

HAND CALCULATION METHOD FOR AIR SUPPLY RATES IN VESTIBULE PRESSURIZATION SMOKE CONTROL SYSTEM

M. Kujime

Nikken Sekkei Ltd, 4-6-2 Koraihashi, Chuo-ku, Osaka 541-8528, Japan

T. Matsushita

Kobe University, 1 Rokkodai-cho, Nada-ku, Kobe, Hyogo 657-8501, Japan

T. Tanaka

DRS, Disaster Prevention Research Institute, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

ABSTRACT

While vestibule pressurization smoke control systems are now popularly used in Japan in place of the smoke extraction methods prescribed in the Building Standards Law, it cannot be said that a rational method for determining the air supply rates required for achieving the smoke control goals has been well-established. As a result, computer simulation models are usually used as the means to estimate the air supply rates. It may not be inappropriate but it causes some difficulties for ordinary designers to try this smoke control system.

This paper proposes a practical design method of vestibule pressurization smoke control systems. This method comprehensively covers the fire scenarios corresponding to every stage of evacuation, namely fire room evacuation, fire floor evacuation and whole building evacuation. The required rates of air supply are determined to meet all the criteria imposed to verify the safety requirements at these three stages of evacuation. The calculation procedure in this method consists of a set of simple formulas for pressure and opening flow rates developed based on the average pressure difference concept so it can only be followed by the use of a hand calculator. This method is expected to help designers and engineers easily understand what and how to do to rationally and effectively design the smoke control system and to help building officials or whoever may concern with approval of the system know how to check its compliance.

1. INTRODUCTION

While only smoke extraction methods are prescribed in the existing government orders associated with the Building Standards Law, the vestibule pressurization smoke control method which directly pressurizes vestibules of staircases to prevent smoke infiltration into staircases is increasingly popular in Japan, particularly for high-rise office buildings, for which protection of staircases by vestibules is required by the government order [1]. This popularity seems to be attributed particularly to that the system allows more flexibility of floor layouts and more rentable space than the smoke extraction method. In addition, this smoke control system often accompanies pressurization of elevator shafts which aims at preventing smoke spread through the shafts. An example of smoke control system of real buildings [2] incorporating vestibule pressurization system is shown in Fig. 1.

The vestibule pressurization smoke control method was introduced by building industries and has been applied to a significant number of buildings to date in Japan. However, several problems can be seen, both logically and technically, in the design procedure of this system. They are:

- The target fire scenarios for the smoke control system are not clearly defined.
- A rational calculation method for estimating required air supply rates to vestibules and elevator shafts has not been well-established.
- Consideration for the fully-developed fire scenario is not sufficient.
- The theoretical bases of pressure difference criteria for smoke stopping across doorways is not solid.
- Use of computer models tends to make it extremely difficult to check if the contents of calculation are appropriate from the side of approving bodies.

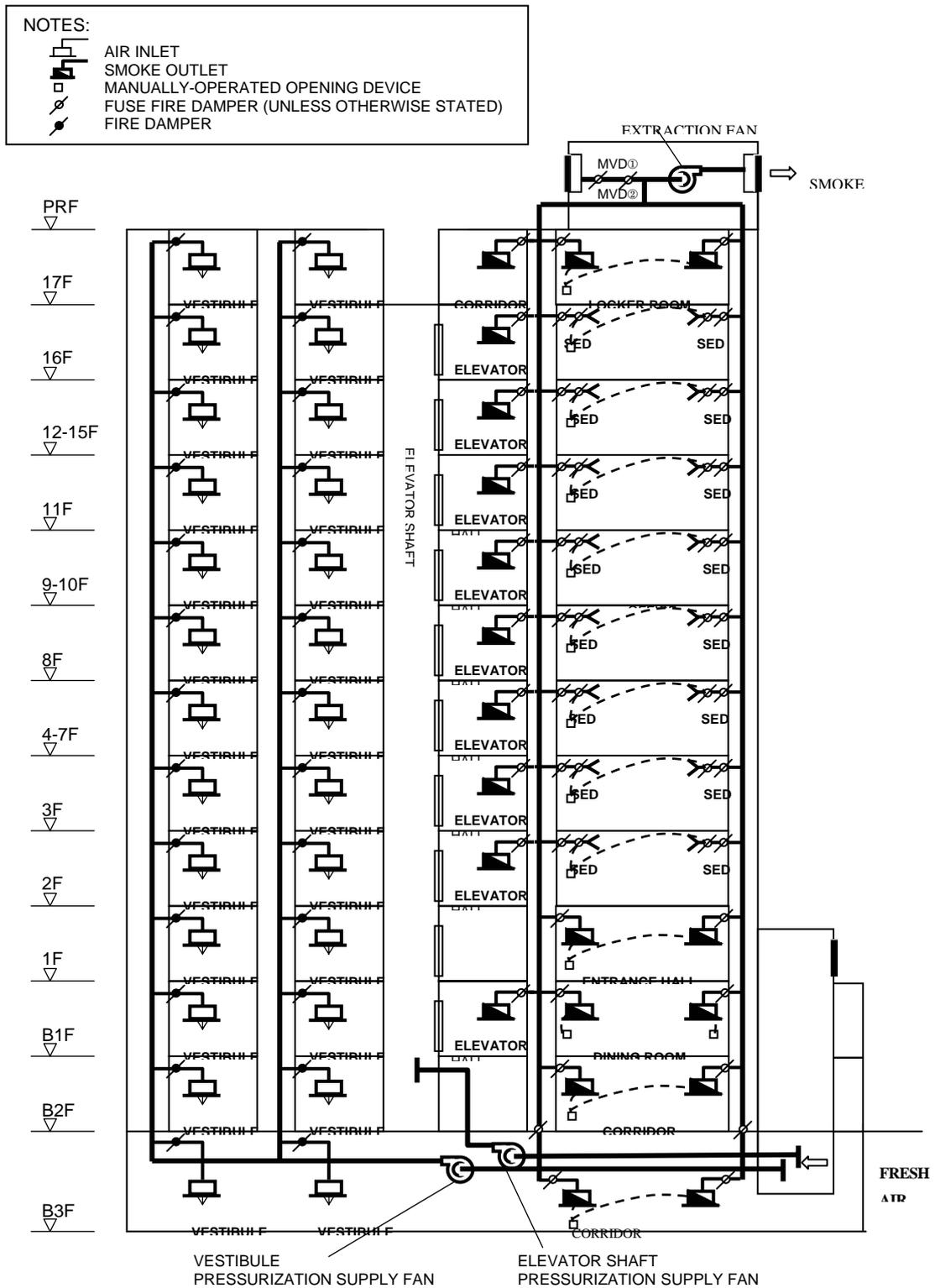


Fig. 1: Example of pressurization smoke control system

In Japan, the transition from the current prescriptive code to a performance-based code is expected in the near future. Once this happens, the verification of safety requirements needs to be possible not only for a limited number of experts but also for a large number of ordinary engineers and building officials. So, a logically clear and technically simple method will be indispensable in this particular problem of designing vestibule pressurization smoke control system as well.

