$ and $\rho_R(0)$ are the air density in the corridor and fire room for the open rate ϕ=0, respectively. h_{CR} is the fire room doorway height and g is gravitational acceleration.

[Step 2] Calculate pressure difference at the doorway between 'the corridor and fire room' $\Delta P_{CRnormal}$. If the total of the air flows from the vestibule and elevator shaft that enter into the fire room under the condition that the corridor is free from smoke, the pressure difference at the doorways between 'the fire room and corridor' $\Delta P_{CRnarmal}$ can be calculated by

$$\Delta P_{CR\,normal} = \frac{\left\{m_{LC\,stop1}(\phi) + m_{LC\,stop2}(\phi) + m_{EC\,stop}(\phi)\right\}^2}{2\rho_C(0)\cdot\left\{\phi\cdot(\alpha A)_{CR.tot}\right\}^2} \tag{23}$$

where $m_{Lcstop1}(\phi)$, $m_{Lcstop2}(\phi)$ and $m_{ECstop}(\phi)$ are the flow rates corresponding to the smoke stop criteria between 'the vestibule and corridor', and 'the elevator shaft and corridor' when the open rate is ϕ, and $(\alpha A)_{CR.tot}$ is the effective opening area when the fire room doors are fully open, that is, when the open rate $\phi=1$.

[Step 3] Calculate the open rate at SST ϕ_{stop}. By equating Eqn.(22) and (23), the relationship for smoke stop condition can be obtained as

$$\phi(\alpha A)_{CR.tot} = \frac{3}{2}\cdot\frac{m_{LC1}(\phi) + m_{LC2}(\phi) + m_{EC}(\phi)}{\sqrt{2\rho_C(0)\cdot(\rho_C(0) - \rho_R(0))\,g\,h_{CR}}} \tag{24}$$

Strictly speaking, a numerical calculation is necessary to solve this formula because the flow rates corresponding to smoke stop conditions $m_{LC1}(\phi)$, $m_{LC2}(\phi)$ and $m_{EC}(\phi)$ depend on the corridor temperature so are the function of the open rate ϕ. However, the using the flow rates calculated using the corridor temperature for the open rate $\phi=1$ is on the safety side. Then, the open rate that corresponds to SST ϕ_{stop} is given by

$$\phi_{stop} = \frac{3}{2}\cdot\frac{m_{LC1stop}(1) + m_{LC2stop}(1) + m_{EC\,stop}(1)}{(\alpha A)_{CR.tot}\sqrt{2\rho_C(0)\cdot(\rho_C(0) - \rho_R(0))\,g\,h_{CR}}} \tag{25}$$

In this case study, $\phi=0.224$ was obtained as the value for SST.

(2) Revision of the lines in Non Smoke Leak Situation (NSLS)

Figure 4 illustrates the lines revised in the range of NSLS by the graphs shown in **Figure 2**.

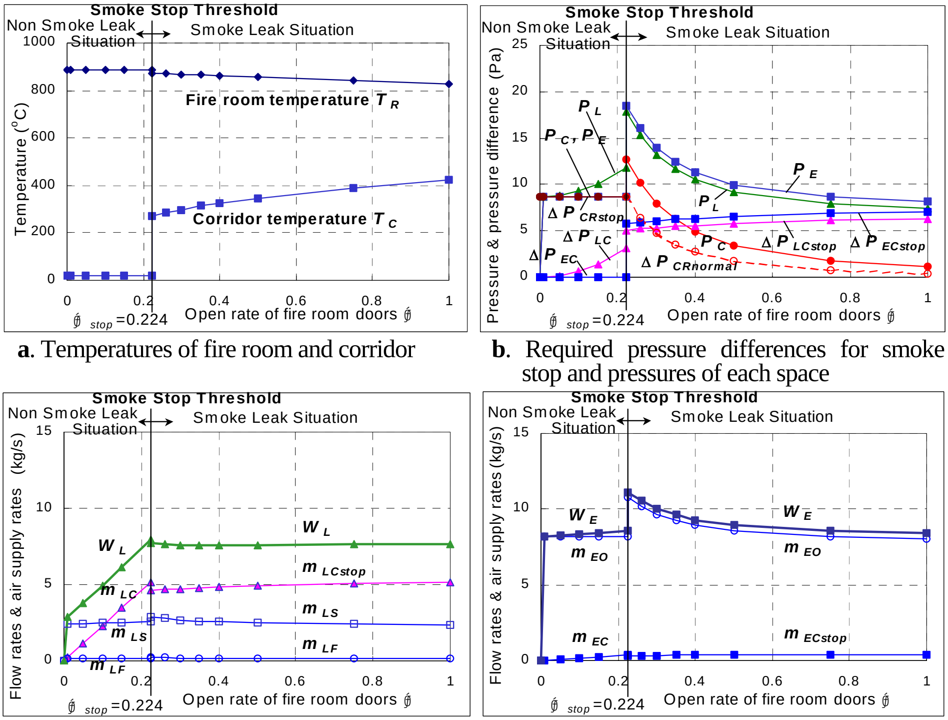
Revision of Temperature of Fire Room and Corridor **Figure 4a** shows the temperatures of the fire room and corridor revised in the range of NSLS. The temperatures of the fire room in this range is the temperature calculated for the open rate $\phi=0$ as stated above, and the corridor temperature is the normal temperature, needless to say.

