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Research Article

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Numerical Simulation of smoke movement in vertical shafts during high-rise fires using a modified network model

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ABSTRACT

A simplified, two-layer zone coupled with network model to quantify the smoke movement during high-rise fires is presented in this paper. The main governing equations, the conservations of mass and energy, and the sub models including the convective heat transfer, radiative heat transfer and fluid mechanics, are considered in the model. The advantage of the model is the consideration of heat transfer due to the importance of temperature distributions in the vertical shaft, and the buoyancy-induced flow and the resulting driving force are strong referred to stack effects. The model is aimed at managing the smoke movement for a successful fire protection plan and improving the occupant safety in the event of fire. The generated results suggest that enlarging the vent size on top of the elevator shaft, pressurizing the floors except the fire floor and reducing the gaps around elevators can raise the location of neutral pressure plane (NPP) and create a safe environment in the upper flows. To a certain degree, the location of NPP will be raised above the total height of structure, thus the smoke will be kept inside and exhausted out of the elevator shaft.

Keywords: smoke movement, stack effects, vertical shafts, pressurizing floors, neutral pressure plane (NPP), high-rise fires.

INTRODUCTION

In the last decade, the number of high-rise buildings has increased rapidly in China, and much more composite materials have been applied in the course of decoration for the artistry quality. This leads to the fact that the smoke control system is more complicated during high-rise fires. The hot smoke is the key cause of fire-related deaths, which has been verified in the occurred fire cases. Large amount of papers have been published due to the impact of smoke control on fire safety and different modeling process, such as field models, zonal models and network models [1-5]. A novel hybrid fire model combining the field and zone models to simulate the smoke propagation in a multi-storey buildings is discussed [5], where the field model is used in fire room and two-layer zone model in corridor. The stack effect or namely 'chimney effect' could be observed due to the temperature differences between the gas in the shaft and the air in the outside environment, and this is the major dragging forces for the smoke propagation in most cases. There is a concept of a horizontal elevation in the shaft called the neutral pressure plane (NPP), where the gas pressure inside the shaft is the same with the outside in the environment. Large numbers of research papers have been published focusing on the smoke control in the vertical shafts [6-8].

As stated above, it is feasible for stairwell pressurization with the fire doors being well sealed, and the elevator shaft would be the path with the least resistance. It is necessary to take some measures to exhaust the smoke inside the shaft and prevent them from entering into the upper floors. Similar to the stairwell pressurization, the floor pressurization can be designed to force the smoke inside the shaft away from the habitable areas by use of the AHU (Air Handling Units). W.Z. Black [9-12] has conducted further studies on the smoke control during high-rise fires using the COSMO codes, which is now under developing. The floor pressurization system could be triggered by a smoke alarm or the water flow from a sprinkler head. The floor pressure above the fire floor is increased and the smoke in the vertical shaft can not be delivered into the upper floors, due to the fact that the NPP has been increased under the floor pressurization above the fire floor.

Nomenclatures

A	area	W	Width of the shaft
ACH	Air changes per hour	z	Elevator above fire source
C_D	Discharge coefficient	Z	Height of interface
C_p	Specific heat	Subscripts	
D_h	Hydraulic diameter of shaft	0	Standard conditions
H	Height of each floor of building	a	Atmosphere
g	Acceleration of gravity	af	Atmosphere and floor
h	Convective heat transfer coefficient	conv	Convective heat transfer
k_a	Absorption of combustion gas	g	Gas layer
k_c	Thermal conductivity	f	Floors
L	Length of the shaft	fs	Floor and shaft
M	Mass flow rate	rad	Radiative heat transfer
N	The total floors	s	Shaft
NPP	Neutral Pressure Plane	U	Upper layer
p	Perimeter of shaft	L	Lower layer
P	Pressure	w	Shaft surface
Pr	Prandtl number	x	Cross-sectional value
Q	Thermal flux	Greek letters	
R	Gas constant	β	Thermal expansion coefficient
Re	Ryenolds number	γ	Ration of specific heat
S	Source item	ε	Emissivity of shaft walls
T	Temperature	ρ	Density
V_s	Velocity	ν	Kinematic viscosity
V	Volume	σ	Stefan-Boltzmann constant