In the method proposed in this paper, the scenarios of fire and evacuation of occupants to be considered and the safety criteria corresponding to the scenarios are clearly defined. Then, the procedure of calculations of the rates of air supply to vestibules and elevator shafts needed to meet the criteria are provided. The calculation procedure consists of a set of simple formulas, which is advantageous as the procedure can be followed by the use of a hand calculator.

2. OUTLINE OF THE SYSTEM

In this study, we consider high-rise office buildings where “special evacuation staircases” (smoke-proof towers) are required. Fig. 2 illustrates a typical floor plan of such office buildings.

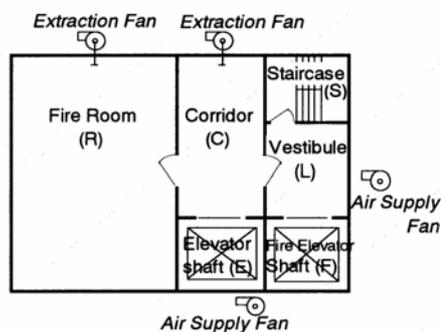


Fig. 2: A typical floor plan

Each floor has an office room, a corridor, a vestibule, a passenger elevator bank, a staircase and a fire elevator bank. These spaces are identified by R, C, L, E, S and F respectively, and the outdoor space is identified by letter O in this paper.

The office room is served by the corridor, which leads to the stairway by way of a vestibule. The bank of the passenger elevator faces the corridor. The vestibule has a role to protect the staircase and the fire elevator from smoke.

Mechanical pressurization is applied to the vestibule and to the shaft of the passenger elevators by separate fans. Mechanical smoke extractions are equipped in the room and the corridor, but will

be shut down when the temperature of the fuse of the fire damper installed where the smoke extraction duct crosses a fire wall rises to the melting point.

Needless to say, floor layouts of real buildings are a little more complex with multiple rooms, stairs, elevator banks and so forth. Nevertheless, the key features of the layouts seen in many office buildings are retained in Fig. 2 so that generic discussions on the pressurization smoke control system are still possible based on this simplified layout.

3. DEFINITIONS OF SCENARIOS, DESIGN FIRES AND SAFETY CRITERIA

3.1 Scenarios Corresponding to Each Stage of Evacuation

Like many other disasters, a fire is an event that is heavily influenced by accidental and stochastic factors. However, it is unavoidable that verification of the appropriateness of a fire safety system is only made under a limited number of selected scenarios because it is practically impossible to consider every condition that may take place by chance. Needless to say, it is desirable that the selected scenarios can cover as many conceivable conditions as possible, but bear in mind that ambitious attempts to cover extremely rare conditions may incur unbearable cost and technical difficulty in realizing the safety measure. The scenarios adopted here are from such point of view as follows:

3.1.1 General

- (a) It is assumed that a fire occurs in a room of the building. In other words, fires in the corridor, in the staircase and so forth are neglected.
- (b) Evacuation in the room of origin starts fairly early after the onset of fire since the occupants can directly recognize the hazardous situation.
- (c) Evacuation from the other rooms on the floor starts somewhat later, and evacuation of the whole building follows further later on since the occupants' perception of the hazard tend to be indirect.
- (d) The temperatures in the office room, the corridor and the vestibule are assumed to be the same at normal time. The outdoor temperature is different from the temperatures in these indoor spaces. The temperatures in the stairs and the elevator shafts are in

between the indoor and the outdoor temperatures.

- (e) Outdoor wind is not considered. (Note: If it is important, it is just easy to take into account the wind effect as long as the calculation is concerned.)

3.1.2 Fire room evacuation

- (a) The onset of fire room evacuation is expected to be at a fairly early stage because of the reason stated in the above.
- (b) It is assumed that the smoke control system has not yet been activated. So, fire room evacuation has to be completed before the room becomes untenable by the filling of smoke layer under no smoke extraction situation. (Note: In order to operate any smoke control system as early as at this stage, it will have to be activated by occupants themselves, but this is presumed to be unreliable.)

3.1.3 Fire floor evacuation

- (a) Fire floor evacuation is deemed to start when the first occupant enters the corridor from the fire room. Evacuation of the other rooms begins some time later.
- (b) The corridor is designed to be free from smoke during the fire floor evacuation.
- (c) The corridor is deemed free from smoke until the smoke layer in the fire room descends below the height of the soffits of the openings to corridor. The smoke control system is designed to be activated before the smoke layer in the room of origin descends below the soffits of the openings.
- (d) After the smoke control system has been actuated, the smoke is stopped at the doorway by making up necessary pressure difference by the combined effect of smoke extraction in the fire room and the pressurization to the vestibule and the elevator shafts.
- (e) The system is so designed as not to allow air flow toward the vestibule or the elevator shaft from the corridor for redundant safety, although theoretically, infiltration of smoke is not supposed to take place if the above condition (d) is met.

3.1.4 Whole building evacuation

- (a) Whole building evacuation is deemed to start when the first occupant gets into the staircase from the fire floor. Some time later, evacuation of the occupants on the other floors follows.