Revision of Pressures of Each Space **Figure 4b** shows the pressure difference and pressure of each space revised in the range of NSLS. First, ΔP_{CRstop} is only a function of temperature difference between 'the corridor and fire room' so is constant irrespective of open rate ϕ. Next, the pressure differences between 'the vestibule and corridor' ΔP_{LC}, and between 'the elevator shaft and corridor' ΔP_{EC} are determined after the flow rates m_{LS} and m_{EC} have been determined as shown in the following paragraph. The pressure of the corridor P_C was obtained using Eqn.(17), then the pressures of the vestibule P_L and elevator shaft P_E were calculated by Eqns.(2) and (3).

Calculation of Required Air Supply Rates **Figure 4c** and **4d** shows the flow rates and required air supply rates to the vestibule and elevator shaft revised in the range of NSLS. First, the required flow rates to stop smoke between 'the corridor and fire room' m_{CRstop} is calculated with the value of pressure difference ΔP_{CRstop} as

$$m_{CRstop} = \frac{2}{3}(\alpha A)_{CR}\sqrt{2\rho_C(\rho_C - \rho_R)gh_{CR}} \tag{26}$$

Since m_{CRstop} is the total rates of the flows into the corridor, either of the flow rates m_{LS} and m_{EC}, can be determined arbitrarily. In this study, air flows m_{LC} and m_{EC} at NSLS are determined proportionally to the ratio of the flow rates between 'the vestibule and corridor' m_{LC}, and 'the elevator shaft and corridor' m_{EC} in the range of SLS. Finally, the required air supply rates to the vestibule W_L and elevator shaft W_E in NSLS can be calculated using Eqns.(7) and (8) as shown in **Figures 4c** and **4d**.



a. Temperatures of fire room and corridor

b. Required pressure differences for smoke stop and pressures of each space

c. Flow rates between 'vestibule and adjacent spaces', and required air supply rates to vestibule

d. Flow rates between 'elevator shaft and adjacent spaces', and required air supply rates to elevator shaft

Figure 4 Influence by open rate of fire room doors (After revised lines at NSLS)

3.3 Study on Revised Graph Lines

As can be seen in **Figure 4**, the lines in the range of NSLS and those in SLS do not meet on SST. The reason of this is that the temperature of the corridor on the side of SLS is calculated by the use of simple formulas, which does not consider reduction of the flow rates from the fire room into the corridor due to rise of the corridor pressure, as stated above, so the predicted corridor temperature is rather higher than the actual situation particularly in the region where the open rate ϕ is close to SST, and the required air supply rates W_L and W_E in **Figures 4c** and **4d** are also rather overestimated. The rise of the corridor pressure leads to the reduction of the gas flows from the fire room into the corridor near SST even in the range of SLS. If this effect is taken into account, the lines in both regions will meet at SST.

To do this, however, a computer program is needed to run to obtain ϕ taking into account so does not go with the way of the simple calculation method for the smoke control design proposed in our study. Although the calculated air supply rates on the side of SLS are overestimated to a certain degree near SST, it is thought that the differences would not be significant if it were compared with the required air supply rates from a detailed calculation.

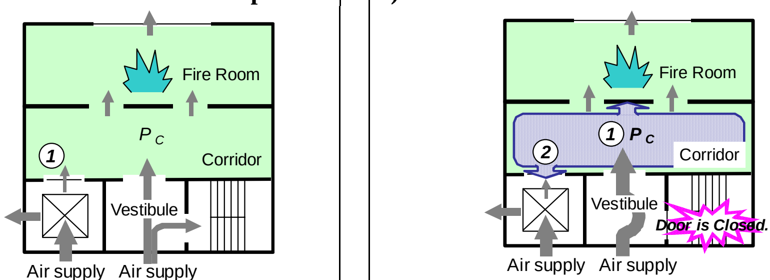
Therefore, it can be said that the values of calculated air supply rates at ϕ_{stop} of the side of SLS are acceptable for required air supply rates in smoke control design practices of actual buildings.