This study aims to reveal the characteristics of smoke movement, such as the pressure distributions and temperature profiles, due to stack effect in the vertical shafts using a simplified two-layer zone coupled with network model, in which the energy conservation is considered in the network model. The heat transfer considered in the energy conservation is a combination of convective and radiative heat transfer. The Radiation Energy Absorption Distribution (READ) method is used for the calculation of radiative heat transfer, in which the coefficient of READ is obtained through Monte-Carlo Method. The output, such as the location of NPP and the amount of smoke exhausting, leads to the results of how to increase the structural safety.

1 MODEL ASSUMPTIONS

The assumptions are necessary to simplify the mathematic models predicting the smoke movement in vertical shafts, and the conservation equations could be solved under such assumptions. The major assumptions are as follows:

(a)The smoke movement in vertical shafts is steady and considered to be one-dimensional. That is, the properties of the smoke vary only with the elevation of the shaft and do not vary with time.
(b)The stairwell doors are closed and there is no pressurization, which is not considered in the calculation.
(d)The gas pressure and temperature in the vertical shaft are uniform for each layer, and the gas temperature in the floors except the fire floor, is set to be the environment temperature. By dosing so, only the conservation of energy in the vertical shaft is just considered.
(d)The fire floor is taken as the first floor, and the opening areas are uniformly distributed along the height of shaft including at the fire floor. The cold fresh air below the fir floor entering into the shaft does not mix up with the combustion gases.
(e)There is a vent to atmosphere on the top shaft and the wind velocity is assumed to be zero in the calculations.

SMOKE CONTROL MODEL

3.1 Model geometry

The building geometry described in the mathematic model is shown schematically in Figure1. The fire is located on the first floor and the construction opening and leaks around doors are uniformly distributed from bottom to the top of building.

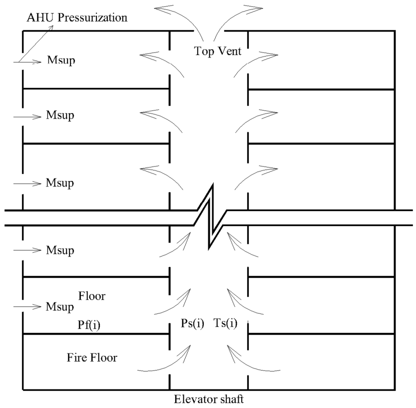

Figure 1: Schematic diagram of structure and elevator shaft

3.2 Governing equations

The hot heavy smoke mixes up with cold fresh air or discharges out, depending on the sign of $M_{as}(i)$ shown in Figure 2, as the flow rises through the vertical shaft as results of stack effect and buoyancy effect. The equation for the *i*-th gas layer in the shaft can be expressed as follows:

$$M_s(i) = M_s(i-1) + M_{fs}(i) \tag{1}$$

Where $M_s(i)$ and $M_s(i-1)$ are the smoke mass flow rates of *i*-th ($1<i\le N$) and *i*-1-th layer in the shaft, respectively, $M_{fs}(i)$ is the mass flow rate due to the door gaps and opening area of building materials, which '+' indicating cold fresh air flows in and '-' indicating hot smoke flows out.

Considered the 1st layer in the shaft being connected with the fire floor, the conservation of mass is written as:

$$M_s(1) = M_{ps} \tag{2}$$

where M_{ps} is the hot smoke entering into the shaft through elevator doors on the fire floor.