- (b) It is assumed that the fire has been fully developed so the windows in the fire room have been broken at this stage. (Note: If the windows have not broken, the fire will not grow to a fully-developed fire, so the conditions for the smoke control system will be reduced to those in the “Fire floor evacuation”.)
- (c) After all the occupants from the fire floor have entered the staircases, it is deemed to be sufficient to stop smoke between the corridor and the vestibule, and to support fire brigade operation and evacuation in staircase. At the same time, smoke is stopped between the corridor and the elevator shaft to prevent smoke spread to other floors. (Note: It will be practically too difficult to prevent smoke entering the corridor under the fully-developed fire situation.)
- (d) Both open and closed situations as illustrated in Fig. 3 are taken into account for the fire room doors, since the reliability of closing the doors is not always high. (Note: If they happen to be closed, the smoke extraction system is deemed to operate. If they happen to be open, the extraction fan may be shut down but the corridor pressure becomes close to outdoor pressure. So, in any case, it is not difficult to maintain necessary pressure differences between the corridor and the vestibule, and between the corridor and the elevator shaft. Incidentally, the extraction fan is not always necessary. It can be replaced by some other means for the corridor pressure relief.)

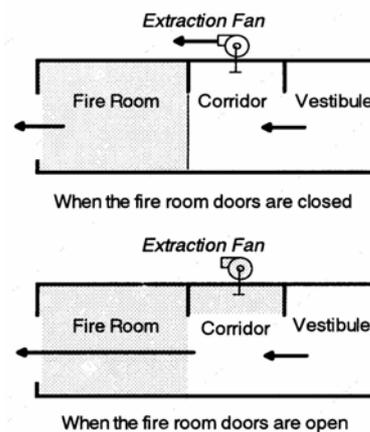


Fig. 3: Scenarios of extraction fan in corridor depending on opening condition

3.2 Design Fire

3.2.1 Heat release rate

The heat release rate of the design fire is assumed to grow as shown in Fig. 4.

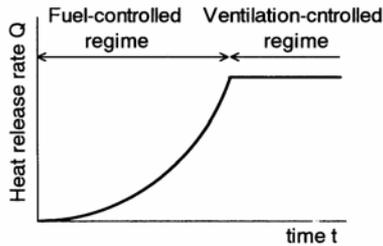


Fig. 4: Design fire in the room of origin

It initially increases in proportion to square of time as:

$$Q = Q_0 t^2 \quad (1)$$

where Q_0 is the coefficient concerning fire growth, but levels off after it reaches to the ventilation limit given as:

$$Q = 1,500 A_{RO} \sqrt{h_{RO}} \quad (2)$$

where $A_{RO} \sqrt{h_{RO}}$ is the ventilation factor of the room of origin.

3.2.2 Fire plume flow rate

The flow rate of fire plume is given by:

$$m_p \approx 0.07 Q^{1/3} z^{5/3} \quad (3)$$

where z is the height from the fire source.

3.3 Safety Criteria

In this study, the safety criteria are defined for the verification of the assurance of the safety of evacuation at each stage.

3.3.1 Fire room evacuation

The smoke layer height z in the fire room should satisfy the following condition [3] until the completion of the fire room evacuation so that the occupants are not exposed to smoke.

$$z > 1.6 + 0.1 H_R \quad (4)$$

where H_R is the ceiling height of the room.

3.3.2 Fire floor evacuation

The pressure difference $\Delta P_{CR}(z)$ across the fire room doorway open to the corridor by the operation of the smoke control system should satisfy:

$$\Delta P_{CR}(z) > 0 \quad (5)$$

to prevent smoke from entering the corridor, where h_{CR} is the height of the doorway.

In addition, the pressure differences between the vestibule and the corridor $\Delta P_{LC}(z)$ and between the elevator shaft and the corridor $\Delta P_{EC}(z)$ should satisfy:

$$\Delta P_{LC}(z) > 0 \quad \text{and} \quad \Delta P_{EC}(z) > 0 \quad (6)$$

respectively, in order to prevent smoke entering the vestibule and the elevator shaft should smoke stopping at the fire room doors fail.

3.3.3 Whole building evacuation

Although contamination of the corridor by smoke is accepted at this stage by the scenario stated in the above, in order to protect the vestibule and the elevator shaft from smoke, the pressure differences between the vestibule and the corridor $\Delta P_{LC}(z)$ and between the elevator shaft and the corridor $\Delta P_{EC}(z)$ should satisfy:

$$\Delta P_{LC}(z) > 0 \quad \text{and} \quad \Delta P_{EC}(z) > 0 \quad (7)$$

respectively, under the condition that the corridor temperature is elevated due to the entering of hot gases from the room of origin.

4. VERIFICATION OF SAFETY AND CALCULATION OF AIR SUPPLY RATES

4.1 Average Pressure Difference and Approximate Average Pressure Difference

In fire situations, large differences in temperature among different spaces may induce large pressure difference along the height of openings, which complicates the calculations of opening flow rates. In the method proposed in this paper, opening flow rates are calculated by the use of "average pressure difference" or further extended "approximate average pressure difference", of which the concepts are described in the appendices. The following equations are based on the "average pressure difference".

4.2 Fire Room Evacuation

The smoke layer height z at the time of completion of room evacuation t_{ER} as shown in Fig. 5 is calculated by the following formula for smoke filling prediction [4].

$$z = \left\{ \frac{2}{5} \times \frac{0.07}{A_R} Q_0^{1/3} t_{ER}^{5/3} + H_R^{-2/3} \right\}^{-3/2} \quad (8)$$

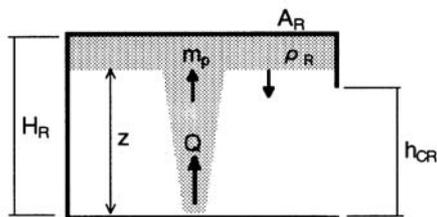


Fig. 5: Smoke layer height at the stage of the fire room evacuation

Hence, it follows that this z has to satisfy the criterion given by equation (4). Incidentally, calculation of the air supply rate is not involved in this safety verification because safety of the fire room evacuation must be assured under no smoke control situation according to the above scenario.

4.3 Fire Floor Evacuation

4.3.1 Average pressure difference and flow rate corresponding to smoke stop condition

The temperatures and the air density of the corridor (C), the vestibule (L) and the lower layer temperature of the fire room (R) are distinguished from each other in the following equations by the subscripts signifying the spaces for clarity, although they are assumed the same at the stage of fire floor evacuation.