4 OPENING CONDITION AND RELIEF OF CORRIDOR PRESSURE

4.1 Smoke Stop between 'Elevator Shaft and Corridor'

The door to the staircase may be opened and closed by some reasons such as evacuation and fire brigade operation. If the door happens to be closed, the air flow that was supposed to leak into the staircase will turn into the corridor, which raises the pressure of the corridor and may cause a risk of loss of the smoke stop condition at the opening between 'the elevator shaft and corridor' and spread of smoke up stairs.

i) When door to staircase is open… | **ii) When door to staircase is closed...**



i) **1.** The smoke stop condition at the opening between 'the elevator shaft and corridor' is satisfied.

ii) **1.** The corridor pressure P_C rises higher than that of **i)**,
2. and there may be a risk to break the smoke stop condition at the opening between 'the elevator shaft and corridor.'

Figure 5 Effect of closure of door to staircase

The following measures can be considered in order to prevent this problem:

(1) Equip a by-pass air relief which operates when the corridor pressure rises to a certain level between 'the corridor and outdoors'.

(2) Determine the air supply rates to the elevator shaft at the stage of design taking into account the pressure rise of the corridor due to closure of the door to the staircase in advance.

4.2 Air Supply Rates to Maintain the Smoke Stop Condition of Elevator Shaft

In the following calculation procedure, the air leaks to the staircases and to fire elevator shaft are neglected to avoid the complexity in the calculation.

(1) Relationships which hold for each space

<u>Flow rates</u> Considering the mass conservation in each of the spaces involved, the following relationships hold for the flow rates of openings.

Corridor : $$m_{LC1} + m_{LC2} + m_{ECstop} = m_{CR} + m_{CO} + m_{CObp} \quad (27)$$

Vestibule1, Vestibule2 : $$W_{L1} = m_{LC1} \qquad W_{L2} = m_{LC2} \quad (28)$$

Elevator Shaft : $$W_E = m_{EC\,stop} + m_{EO} \quad (29)$$

where, m_{ECstop} is the flow rates corresponding to the smoke stop condition at the doorways between 'the elevator shaft and corridor', and m_{CObp} is the flow rates at the by-pass opening between 'the corridor and outdoors'. Note that all the air supplied to the vestibules are assumed to flow into the corridor in Eqn.(28) so the condition described by Eqns.(27)-(29) implies the condition in which the highest pressure rise is induced in the corridor.

<u>Pressure</u> The following relationship holds for pressures of the elevator shaft and corridor.

Elevator Shaft : $$P_E = P_C + \Delta P_{EC\,stop} \quad (30)$$

where ΔP_{ECstop} is the pressure difference for the smoke stop condition at the doorways between 'the elevator shaft and corridor'.

Equations for Flow Rates   The flow rates of each opening can be given by

Corridor and Fire room : $$m_{CR} = (\alpha A)_{CR}\sqrt{2\rho_C \Delta P_{CR}} \tag{31}$$

Corridor and Outdoors : $$m_{CO} = (\alpha A)_{CO}\sqrt{2\rho_C P_C} \tag{32}$$

Corridor and Outdoors (By-pass) : $$m_{CObp} = (\alpha A)_{CObp}\sqrt{2\rho_C P_C} \tag{33}$$

Elevator shaft and Corridor : $$m_{EC\,stop} = (\alpha A)_{EC}\sqrt{2\rho_E \Delta P_{EC\,stop}} \tag{34}$$

Elevator shaft and Outdoors : $$m_{EO} = (\alpha A)_{EO}\sqrt{2\rho_E P_E} \tag{35}$$

where, $(\alpha A)_{CObp}$ is the opening area of the by-pass between 'the corridor and outdoors'.

(2) Calculation method of the air supply rates to elevator shaft

The required air supply rates to the elevator shaft to keep smoke stop condition between 'the elevator shaft and corridor' even when the corridor pressure rises due to the closure of the door to the staircase can be obtained by the following procedures.

[Step 1] Select the effective opening area of by-pass equipped between 'the corridor and outdoors' $(\alpha A)_{CObp}$ arbitrarily. However, it should be born in mind that the corridor pressure rises high and the air supply rates to the elevator shaft increases as $(\alpha A)_{CObp}$ become small.

