A Study on the Characteristics of Smoke Control Using Lower Part Pressurization with an Opening in a Large Scale Space

Ju, Hyeon-don · Ahn, Dae-young

Abstract

Smoke control systems of an atrium keep occupants safe from smoke generated during unwanted fires. The two-zone layer interface of the atrium is clearer than small room or corridor. Smoke control in large spaces are achieved using pressurization of the lower layer by mechanical ventilation. The objective of this study are to calculate the inflow and outflow mass rates through the upper and lower opening of the atrium, to study the lower part pressurization with or without the lower opening of the atrium, and to predict the steady-state smoke layer height which the mass outflow rate through the upper opening is more or less equal to the mass rate of fire plume. The smoke layer height are analyzed by FDS developed by the National Institute of Standard and Technology, USA. The part of analyzed results by FDS are compared with the experimental results performed by Yamana and Tanaka. It is known that the lower part pressurization smoke control for the mass flow of the lower opening directing into the atrium from outside were superior to the smoke control directing into the outside from the atrium.

Key words : Atrium, Pressurization, Smoke control, Mechanical ventilation

요 지

아트리움의 제연시스템은 예기치 못한 화재가 발생할 경우에 생성되어지는 연기로부터 거주자를 안전하게 보호하는 기능을 한다. 아트리움 등 대형공간은 하부 차가운 공기층과 상부 뜨거운 연기층의 경계가 작은 방이나 복도보다도 확실하게 나타난다. 본 논문의 목적은 아트리움의 상하 개구부를 통하는 나가고 들어오는 차가운 공기와 연기의 질량유량을 계산하고, 아트리움의 하부 개구부의 유무에 따른 하부 가압 제연방식을 연구하고, 나아가 풀룸의 유량과 상부 개구부로 흐르는 유량이 거의 유사한 정상상태일 때 연기 층의 높이를 예상하는데 있다. 그리고 미국의 국립표준기술국에 의해 개발된 FDS 소프트웨어에 의해 연기 층의 높이를 해석하였다. FDS에 의해 해석된 일부 결과들은 Yamana와 Tanaka 등에 의해 수행된 실험결과들과 비교하였다. 본 연구에 의해 하부 개구부의 질량유량이 외부 환경으로부터 아트리움 내로 흐를 경우가 아트리움 내로부터 외부로 흐를 경우보다 우수한 제연 효과를 나타냄을 알 수 있었다.

핵심용어 : 아트리움, 가압, 연기제어, 기계환기

1. Introduction

In a building an atrium is considered as a large space with openings. The atrium is found in hotels, commercial buildings, and shopping malls. Smoke control systems of the atrium keep occupants safe from smoke generated during unwanted fires. In the atrium most of cooling air through lower opening entrain at the edge of the plume of a fire. Perhaps the smoke layer is at the upper level and the cooling air layer is the lower level of the atrium. The layer interface of the atrium is clearer than small room or corridor. Atrium smoke control and smoke control in similar large spaces are achieved using ventilation system, pressurization

system and pressurization and extraction system. Difference in smoke removal rate among the above three smoke control systems was small when an opening was closed (Park, 2003). The smoke production rate (and the required exhaust rate) for the fire in the atrium increases as the heat release rate of design fire increases. Therefore, establishment of design fire is the critical step in design of atrium smoke control systems.

Full scale smoke control experiments have been conducted to investigate the smoke filling behaviors in a large scale space under various smoke control conditions. The experimental results served as the validation study of the simple analytical theories, for example, two-zone model.