As a conservative assumption, a steady fire having the same heat release rate as that at the time of completion of the fire floor evacuation t_{EFLR} is considered in the room, that is:

$$Q = Q_0 t_{EFLR}^2 \quad (9)$$

The smoke layer height in the fire room z may either be lower or higher than the soffit height of the doorway h_{CR} depending on the designed smoke extraction rate as shown in Figs. 6a and 6b.

4.3.1.1 When the smoke layer is lower than the doorway height ($z < h_{CR}$)

Based on the steady state fire assumption, the following relationship holds for the mass conservation of the room as follows:

$$m_p = U_R = m_{CR} - m_{RO} \quad (10)$$

where m_p and U_R are the plume flow rate at the height of the layer interface and the smoke

extraction rate in the fire room respectively, m_{CR} and m_{RO} are the flow rates from the corridor to the fire room and from the fire room to outdoor respectively.

Also, regarding the heat conservation, we have:

$$Q = C_p m_p (T_f - T_R) + h \{ A_R + D_R (H_R - z) \} (T_f - T_R) \quad (11)$$

where T_f and T_R are the smoke layer and the room temperatures respectively. A_R , H_R and D_R are the floor area, the ceiling height and the perimeter of the room respectively, and C_p and h are the specific heat of air at constant pressure and the total heat transfer coefficient. In the second term on the right hand side of equation (11) expressing the heat transfer from the smoke layer to the room boundary, the temperature rise of the boundary surface is neglected for simplicity. A sufficiently conservative estimate of the fire behavior will be obtained by this treatment since the discussion here is confined to the early stage of fire and the heat release rate is taken as the maximum during the evacuation.

Using these relationships, the doorway flow rate and the average pressure difference to stop smoke at the doorway can be obtained by sequentially following the procedure (4.3.1.1-1)-(4.3.1.1-6):

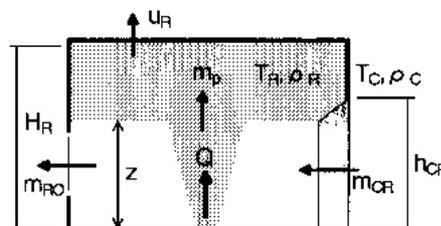


Fig. 6a: Flow patterns in the fire room at the stage of fire floor evacuation when $z < h_{CR}$

(4.3.1.1-1) Arbitrarily choose the value of either smoke layer height z or mechanical extraction rate u_R provided that:

$$U_R < 0.07 Q^{1/3} h_{CR}^{5/3} \quad (12)$$

(4.3.1.1-2) Calculate the other that was not chosen in (4.3.1.1-1) using the following equations :

$$m_p = 0.07 Q^{1/3} z^{5/3} \quad (13)$$

and

$$\text{Vestibule (L): } W_L = m_{LC} + m_{LS} + m_{LF} \quad (26)$$

$$\text{Elevator shaft (E): } W_E = m_{EC} + m_{EO} \quad (27)$$

where m , U and W denote the rate of the opening flow, the smoke extraction and the air supply respectively. The subscripts of single letter R, C, L, O, etc., identify the space at which the mechanical ventilation is applied and the subscripts of double letters CR, RO, LS, etc., signify the direction of the opening flow.

4.3.3 Calculation procedure for air supply rates

Based on the above relationships, the air supply rates to the vestibule and the elevator shaft necessary to satisfy the smoke stop criterion set by equation (5) can be calculated by the procedure as follows:

(4.3.3-1) Determine the smoke extraction rate in the fire room u_R and calculate the doorway flow rate m_{CR} and the average pressure difference ΔP_{CR} corresponding to the smoke stop condition at the doorway between the fire room and the corridor based on the method described in 3.3.1.

(4.3.3-2) Calculate the fire room pressure as:

$$P_R (= \Delta P_{RO}) = \begin{cases} \frac{m_{RO}^2}{2\rho_R (\alpha A)_{RO}^2} & (m_{RO} \geq 0) \\ -\frac{m_{RO}^2}{2\rho_O (\alpha A)_{RO}^2} & (m_{RO} < 0) \end{cases} \quad (28)$$

where $m_{RO} = m_{CR} - U_R$

(4.3.3-3) Calculate the corridor pressure by:

$$P_C = P_R + \Delta P_{CR} \quad (29)$$

(4.3.3-4) Calculate the air leak from the corridor to the outdoor by:

$$m_{CO} = \begin{cases} (\alpha A)_{CO} \sqrt{2\rho_C |P_C|} & (P_C \geq 0) \\ -(\alpha A)_{CO} \sqrt{2\rho_O |P_C|} & (P_C < 0) \end{cases} \quad (30)$$

where $(\alpha A)_{CO}$ is the effective opening area between the corridor and the outdoor.

(4.3.3-5) Determine the flow rates from the vestibule to the corridor and from the elevator shaft to the corridor so as to satisfy equations (31) and (32):

$$m_{LC} + m_{EC} = m_{CR} + m_{CO} \quad (31)$$

and

$$m_{LC} > 0 \quad \text{and} \quad m_{EC} > 0 \quad (32)$$

There is a certain degree of freedom in the choice of the values of m_{LC} and m_{EC} . Note, however, this choice eventually affects the air supply rates to the vestibule and the elevator shaft.

(4.3.3-6) Calculate the average pressure differences between the vestibule and the corridor ΔP_{LC} and between the elevator shaft and the corridor ΔP_{EC} by:

$$\Delta P_{LC} = \frac{m_{LC}^2}{2\rho_L (\alpha A)_{LC}^2} \quad \text{and} \quad \Delta P_{EC} = \frac{m_{EC}^2}{2\rho_E (\alpha A)_{EC}^2} \quad (33)$$

respectively.