[Step 2] Calculate smoke stop condition between 'the elevator shaft and corridor.' The smoke stop pressure criterion between 'the elevator shaft and corridor' ΔP_{ECstop} is given by

$$\Delta P_{ECstop} = \frac{4}{9}(\rho_E - \rho_C) g\, h_{EC} \tag{36}$$

Substituting Eqn.(36) into Eqn.(34), one can obtain the flow rates m_{ECstop} corresponding to the smoke pressure stop criterion.

[Step 3] Calculate the pressures of the corridor P_C and elevator shaft P_E. With the relationship m_{CR}=m_{RO}, the flow rate between 'the corridor and fire room' m_{CR} can be given as follows:

$$m_{CR} = (\alpha A)_{ECRO}\sqrt{2\rho_C P_C} \tag{37}$$

where $(\alpha A)_{ECRO}$ is the effective area, which can be calculated by the following formula.

$$\sqrt{\rho_C}(\alpha A)_{ECRO} = \frac{1}{\sqrt{\dfrac{1}{\rho_C (\alpha A)_{CR}{}^2} + \dfrac{1}{\rho_R (\alpha A)_{RO}{}^2}}} \tag{38}$$

By substituting Eqn.(28),(32),(33) and (37) into Eqn.(27), the corridor pressure can be given by

$$P_C = \frac{(W_{L1} + W_{L2} + m_{EC\,stop})^2}{2\rho_C \{(\alpha A)_{ECRO} + (\alpha A)_{CO} + (\alpha A)_{CObp}\}^2} \tag{39}$$

The pressure of the elevator shaft P_E can be calculated by Eqn.(30).

[Step 4] Calculate the required air supply rates to the elevator shaft corresponding to the smoke stop criterion. Substituting Eqn.(35) into Eqn.(29), the required air supply rates to the elevator shaft W_E can be calculated by

$$W_E = m_{EC\,stop} + (\alpha A)_{EO}\sqrt{2\rho_E P_E} \tag{40}$$

CONCLUSIONS

1. There are two situations for the corridor at the stage of fully developed fire, Non Smoke Leak Situation (NSLS) and Smoke Leak Situation (SLS). The required air supply rates at SLS on Smoke Stop Threshold (SST) can be adopted for the required air supply rates in the smoke control design. This method has an advantage in determining required air supply rates, because adequate air supply rates can be obtained even though the actual scenario for opening condition of fire room doors are hard to obtain.

2. When the doors of staircases are closed, the corridor pressure rises higher than that predicted under the condition that the doors are open. In this case, smoke stop between 'the elevator shaft and corridor' may be lost. There are two ways to keep smoke stop between 'the elevator shaft and corridor', one is to install a by-pass opening between 'the corridor and outdoors', and the other is to increase the air supply rates to the elevator shaft. The required air supply rates to the elevator shaft may increase if the size of the by-pass opening is large.

3. The steps in design procedure for pressurization considering opening conditions of the doors of the fire room and staircases are listed below.

1) Obtain the open rate of the fire room that indicates SST.
2) Calculate the air supply rates to the vestibule and elevator shaft by the use of the open rate at SST on the side of SLS.
3) Define the size of the by-pass between 'the corridor and outdoors.'
4) Calculate the required air supply rate to the elevator shaft.
5) Check if the size of the by-bass and the air supply rates calculated are adequate or not.
6) Repeat the procedure of the steps 3)-5) if necessary, until the final air supply rate to the elevator shaft is obtained.

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NOMENCLATURE

Symbol

A_{ij}	opening area between 'space *i* and *j* '(m^2)
c	specific heat (kJ/kgK)
g	acceleration of gravity (m/s^2)
h_{ij}	height of opening between 'space *i* and *j* ' (m)
k	heat conductivity (kW/mK)
m_{ij}	flow rate through opening from space *i* to *j* (kg/s)
P_i	pressure of space *i* (Pa)
ΔP_{ij}	pressure difference at opening between 'space *i* and *j*' (Pa)
T_i	temperature of space *i* (K)
ΔT_i	rise of temperature of space *i* (K)
u_i	extraction rate in space *i* (kg/s)
W_i	air supply rates to space *i* (kg/s)
$(\alpha A)_{ij}$	effective area of opening between 'space *i* and *j* ' (m^2)
ρ_i	air density of space *i* (kg/m^3)

Subscript

O	outdoors
R	fire room
C	corridor
L	vestibule
S	staircase
E	elevator shaft
F	fire elevator shaft
stop	smoke stop criteria
normal	situation assumed that corridor temperature is normal
bp	by-pass opening
tot	total

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