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The basic idea of lower part pressurization with a lower opening is to increase the smoke exhaustion efficiency of the vents equipped at the upper part of a space by increasing the internal pressure of the space (Yamana and Tanaka, 1985). Calculations have been made for situations where Yamana and Tanaka did not calculate the increase in depth with time (Hinkley, 1988). An overview of the principal design considerations of smoke management systems for covered malls and atria was provided by SFPE Handbook (Milke, 2002). The pressurization system of a room with openings showed less smoke removal rate than the ventilation system and the pressurization and extraction system, and is not recommended for large scale spaces with large openings (Park, 2003). There might be exchange mass flow rate across the interface of smoke layer and cooling air layer in an atrium when a mechanical smoke exhaust system is operating. The mass flow rate across the smoke layer interface can be 30% of the mass exhaust rate of the exhaust system (Chow *et al.*, 2006). The effects of various make-up air supply arrangements and velocities in an atrium smoke management system are examined. Disturbing the fire and smoke plume results in a significant increase in the smoke production rate, as evidenced by a deeper smoke layer (Kerber and Milke, 2007). The effects of vent location, outside temperature, wind velocity and fire size on the performance of natural venting of the vertical vent were numerically investigated using CFAST. The larger fire size becomes, the more mass flow rate through a vent becomes, but the lower interface height of smoke layer becomes (Jeon *et al.*, 2008). Natural smoke exhaust method is preferred when the exhaust vents are located at the ceiling of the atrium. When the smoke exhaust vents are located on the walls of the atrium, the higher positions of the exhaust vents are preferred. And the descending process of the smoke layer is the slowest when the fire source is at the corner of the atrium (Qin *et al.*, 2009). The inflow and outflow mass rates through the doorway located between a burn room and an adjacent room have been researched to predict the neutral-plane of the doorway in the stratified fire cases of the two-room's enclosure (Ju and Kim, 2012).

Because of the size of the atrium, it is difficult to conduct experiments about smoke control system. Therefore in the large spaces, numerical simulation method play an important role in researching smoke movement and fire phenomena. The one model of the simulation method is two-zone model dividing the fire room into a cooling air layer and a smoke layer. The layers have different uniform properties respectively. The other model is the field model (Computational Fluid Dynamics model) using finite difference method. In our paper the Numerical simulations are performed through the FDS (Version 5.3) computer code developed by NIST. The FDS is a Computational Fluid Dynamics

(CFD) model of fire-driven fluid flow. The FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. The partial derivatives of the conservation equations of mass, momentum, and energy are approximated by the finite difference method. Turbulent motions are separated into large and small eddy motions in LES. Turbulent eddies that account for most of the large scale motion are large enough to be calculated with sufficient accuracy from the equations of the fluid mechanics. Therefore motion of large eddies is simulated directly, but the small-scale eddy motion is approximated by means of the Smagorinsky form. Two combustion models are used in the FDS. Diffusion of fuel and oxygen are modeled directly for DNS with global one-step, finite-rate chemical reaction. The model is based on the assumption that the combustion is mixing-controlled and that the reaction of fuel and oxygen is infinitely fast (McGrattan *et al.*, 2009; Guan and Kwok, 2009). The schematic drawing of the computational geometry is shown in Fig. 4, which has been made possible by Smokeview, a post-processor graphical-user-interface application (Forney, 2008).

In the natural venting system of the atrium or the lower part pressurization without the lower opening, the outflow mass flow rate through the upper opening is more or less equal to the inflow rate through the fan, but the outflow rate is unequal to the inflow rate in the lower part pressurization with the lower opening of the atrium. The mass flow of the lower opening is directed into outside from the atrium or into the atrium from outside according to the mass flow rate supplied by fan. Thus, the objective of this study are (1) to calculate the inflow and outflow mass rates through the upper and lower opening of the atrium, (2) to study the lower part pressurization with or without the lower opening of the atrium, and (3) to predict the steady-state smoke layer height which the outflow mass flow rate through the upper opening is more or less equal to the mass rate of fire plume. Therefore this study represents the smoke layer heights with various mass flow rates by the fan. And the smoke layer height in the atrium will be calculated if the pressure differences through the upper and lower openings are used. The lower part pressurization smoke control for the mass flow of the lower opening directing into the atrium from outside were superior to the smoke control directing into the outside from the atrium.