(4.3.3-7) Calculate the vestibule pressure P_L by:

$$P_L = P_C + \Delta P_{LC} \quad (34)$$

(4.3.3-8) Calculate the air leak from the vestibule to the staircase and to the fire elevator shaft using the vestibule pressure P_L , the air leak from the vestibule to the staircase m_{LS} can be calculated by:

$$m_{LS} = \frac{(\alpha A)_{LS} (\alpha A)_{SO} \sqrt{2\rho_L \rho_S}}{\sqrt{\rho_L (\alpha A)_{LS}^2 + \rho_S (\alpha A)_{SO}^2}} \sqrt{P_L + |\rho_S - \rho_O| g H_{LS}} \quad (35)$$

where $(\alpha A)_{LS}$ and $(\alpha A)_{SO}$ are the effective opening areas between the vestibule and the staircase and between the staircase and the outdoor, respectively, H_{LS} is the vertical distance between these openings.

Likewise, the air leak from the vestibule to the fire elevator m_{LF} can be calculated by:

$$m_{LF} = \frac{(\alpha A)_{LF} (\alpha A)_{FO} \sqrt{2\rho_L \rho_F}}{\sqrt{\rho_L (\alpha A)_{LF}^2 + \rho_F (\alpha A)_{FO}^2}} \sqrt{P_L + |\rho_F - \rho_L| g H_{LF}} \quad (36)$$

where $(\alpha A)_{LF}$ and $(\alpha A)_{FO}$ are the effective opening areas between the vestibule and the fire

elevator shaft and between the fire elevator and the outdoor, respectively. H_{LF} is the vertical distance between these openings.

(4.3.3-9) Calculate the required air supply rate to the vestibule W_L by:

$$W_L = m_{LC} + m_{LS} + m_{LF} \quad (37)$$

(4.3.3-10) Calculate the elevator shaft pressure at the level of the fire floor by:

$$P_E = P_C + \Delta P_{EC} \quad (38)$$

(4.3.3-11) Calculate the air leak from the elevator shaft to the outdoor m_{EO} by:

$$m_{EO} = (\alpha A)_{EO} \sqrt{2\rho_E (P_E + |\rho_E - \rho_o| g H_{CE})} \quad (39)$$

where $(\alpha A)_{EO}$ is the effective opening between the elevator shaft and the outdoor, H_{CE} is the vertical distance of the opening between the corridor and the elevator shaft and the opening between the shaft and the outdoor.

(4.3.3-12) Calculate the required air supply rate to the elevator shaft W_E by:

$$W_E = m_{EC} + m_{EO} \quad (40)$$

4.4 Whole Building Evacuation

4.4.1 Average pressure difference and the flow rate corresponding to smoke stop criterion

4.4.1.1 Determination of temperature conditions

At the stage of whole building evacuation, a fully-developed fire is considered in the fire room and the corridor may be exposed to hot gases from the fire room. Accordingly, the temperature in the corridor is no longer the same as that of the vestibule. At this stage, the corridor is abandoned and only the vestibule and the elevator shafts are protected from smoke. The temperatures of the fire room and the corridor need to be first assessed to obtain the smoke stop conditions at the openings from the corridor to the vestibule and to the elevator shaft. It can be done using some appropriate means such as the simple formulas proposed by Tanaka et al. [5].

4.4.1.2 Smoke stop criteria

Once the corridor temperature is given, the average pressure differences ΔP_{LC} and doorway flow rates m_{LC} corresponding to smoke stop criteria between

the vestibule and the corridor, and ΔP_{EC} and m_{EC} between the elevator shaft and the corridor are given by:

$$\Delta P_{LC} = \frac{4}{9} \Delta \rho_{LC} g h_{LC} \quad \text{and} \quad m_{LC} = \frac{2}{3} (\alpha A)_{LC} \sqrt{2\rho_L g \Delta \rho_{LC} h_{LC}} \quad (41)$$

$$\Delta P_{EC} = \frac{4}{9} \Delta \rho_{EC} g h_{EC} \quad \text{and} \quad m_{EC} = \frac{2}{3} (\alpha A)_{EC} \sqrt{2\rho_E g \Delta \rho_{EC} h_{EC}} \quad (42)$$

4.4.2 Relationships used for the calculation of required air supply rates

Fig. 8 illustrates the flow patterns expected at the stage of whole building evacuation.

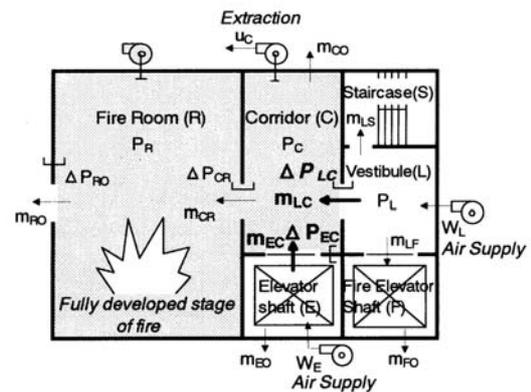


Fig. 8: Flow patterns at the stage of whole building evacuation

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

4.4.2.1 Pressures

$$P_C = P_R + \Delta P_{CR} \quad (43)$$

$$P_L = P_C + \Delta P_{LC} \quad (44)$$

$$P_E = P_C + \Delta P_{EC} \quad (45)$$

4.4.2.2 Flow rates

$$\text{Fire room (R): } m_{CR} = m_{RO} \quad (46)$$

$$\text{Corridor (C): } m_{LC} + m_{EC} = m_{CR} + m_{CO} + U_C \quad (47)$$

$$\text{Vestibule (L): } W_L = m_{LC} + m_{LS} + m_{LF} \quad (48)$$

$$\text{Elevator shaft (E): } W_E = m_{EC} + m_{EO} \quad (49)$$

4.4.3 Calculation procedure for air supply rates

Based on the above relationship, the air supply rates required to meet the smoke stop criteria given

by equations (41) and (42) can be calculated by the following procedure:

(4.4.3-1) Determine the flow rates and the average pressure differences between the vestibule and the corridor, i.e. m_{LC} and ΔP_{LC} , and between the elevator shaft and the corridor, i.e. m_{EC} and ΔP_{EC} , by equations (41) and (42) according to the procedure described in 4.4.1.

(4.4.3-2) Calculate the corridor pressure P_C by:

$$P_C = \frac{(m_{LC} + m_{EC} - U_C)^2}{2 \rho_c (\alpha A)_{co}^2} \quad (50)$$

where $(\alpha A)_{co}$ is the effective opening area calculated by combining the series or parallel openings which connect the corridor to the outdoor. Note, if the corridor temperature becomes so high that the smoke extraction is shut down, which may occur when the door between the fire room and the corridor is left open, P_C is calculated by letting U_C be 0.