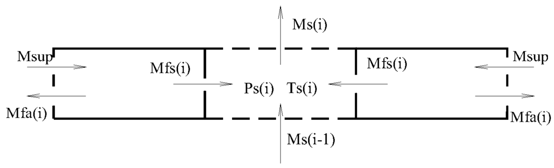

Figure 2: Mass conservation of the *i*-th layer in the structure (1<*i*≤*N*)

In a similar way, the mass conservation for the *i*-th floor could be obtained.

$$M_{\sup} = M_{fs}(i) + M_{fa}(i) \tag{3}$$

Where M_{sup} is the air mass flow rate provided with AHU, $M_{fa}(i)$ is the mass flow rates from the floors to the environment due to the opening area of building materials ($1\le i\le N$).

According to Figure 2, the conservation of energy applied to the *i*-th ($1<i\le N$) gas layer and the *i*-th ($1\le i\le N$) surface element in the vertical shaft is expressed as follows, respectively.

$$\begin{aligned}&4k_a\sigma dV\cdot T_s^4(i)+M_s(i)\cdot C_pT_s(i)+hdA\cdot(T_s(i)-T_w)=\\&4k_a\sigma\sum_j Rgg(j,i)\cdot T_s^4(i)+\varepsilon_w\sigma dA\sum_j Rwg(j,i)\cdot T_w^4+\\&M_s(i-1)C_pT_s(i-1)+M_{fs}(i)C_p[\delta(P_f(i),P_s(i))T_a(i)\\&+(1-\delta(P_f(i),P_s(i))\cdot T_s(i))]\end{aligned}\tag{4}$$

$$\begin{aligned}&\varepsilon_w\sigma\cdot dA\cdot T_w^4+Q_w(i)\cdot dA=h\cdot dA\cdot(T_s(i)-T_w)\\&+\varepsilon_w\sigma\cdot dA\cdot\sum_j Rww(j,i)\cdot T_w^4\\&+4k_a\sigma dV\sum_j Rgw(j,i)\cdot T_s^4(i)\end{aligned}\tag{5}$$

For the 1st gas layer, the conservation of energy is:

$$\begin{aligned}&4k_a\sigma\cdot dV\cdot T_s^4(1)+M_s(1)\cdot C_p\cdot T_s(i)+h\cdot dA\cdot(T_s(1)-T_w)\\&=4k_a\sigma\cdot\sum_j Rgg(j,1)\cdot T_s^4(1)+\varepsilon_w\sigma\cdot dA\cdot\sum_j Rwg(j,1)\cdot T_w^4\\&+M_{ps}\cdot C_p\cdot T_{AV}+M_{fs}(1)\cdot C_p\cdot[\delta(P_f(1),P_s(1))\cdot T_a(1)\\&+(1-\delta(P_f(1),P_s(1))\cdot T_s(1))]\end{aligned}\tag{6}$$

Where $Rgg(i, j)$, $Rgw(i, j)$, $Rwg(i, j)$ and $Rww(i, j)$ are the radiation energy absorption distribution coefficient stated later in this paper, $\delta(i, j)$is a judgment function:

$$\delta(i,j)=\begin{cases}1, & i\geq j\\0, & i<j\end{cases}\tag{7}$$

The item Q_w(i) in Eq.(5) is the thermal heat flux absorbed by the *i*-th shaft surface, which would decrease the smoke temperature as rising upward inside the shaft. Eqs. (4), (5) and (6) keep the balance of energy flowing in and out for each gas layer and each surface element. The energy conservation accommodates the infiltrated cold fresh air which is used for the smoke movement in the shaft. Eqs. (4), (5) and (6) can be integrated using Levenberg-Marquardt Method for gas temperature of each layer and Eq. (1) using Newton-Rampson Method for gas pressures in shaft.

RESULTS AND DISCUSSION

The results are generated by solving the governing equations and the sub models stated above for a 30-storey, 1500m^2 structure that has a single elevator shaft with four cars. The heat release rate is set to be 5000kW. Results for other variables, such as the building exterior surface, the shaft constructions and stairwell pressurization, will be considered in the subsequent papers.