2. Lower Part Pressurization with a Vent in a Two-layer Model

In researching the smoke filling process in a large scale space, for examples, an atrium, the two-layer system may be assumed. Consider Fig. 1 showing the atrium that is pres-

Fig. 1. Schematic Diagram of an Atrium Pressurized by Mechanical Ventilation into the Lower Layer ($\dot{m}_o = \dot{m}_p = \dot{m}_e = \dot{m}_d = 0$)

surized by mechanical ventilation such as a fan into the lower layer. The atrium with height, H_E from floor is divided into an upper smoke layer and a lower cooling air layer (Karlsson and Quintiere, 2000). At some time, the upper layer has temperature T_g and density ρ_g . The mass of the cooling layer is m_a and the density is ρ_a at cooling air layer thickness z from the floor area of the atrium A . The mass of cooling layer is shown as follows:

$$m_a = \rho_a \cdot A \cdot z \quad (1)$$

By forced ventilation into the lower layer the atrium becomes pressurized. This smoke control method not only results in increased pressures across the smoke vents in the upper layer, but also prevents smoke originated outside the space to enter.

As shown in Fig. 1, $\dot{m}_d$ is steady-state mass flow rates into or out of the lower layer, $\dot{m}_e$ is steady-state mass flow rates out of the upper layer and $\dot{m}_p$ is plume mass flow rate into the upper layer of the atrium. Mass flow rate from the fan into the lower layer is denoted $\dot{m}_o$. The plume mass flow rate at the height from the floor of the atrium, z , is given by

$$\dot{m}_p = k \dot{Q}^{1/3} z^{5/3}, k = 0.21 \left(\frac{\rho_a^2 g}{c_p T_a} \right)^{1/3} \quad (2)$$

where ρ_a is the air density of the cooling layer, g is the acceleration due to gravity, c_p is the specific heat at constant pressure, T_a is the temperature of the cold air layer in the atrium and $\dot{Q}$ is energy release rate.

The conservation of mass for the cooling air layer can be written as

$$\frac{d}{dt}(m_a) + |\dot{m}_p - \dot{m}_o| - \dot{m}_d = 0 \quad (3)$$

Combining with Eq. (1), Eq. (3) can be written as

$$\frac{d}{dt}(\rho_a A \cdot z) + |\dot{m}_p - \dot{m}_o| - \dot{m}_d = 0 \quad (4)$$

The cooling air layer interface height might be kept constant when $dm_d/dt=0$, $dz/dt=0$ and $d\rho_a/dt=0$. Then the mass conservation for the lower layer expressed by Eq. (4) is now written as

$$|\dot{m}_p - \dot{m}_o| - \dot{m}_d = 0 \quad (5)$$

And for the upper layer as

$$\dot{m}_p = \dot{m}_e (\equiv \dot{m}) \quad (6)$$

It has been assumed that at steady state the temperature in the smoke layer remains constant. Therefore, the energy release rate produced in the atrium, $\dot{Q}$, must equal the energy release rate lost due to smoke leaving the smoke layer and the energy release rate lost to the atrium boundaries, that is to say, the ceiling and the walls of atrium that are in contact with the smoke layer, A_w .

$$A_w = a \cdot b + 2 \cdot (a + b) \cdot (H_E - z) \quad (7)$$

where a , b are the length of the ceiling or the floor respectively when the atrium is a rectangular parallelepiped.

$$\dot{Q} = \dot{m}_e c_p (T_g - T_a) + h \cdot A_w (T_g - T_a) \quad (8a)$$

where h is heat transfer coefficient.

Eq. (8a) is rearranged by the temperature T_g of the upper layer as follows:

$$T_g = T_a + \frac{\dot{Q}}{c_p \cdot \dot{m}_e + h \cdot A_w} \quad (8b)$$

The steady-state mass flow rate through the lower opening, $\dot{m}_d$, is given as

$$\dot{m}_d = C_d \cdot \rho_a \cdot v_d \cdot A_D \quad (9)$$

where C_d is flow coefficient and A_D is an inlet opening area at the lower layer. The velocity of the cooling air through the opening is shown in as follows:

$$v_d = \sqrt{\frac{2 \cdot \Delta P_1}{\rho_a}} \quad (10)$$

where ΔP_1 is pressure difference across the opening at the lower layer. Combining Eq. (9) and Eq. (10), ΔP_1 is given by Eq. (11) as

$$\Delta P_1 = \frac{\dot{m}_d^2}{2 \rho_a (C_d \cdot A_D)^2} \quad (11)$$

The steady-state mass flow rate through the upper opening, $\dot{m}_e$, is given as

$$\dot{m}_e = C_d \cdot \rho_g \cdot v_e \cdot A_E \quad (12)$$

where A_E is an outlet opening area at the upper layer. The velocity of the smoke through the opening is shown in as follows:

$$v_e = \sqrt{\frac{2 \cdot \Delta P_u}{\rho_g}} \quad (13)$$

where ΔP_u is the pressure difference across the opening at the upper layer. Combining Eq. (12) and Eq. (13), ΔP_u is given by Eq. (14) as

$$\Delta P_u = \frac{\dot{m}_e^2}{2\rho_g(C_d \cdot A_E)^2} \quad (14)$$

If $\dot{m}_o$ is greater than $\dot{m}_p$, $\dot{m}_d$ of the lower layer vent were originated from the lower layer to outside. But $\dot{m}_o$ is smaller than $\dot{m}_p$, $\dot{m}_d$ of the lower vent were originated from outside the space to the lower layer. And it will be discussed three cases as follows:

- Case 1: $\dot{m}_o = \dot{m}_p = \dot{m}$, $\dot{m}_d = 0$, $\dot{m}_p = \dot{m}_e = \dot{m}$
- Case 2: $\dot{m}_o < \dot{m}$ (of case 1), $\dot{m}_d = \dot{m} - \dot{m}_o$, $\dot{m}_e = \dot{m}$
- Case 3: $\dot{m}_o > \dot{m}$ (of case 1), $\dot{m}_d = \dot{m}_o - \dot{m}$, $\dot{m}_e = \dot{m}$

(a) Case 1

Case 1 is similar to natural smoke ventilation with the openings of the atrium. As shown in Fig. 1, the pressure difference across the fan is ΔP_f , and the mass flow rate from the fan is denoted $\dot{m}_o$. The steady-state mass flow rate through the lower opening, $\dot{m}_d$, is ignored, $\dot{m}_d = 0$ because of $\dot{m}_o = \dot{m}_p$ and it is assumed in two-layer model that the pressure drop in the lower layer is ΔP_f . The velocity of the cooling air, v_f , through the fan is shown in as follows:

$$v_f = \sqrt{\frac{2 \cdot \Delta P_f}{\rho_a}} \quad (15)$$

Substituting z_o to z and combining $\dot{m}_o = \dot{m}_p = \dot{m}$ in Eq. (2), the steady state height z_o is

$$z_o = \left(\frac{\dot{m}_o}{k\dot{Q}^{1/3}} \right)^3 \quad (16)$$

For the upper opening, it is known that the pressure difference can be expressed as $\Delta P_u = (\rho_a - \rho_g)g(H_E - H_N)$, where H_N is neutral plane height. Also, by the smoke layer height, z_o , and the pressure drop of the lower layer, ΔP_f , the hydrostatic pressure difference of the upper opening can be expressed as

$$\Delta P_u = (\rho_a - \rho_g)g(H_E - z_o) - \Delta P_f \quad (17)$$

Combining Eq. (12), (13) and Eq. (17), $\dot{m}_e$, the mass flow rate through the upper opening is given by Eq. (18) as

$$\dot{m}_e = C_d \cdot A_E \cdot \sqrt{2\rho_g \sqrt{(\rho_a - \rho_g)g(H_E - z_o) - \Delta P_f}} \quad (18)$$

(b) Case 2

In Case 2, as shown in Fig. 2, $\dot{m}_o$ and $\dot{m}_d$ are the steady-state mass flow rates into the atrium and $\dot{m}_e$ is the mass