(4.4.3-3) Calculate the average pressures of the vestibule

Now that the pressure difference for smoke stop conditions and the corridor pressure have been obtained, the pressures of the vestibule P_C can be obtained as :

$$P_L = P_C + \Delta P_{LC} \quad (51)$$

(4.4.3-4) Calculate the air leak from the vestibule to the staircase and to the fire elevator

The procedure to calculate the air leak from the vestibule to the staircase m_{LS} and to the fire elevator m_{LF} is exactly the same as (4.3.3-8).

(4.4.3-5) Calculate the air supply rate to the vestibule by :

$$W_L = m_{LC} + m_{LS} + m_{LF} \quad (52)$$

(4.4.3-6) Calculate the average pressure of the elevator shaft at the level of the fire floor P_E by:

$$P_E = P_C + \Delta P_{EC} \quad (53)$$

(4.4.3-7) Calculate the air leak from the elevator shaft

The procedure to calculate the air leak from the elevator shaft to the outdoor m_{EO} is exactly the same as (4.3.3-11).

(4.4.3-8) Calculate the air supply rate to the elevator shaft by:

$$W_E = m_{EC} + m_{EO} \quad (54)$$

4.5 Final Determination of the Air Supply Rates and Pressure Relief Vents

4.5.1 Adjustment of the air supply rates for fire floor and whole building evacuation

Since the smoke stop criteria are different between fire floor evacuation and the whole building evacuation, the results of the required air supply rates are different accordingly between the two stages of evacuation. But practically, the same fan is used in both stages, so the air supply rates should be adjusted to the same rate to cope with any stage of evacuation. This adjustment can be done to obtain the final flow rates as follows:

Letting the flow rates from the vestibule to the corridor and from the elevator shaft to the corridor obtained for fire floor evacuation be m_{LC1} and m_{EC1} , respectively, and those for whole building evacuation be m_{LC2} and m_{EC2} , respectively, the flow rates from the vestibule to the corridor m^*_{LC} and from the elevator shaft to the corridor m^*_{EC} are finally determined so as to satisfy:

$$m^*_{LC} + m^*_{EC} \geq m_{LC1} + m_{EC1} \quad (55)$$

$$m^*_{LC} \geq m_{LC2} \quad \text{and} \quad m^*_{EC} \geq m_{EC2} \quad (56)$$

Using the determined m^*_{LC} and m^*_{EC} , calculate the air supply rates to the vestibule W_L and to the elevator shaft W_E according to the same procedure described in "4.3 Fire Floor Evacuation."

4.5.2 Designing of bypass pressure relief vents

In the above, the condition of the doors between the vestibule and the corridor and between the vestibule and the staircase were not mentioned but the air supply rates may be calculated under the condition that all the doors are fully open in order to cope with the worst scenario for the air supply rates. As a result, the pressure rise may become too high for occupants to open a door when the doors happen to be closed. Therefore, adequate pressure relief should be considered. In addition, if the corridor pressure exceeds the elevator shaft pressure, the criterion set by equation (6) is violated. So, adequate pressure relief vents may be needed between the corridor and the vestibule and between the corridor and the outdoor. However, the details of the design of pressure relief vent is omitted in this paper.

Fig. 9 illustrates the procedure for determining the air supply rates in pressurization smoke.

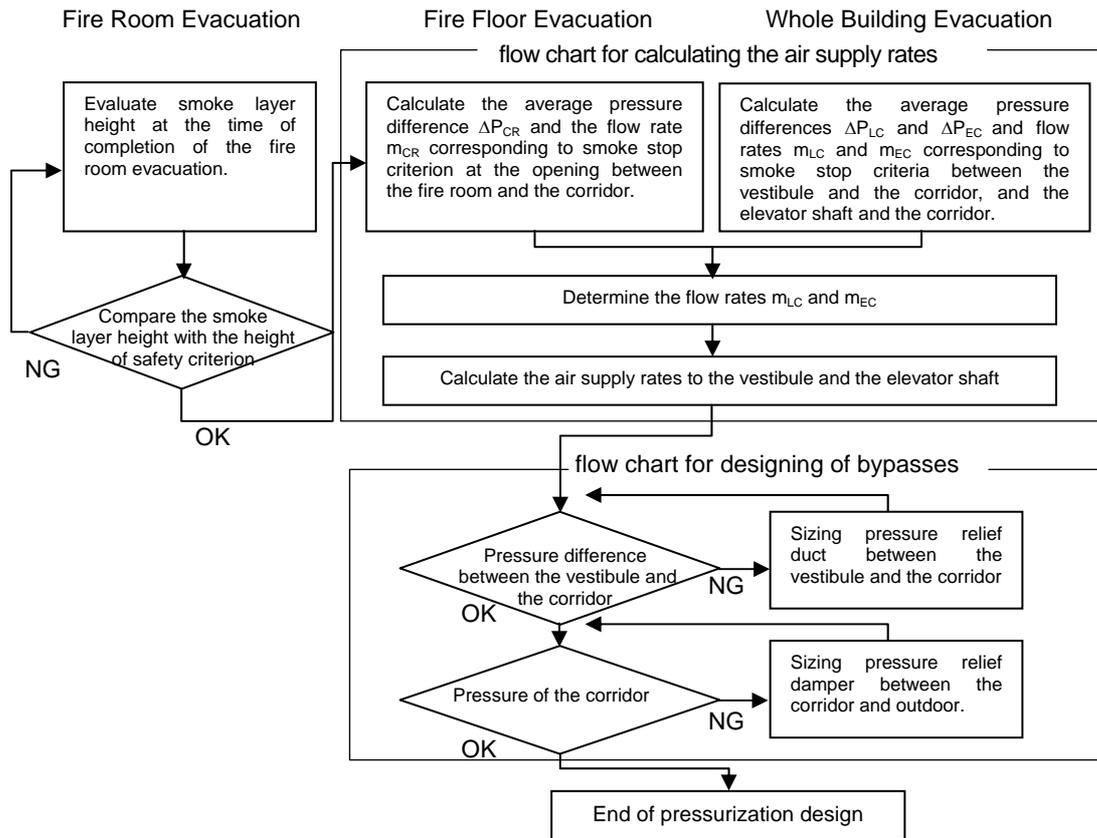


Fig. 9: Procedure for determining air supply rates in pressurization smoke control system

5. COMPARISON WITH COMPUTER MODEL PREDICTION

The accuracy of the simple method in this paper was investigated by the comparison with the prediction by a computer model. The computer model was constructed by incorporating the function to the smoke stop criteria into an existing one-layer zone multi-room smoke movement program developed by Matsushita [6].