4.1 Top vent area

The influences of top vent size are shown in Figure 3, which plot the total mass flow rate inside the elevator shaft as the vent area ration is changed with no doors open.

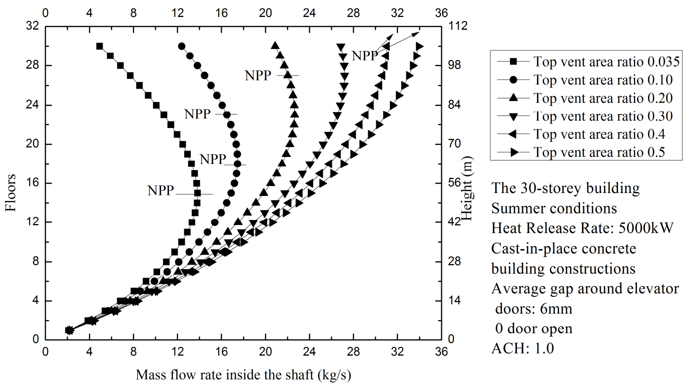

Figure 3: Mass flow rate inside shaft with variable top vent sizes

Increasing the top vent size from the minimum size required by the building codes (3.5% of the shaft cross-section area [13]) to a vent that has an area of 50% of the shaft enhances the total mass flow rate out of the elevator shaft.

By changing the top vent size from 3.5%, to 10%, 20% and 30% of the shaft area with no door opens, the NPP is raised from the 15th to the 19th, 23rd and 27th floors, respectively, and it is above the maximum height of the building with the top vent size of 40% and 50%, which can be seen from Figure 3.

4.2 Floor pressurization using AHU

The gas mass flow rate at each floor with no doors open is shown in Figure 4.

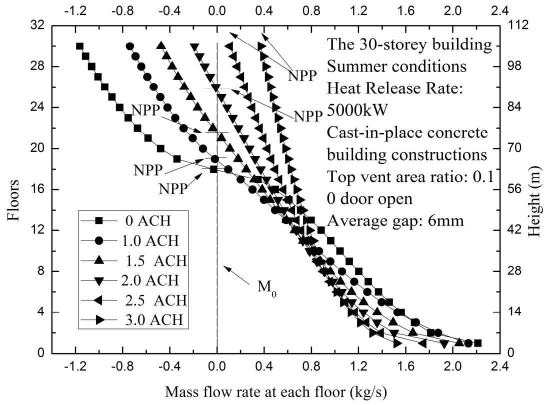

Figure 4: Effects of floor pressurization capacity with different ACH

The value of mass flow rate at each floor less than zero indicates that the flow out of the shaft and vice versa. The vertical straight line in the figure, viz. M_0, indicates that the quantity of mass flow rate at each floor equaling zero, and the line intersects with the other curves at the elevation where the NPP is located. Figure 4 shows that the location of NPP is raised from 17th floor to 18th, 21st and 25th floors with ACH ranging from 0 to 2.0. When the quantity of ACH is at 2.5 or 3.0, the location of NPP is above the total height of building. The results indicate that floor pressurization has a sizable impact on the location of NPP and the quantity of ACH is modest acceptable with the existing AHU.

CONCLUSION

A simplified, two-layer zone coupled with network model which includes both convective and radiative heat transfer is presented in this paper. The mathematic model involves pressurizing the floors above the fire floor so that the smoke will kept inside the shaft.

Enlarging the top vent area size will move the NPP upward, so as to raise it above the total height of structure, and this will create a safer environment for the upper floors. The quantity of air flow rate pressurizing each floor is modest, which is smaller than the existing AHU. This will increase the pressure on each floor except the fire floor so as to prevent the smoke from infiltrating the floors.

The floor pressurizing floors plan coupled with larger top vent size and tighter elevator doors can raise the location of NPP and deliver a lot of smoke through the vertical shaft. Thus, these can be employed in the smoke control system to improve occupants' safety during high-rise fires.

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