Fig. 2. Schematic Diagram of an Atrium Pressurized by Mechanical Ventilation into the Lower Layer ($\dot{m}_d = \dot{m}_e - \dot{m}_o$, $\dot{m}_e = \dot{m}_p$)

flow rates out of the atrium. It is important that $\dot{m}_d$ is directed into the lower layer of the atrium from outside. And $\dot{m}_p = \dot{m}_o + \dot{m}_d$ and $\dot{m}_p = \dot{m}_e$. Substituting z_o to z and combining $\dot{m}_p = \dot{m}_o + \dot{m}_d$ in Eq. (2), the steady-state height z_o is

$$z_o = \left(\frac{\dot{m}_o + \dot{m}_d}{k\dot{Q}^{1/3}} \right)^3 \quad (19)$$

For the upper opening it is known that the pressure difference can be expressed as $\Delta P_u = (\rho_a - \rho_g)g(H_E - z_o) - (\Delta P_f + \Delta P_1)$, where H_N is the neutral layer height. Also, by the smoke layer height, z_o and the pressure drop of the lower layer, $\Delta P_f + \Delta P_1$, the hydrostatic pressure difference of the upper opening can be expressed as

$$\Delta P_u = (\rho_a - \rho_g)g(H_E - z_o) - (\Delta P_f + \Delta P_1) \quad (20)$$

Combining Eq. (12), (13) and Eq. (20), $\dot{m}_e$, the mass flow rate through the upper opening is given by Eq. (21) as

$$\dot{m}_e = C_d \cdot A_E \cdot \sqrt{2\rho_g \sqrt{(\rho_a - \rho_g)g(H_E - z_o) - (\Delta P_f + \Delta P_1)}} \quad (21)$$

(c) Case 3

In Case 3, as shown in Fig. 3, $\dot{m}_o$ is the steady-state mass flow rates into the atrium. But $\dot{m}_d$ and $\dot{m}_e$ is the mass flow rates out of the atrium. $\dot{m}_d$ is directed into outside from the lower layer of the atrium. $\dot{m}_p = \dot{m}_o - \dot{m}_d$ and $\dot{m}_p = \dot{m}_e$.

Fig. 3. Schematic Diagram of an Atrium Pressurized by Mechanical Ventilation into the Lower Layer ($\dot{m}_d = \dot{m}_o - \dot{m}_e$, $\dot{m}_e = \dot{m}_p$)

For the upper opening the hydrostatic pressure difference of the upper opening can be expressed as Eq. (22) by the steady-state smoke layer height, z_o and the pressure drop of the lower layer, $\Delta P_f - \Delta P_1$.

$$\Delta P_u = (\rho_a - \rho_g)g(H_E - z_o) - (\Delta P_f - \Delta P_1) \quad (22)$$

Combining Eq. (12), (13) and Eq. (22), the mass flow rate through the upper opening, $\dot{m}_e$, is given by Eq. (23) as

$$\dot{m}_e = C_d A_E \sqrt{2\rho_g g (H_E - z_o) - (\Delta P_f - \Delta P_1)} \quad (23)$$

And substituting z_o to z and combining $\dot{m}_p = \dot{m}_o - \dot{m}_d$ in Eq. (2), the steady state height z_o is

$$z_o = \left(\frac{\dot{m}_o - \dot{m}_d}{k\dot{Q}^{1/3}} \right)^3 \quad (24)$$

3. Numerical Analysis and Results

It were conducted the experiments of smoke control in large scale spaces by Yamana and Tanaka. A atrium was of length 30.0 m, width 24.0 m and height 26.3 m. Therefore, the floor area is 720 m². The methanol gas of the burner was supplied at the burning rates of 6.67×10^{-2} kg/s which are corresponded to the heat release rates of 1300 kW (Yamana and Tanaka, 1985).