The conditions of the building for simulation are summarized below.

Building : 10-story office building (The plan is referred to Figure 2.)

Height of floor : 3.5m

Fire floor : Second story

Opening condition:

Doors of the fire room, windows of the fire room (15% of all), doors to the vestibule and stairwell on the fire floor, ground floor door to the outside are open, and others are all closed. Each leak from the elevator shaft and

the stairwell to the outdoor is considered as an opening at the top of those shafts.

Temperature:

The computer model case was simulated with 10°C for outdoor, 20°C for room, 18°C for corridor and 15°C for the other shafts as the initial temperatures in winter. Outdoor wind is not considered.

The simple method case was calculated in fully-developed stage of fire with temperature 600°C for the fire room, 100°C for corridor and 15°C for the shafts.

As shown in Fig. 10, the required air supply rates calculated by the simple method proposed in this paper are reasonably close to the computer prediction both for the vestibule and the elevator shaft. The errors are approximately 3% for vestibule and 20% for elevator shaft. Besides, the results of the simple method are always larger than those of the computer model, that is, the simple method always calculates the required air supply rate for safety side.

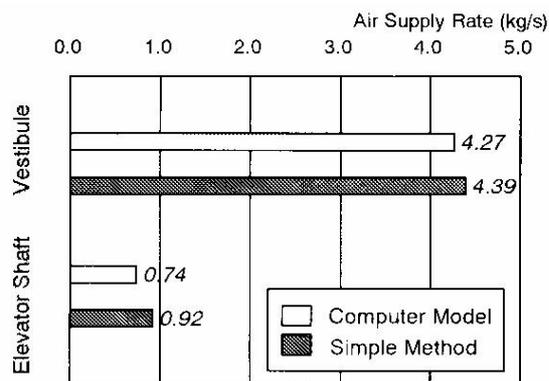


Fig. 10: Comparison of the required air supply rates

6. CONCLUSION

Although determining the air supply rates is a very important process in the design of vestibule and elevator shaft pressurization smoke control system, a rational calculating method for the air supply rates has not yet been established in Japan. This paper intended to propose a logically clear and technically simple method to solve the problems.

As a result, this calculation method has the following advantages: all the fire scenarios including evacuation at fully developed fire can be taken into account for fire safety criterion, the base of pressure difference criterion for smoke stopping is logically and technically clear, and the procedures of this method consisting of simple formulas make it possible to check the contents of calculation and the verification of safety requirement even for ordinary designers or building officials.

The comparison between the simple method in this paper and the computer model indicates that the simple method is almost as accurate as the computer model. This calculation method for the air supply rates is considered to be useful in the design practice of vestibule pressurization smoke control system.

ACKNOWLEDGEMENT

This paper was supported by the members of Pressurization Smoke Control System Research Committee of the Kinki branch, the Architecture Institute of Japan. The authors gratefully acknowledge their informative inputs.

NOMENCLATURE

Symbols

- A_i space area (m^2)
- A_{ij} opening area between space i and space j (m^2)
- B_{ij} width of opening between space i and space j (m)
- D_i circumference length of space (m)
- g acceleration of gravity (ms^{-2})
- H_i ceiling height of space i (m)
- h_{ij} height of opening between space i and space j (m)
- h heat transfer coefficient ($kWm^{-2}K^{-1}$)
- m_{ij} flow rate through the opening from space i to space j (kgs^{-1})
- P_i pressure of space i (Pa)
- ΔP_{ij} pressure difference across opening between space i and space j (Pa)
- Q heat release rate (kW)
- T_i temperature of space i (K)
- t evacuation time (s)
- U_i extraction rate in space i (kgs^{-1})
- W_i air supply rate to space i (kgs^{-1})
- z height of smoke layer (m)
- $(\alpha A)_{ij}$ effective flow coefficient and area of opening between space i and space j (m^2)
- ρ_i air density of space i (kgm^{-3})
- $\Delta\rho_{ij}$ air density difference across opening between space i and space j (kgm^{-3})

Subscripts

- O outdoor
- R fire room
- C corridor
- L vestibule
- S staircase
- E elevator shaft
- F fire elevator shaft
- f upper layer

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APPENDIX 1: AVERAGE PRESSURE DIFFERENCE

In many building fire issues, it is necessary to consider multiple spaces at very different temperatures, which make it complicated to calculate mass flow rate through openings. To avoid this complexity, average pressure difference is used for the calculation of doorway flow rates.

(1) Definition of average pressure difference

Letting m_{net} be the net gas flow rate, average pressure difference is defined as:

$$\Delta P = \frac{m_{net}^2}{2\rho(\alpha A)^2} \quad (A1)$$

This definition indicates that only the net flow rate through opening is the target of interest and intends to use the ordinary formula for orifice flow rate to calculate the net opening flow rate using regardless the conditions of temperatures and neutral plane height at an opening, that is:

$$m_{net} = \alpha A \sqrt{2\rho \Delta P} \quad (A1a)$$

(1) Average pressure difference and flow pattern

Whenever necessary, actual patterns of pressure difference and flow can be obtained from the average pressure difference, since they are corresponding to each other as follows:

Letting s be the ratio of neutral plane height to opening heights,

(a) when $s \geq 1$

The net opening flow rate m_{net} under different space temperatures is normally calculated by:

$$m_{net} = m_1 = \frac{2}{3} \alpha B \sqrt{2\rho_0 g \Delta \rho} h^{\frac{3}{2}} \left\{ s^{\frac{3}{2}} - (s-1)^{\frac{3}{2}} \right\} \quad (A2)$$

where h is the opening height, $\Delta \rho$ is the difference of air density in the spaces connected by the opening (let they be 0 and 1), that is $\Delta \rho = |\rho_0 - \rho_1|$ and s is the ratio defined as $s = z_n / h$ where z_n is the neutral plane height above the lower edge of the opening.

On the other hand, using the average pressure difference defined above, m_{net} can also be given by:

$$m_{net} = \alpha A \sqrt{2\rho_0 \Delta P} \quad (A3)$$

Equating equations (A2) and (A3) leads to the following equation (A4), in which actual pattern of opening flow corresponding to average pressure difference ΔP can be obtained by solving equation (A4) for s .

$$s^{\frac{3}{2}} - (s-1)^{\frac{3}{2}} = \frac{3}{2} \sqrt{\frac{\Delta P}{\Delta \rho g h}} \quad (A4)$$

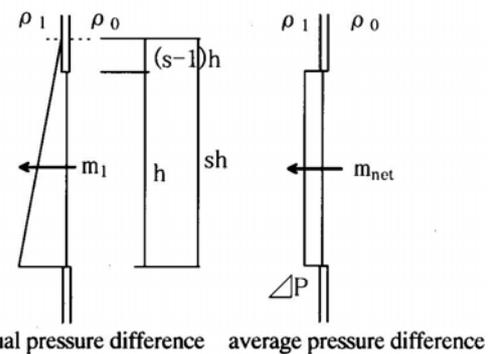


Fig. a1: Concept of average pressure difference when $s \geq 1$

(b) when $s_N \leq s < 1$

Likewise, from the following equations (A5) and (A6):

$$m_{net} = m_1 - m_2 = \frac{2}{3} \alpha B \sqrt{2\rho_0 g \Delta \rho} h^{\frac{3}{2}} \left\{ s^{\frac{3}{2}} - (\rho_1 / \rho_0)^{\frac{1}{2}} (1-s)^{\frac{3}{2}} \right\} \quad (A5)$$

and

$$m_{net} = \alpha A \sqrt{2\rho_0 \Delta P} \quad (A6)$$

the equation which gives the relationship between ΔP and s is obtained as follows:

$$s^{\frac{3}{2}} - (\rho_1 / \rho_0)^{\frac{1}{2}} (1-s)^{\frac{3}{2}} = \frac{3}{2} \sqrt{\frac{\Delta P}{\Delta \rho g h}} \quad (A7)$$

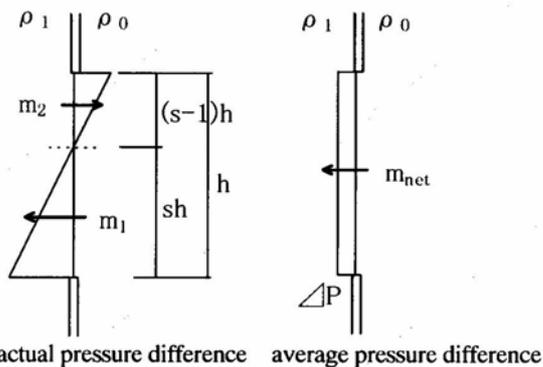


Fig. a2: Concept of pressure difference when $s_N \leq s < 1$

where s_N is the value of s when the in- and out-flows are balanced at the opening.

$$s_N = \frac{1}{1 + (\rho_o/\rho_i)^{1/3}} \quad (A8)$$

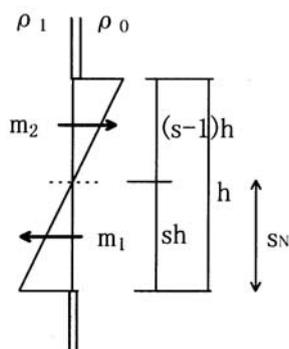


Fig. a3: Flows when the in- and out-flows are balanced at the opening ($m_1 = m_2$)

Similarly, the equations for the relationship of ΔP and s for the cases of (c) $0 \leq s < s_N$ and (d) $s < 0$ can be developed if necessary.

(2) Smoke stop condition

Substituting $s = 1$ into equations (A2) and (A3) yields required smoke stop condition at the opening in terms of average pressure difference and flow rate respectively:

$$\Delta P = \frac{4}{9} \Delta \rho g h \quad \text{and} \quad m_{net} = \frac{2}{3} \alpha B \sqrt{2 \rho_o g \Delta \rho h^3} \quad (A9)$$

APPENDIX 2: APPROXIMATE AVERAGE PRESSURE DIFFERENCE

It is known that the pressure difference at the middle height of an opening is sufficiently close to the average pressure difference over the opening in

many cases. Taking this fact into account, the approximate average pressure difference across an opening is defined here as the pressure difference at the height of neutral plane when the in- and out-flows are balanced at the opening. This definition assures that the net gas flow rate is zero when the approximate average pressure difference is zero.

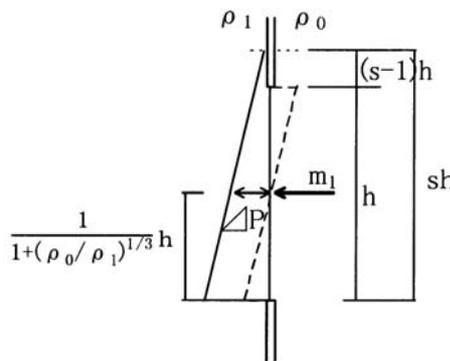


Fig. a4: Concept of approximate average pressure difference

Hence, the approximate average pressure difference is calculated by:

$$\Delta P = \Delta \rho g h |s - s_N| \quad (A10)$$

Approximate net opening flow rate is calculated using the approximate average pressure difference as:

$$m_{net} = \begin{cases} \alpha A \sqrt{2 \rho_o \Delta P} & (s \geq s_N) \\ \alpha A \sqrt{2 \rho_i \Delta P} & (s < s_N) \end{cases} \quad (A11)$$

The approximate net flow rate given by equation (A11) is very close to the exact net flow rate when $s > 1$ and $s < 1$ while the accuracy is only fair when $0 < s < 1$ except when $s = s_N$. However, the absolute value of the net flow rate is small in the latter case, so the effect of the error on the calculation can be neglected.