In simulation trials, the atrium was of length 30.0 m, width 24.0 m and height 26.3 m, and a large ambient space of length 30.0 m, width 2.0 m and height 26.4 m as shown in Fig. 4. The atrium has the upper opening of width 3.0 m and height 2.2 m and the lower opening of width 6.0 m and height 0.6 m. Also, as shown in Fig. 4, the cooling air for pressurizing the large space was supplied to the lower part of the space through the ducts of width 5.0 m and height 2.0 m on the first floor by operating two fans. The rate of

Fig. 4. Geometry of an Atrium's Model

Fig. 5. Grid Distribution Used in Numerical Simulations

air supply 23.5 m³/s (or mass flow rate 29.14 kg/s) and pressure difference 3.41 Pa were obtained based on the flow velocity 2.35 m/s at the duct opening in Test No. D-3 of Yamana and Tanaka' experiments (Yamana and Tanaka, 1985).

Numerical experiments were conducted for different methanol gas supplies. A square diffusion burner supplied with methanol of size 180 cm × 180 cm was used as the fire source on the floor of the space. The burner was located at the center of the atrium. The methanol gas of the burner was supplied at the burning rates of 3.33×10^{-2} kg/s, 6.67×10^{-2} kg/s and 9.99×10^{-2} kg/s which are corresponded to the heat release rates of 650, 1300 and 2600 kW, respectively (Yamana and Tanaka, 1985).

As shown in Figs. 4 and 5, the minimum grid size of 0.2 m was used in simulations. A three-dimensional Cartesian coordinates were assigned with x , y , z . In atrium, the numbers of cells along x , y and z directions are 150, 120 and 132, respectively and the total number of the cells is 2,376,000 ($= 150 \times 120 \times 132$). In the outside of the atrium, the numbers of cells along x , y and z directions are 150, 10 and 132, respectively and the total number of the cells is 198,000 ($= 150 \times 10 \times 132$).

The boundary conditions for the walls, ceiling and floor of the atrium are shown as Table 1. The ceiling and floor are specified as concrete and all of the walls are specified as gypsum board. Ambient temperature and pressure are 12.5°C and 101.325 kPa, respectively. Environmental space

Table 1. Material Properties

Material Properties	Concrete	Gypsum
Specific heat (kJ/kg-K)	0.84	1.09
Density (kg/m ³)	1440	930
Thermal conductivity (W/m/K)	0.48	0.17
Thickness(m)	0.2	0.2

is extended 2.0 m outside the atrium. In the space, zero gradients for velocity and temperature are given, and pressure also given the ambient pressure.

The data of the smoke layer height produced from the temperature examined by thermocouple and the observation by eye are plotted in Fig. 6. Also, the smoke-filling curve shown by the dotted line is referred to as the “standard filling” curve by Yamana and Tanaka. According to the results in Fig. 6, the smoke layer height predicted by FDS almost agrees with the layer height examined by thermocouple. As can be seen, the descent of the smoke layer is very quick at first but slows down later because the rate of air entrainment from the lower layer decreases as the smoke layer descends.

Fig. 7 also shows the temperature measured at heights of 8 m, 16 m and 24 m. In two-zone model analysis assuming a constant average value of the smoke layer, for examples, a smoke temperature, is reasonable because the temperature increases of 16 m and 24 m are relatively low. At height of 8m, simulation value and experimental value is occurred much more differently. But the simulation value at height of 5 m is similar to the experimental value at height of 8 m.

Fig. 6. Comparison of Smoke Layer Heights

Fig. 7. Comparison of Temperatures according to Heights from Floor

As shown in Fig. 8, the temperatures of the upper smoke layer and lower cooling air layer of two-zone model analyzed by FDS are revealed in the case of the fire size of 1300 kW. It is reasonable in two-zone model that the temperatures of the upper layer and lower layer are assumed

Fig. 8. Two-layer Temperatures

(a) Volume flow rates of the upper and lower openings.

(b) Pressure differences of upper and lower openings.

(c) Comparison of smoke layer heights.

Fig. 9. Calculation Procedure of Two-zone Method

25°C and 12.5°C, respectively. Also, Fig. 9(a), (b) and (c) are revealed in the case of the fire size of 1300kW. Fig. 9(a) shows the volume flow rates of the upper and lower opening analyzed by FDS. The pressure differences of the upper and lower opening are given by Eq. (11) and Eq. (14) and are shown in Fig. 9(b). The smoke layer height is given by Eq. (24) and is analogous to the height analyzed by FDS as shown in Fig. 9(c) (Yamana and Tanaka, 1985; Karlsson and Quintiere, 2000).

Fig. 10 shows the mass flow rates of the lower opening, which were gotten by simulation tests varying the air supply rate of the fan in the fire size of 1300 kW. The lower and upper openings were activated in 180 sec and 210 sec, respectively. $\dot{m}_o$ is the mass flow rate from the fan into the lower layer and the mass flow rate ratios are given by $S = \dot{m}_o / 23.5 \text{ (m}^3/\text{sec)}$. The mass flow rates of the lower opening is always directed into outside from the atrium in case of $S=1, 1.25$ and 1.5 and into the atrium from outside in case of $S=0, 0.25$ and 0.5 . In case of $S=0.75$, at the first time the mass flow rates is directed into outside but later is directed into the atrium. Fig. 11(a), (b) and (c) are revealed in the case of the fire size of 1300 kW. Fig. 11(a) shows the smoke layer heights in case of $S=1, 1.25$ and 1.5 and Fig. 11(b) shows the smoke layer heights in case of $S=0, 0.25, 0.5$ and 0.75 . Also, Fig. 11(c) accurately shows the smoke layer heights in $S=0, 0.25, 0.5, 0.75, 1, 1.25$ and 1.5 . It is known that the lower part pressurization smoke control for the mass flow of the lower opening directing into the atrium from outside were superior to the smoke control directing into the outside from the atrium. Especially, that is to say, the case of $S=0$ is natural venting. As shown in Fig. 7 and Fig. 11(c), the natural venting activating the lower and upper openings after pre-flashover fire elapse is recommended.

The atrium not having the lower opening is modeled and analyzed by FDS. As shown in Fig. 12, the smoke layer height of the atrium not having the lower opening is com-

pared with the height of the atrium having the lower opening in the case of the fire size of 1300 kW. Fig. 12 shows both smoke layer heights are alike.

Fig. 11. Comparison of Smoke Layer Heights

Fig. 10. Comparison of Mass Flow Rates of the Lower Opening According to Air Supply Rate

Fig. 12. Comparison of Smoke Layer Heights according to Lower Opening

Fig. 13. Comparison of Smoke Layer Heights according to Energy Release Rates

The smoke layer heights of the three fire sizes of 650 kW, 1300 kW and 2600 kW are shown in Fig. 13, respectively. The heights analyzed for 2600 kW almost agree with the heights for 1300 kW. But the smoke layer for 650 kW are a little higher than the smoke layers for 1300 kW and 2600 kW.

4. Conclusions

When a fire was happened in the atrium, the smoke layer heights were analyzed numerically by the FDS. The descent of the smoke layer is very quick at first but slows down later. The smoke layer height predicted by FDS almost agrees with the layer height examined by thermocouple.

The lower part pressurization smoke control for the mass flow of the lower opening directing into the atrium from outside were superior to the smoke control directing into the outside from the atrium. And the natural venting activating the lower and upper openings after pre-flashover fire elapse is recommended.

The smoke layer height of the atrium not having the lower opening is similar to the height of the atrium having the lower opening. And the smoke layer heights analyzed for the fire size of 2600 kW almost agree with the heights for the fire size of 1300 kW.

Nomenclature

- g = acceleration due to gravity (m/s^2)
 H_N = neutral-plane height at the atrium from the floor (m)
 H_E = atrium height (m)
 $\dot{m}_d$ = steady-state mass flow rates into or out of the lower layer of the atrium (kg/s)
 $\dot{m}_e$ = steady-state mass flow rates out of the upper layer of the atrium (kg/s)
 $\dot{m}_p$ = plume mass flow rate into the upper layer of the atrium (kg/s)
 $\dot{m}_o$ = mass flow rate from the fan into the lower layer (kg/s)
 T_a = temperature of the cold air layer in the atrium (K)
 T_g = temperature of the hot air layer in the atrium (K)

- z = cooling air layer thickness from the floor area of the atrium (m)
 A = floor area of the atrium (m^2)
 c_p = specific heat at constant pressure ($\text{kJ}/(\text{kg}\cdot\text{K})$)
 $\dot{Q}$ = energy release rate (kW)
 a, b = lengths of the ceiling (m)
 h = heat transfer coefficient ($\frac{\text{kJ}}{\text{m}^2 \cdot \text{K}}$)
 C_d = flow coefficient
 A_D = inlet opening area at the lower layer (m^2)
 A_E = outlet opening area at the upper layer (m^2)
 ΔP_1 = pressure difference across the opening at the lower layer (N/m^2)
 ΔP_u = pressure difference across the opening at the upper layer (N/m^2)
 ΔP_f = pressure difference across the fan (N/m^2)
 v_d = velocity of the cooling air through the lower opening (m/s)
 v_e = velocity of the smoke through the upper opening (m/s)
 v_f = velocity of the cooling air through the fan (m/s)
 z_o = steady state cooling air height from the floor (m)
 ρ_a = air density of the cooling layer in the atrium (kg/m^3)
 ρ_g = smoke density of the smoke layer in the atrium (kg/m^3)

References

- Forney, G.P. (2008) User's Guide for Smokeview Version 5- A Tool for Visualizing Fire Dynamics Simulation Data, NISTSP 1017-1, National Institute of Standards and Technology.
Hinkley, P.L. (1988) Comparison of An Established Method of Calculation of Smoke Filling of Large Scale Spaces With Recent Experiments, Fire Science and Technology, Vol. 8, No.1, pp. 1-8.
Jeon, H.K., Choi, Y.S. and Choo, H.L. (2008) A Numerical Study for the Performance of Natural Smoke-venting of a Vertical Vent, T. of Korean Institute of Fire & Eng., Vol. 22, No.4, pp. 1-10.
Ju, H.D. and Kim, H.H. (2012) Flow Coefficients of Doorway Flow Field in Two-room Building Fires, J. of the Korean Society of Hazard Mitigation, Vol. 12, No. 4, pp. 133-142.
Karlsson, B. and Quintiere, J.G. (2000) Enclosure fire dynamics, CRC Press.
Kerber, S. and Milke J.A. (2007) Using FDS to Simulate Smoke Layer Interface Height in a Simple Atrium, Fire Technology, Vol. 43, pp. 45-75.
McGrattan, K., Baum, H., Rehm, R., Mell, W., McDermott, R., Hostikka, S. and Floyd, J. (2009) Fire Dynamics Simulator (Version 5.2) Technical Reference Guide, NISTSP 1018-5, National Institute of Standards and Technology.
Milke, J.A. (2002) Smoke Management in Covered Malls and Atria, The SFPE Handbook of Fire protection Engineering, NFPA.
NFPA 92B (2005) Standard for Smoke Management Systems in Malls, Atria, and Large Areas, NFPA.
Park, W.C. (2003) A Numerical Study on Smoke Control for Smoke Control Systems and Air Flowrate, T. of Korean Institute of Fire & Eng., Vol. 17, No.2, pp. 56-61.
Qin, T.X., Guo, Y.C., Chan, C.K. and Lin, W.Y. (2009) Numerical

Simulation of the Spread of Smoke in An Atrium Under Fire Scenario, Building and Environment, Vol. 44, pp. 56-65.
Tanaka, Takeyoshi and Yamana, Toshio (1985) Smoke control in large scale spaces(Part 1: Analytic Theories For Simple Smoke Control Problems), Fire Science and Technology, Vol. 5, No.1, pp. 31-40.
Tanaka, Takeyoshi and Yamana, Toshio (1985) Smoke control in

large scale spaces(Part 2:Smoke Control Experiments In A Large Scale Space), Fire Science and Technology, Vol. 5, No.1, pp. 41-54.

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