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Research Article

Computational Simulation of Smoke Temperature Diffusion in High-rise Buildings Fires

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Abstract: In order to control the smoke diffusing and prevent the damage to the people, the smoke temperature was researched. In high-rise building fires, the most immediate threat to passengers' life is not the direct exposure to fire but the smoke inhalation because it contains hot air and toxic gases, so it has positive meaning to find the rules of the smoke temperature distribution. The variable rule of smoke temperature field distribution in passages of high-rise building was the foundation of fire fighting project. Heat-transfer process between smoke and building walls was analyzed by establishing difference equation of heat balance and diffusion process between smoke and transverse passage of high-rise building was analyzed by mathematical model of air mixed with smoke. The variable rule of smoke temperature, diffusion time and length of exit passageway was analyzed by case. Smoke temperature variation in smoke diffusion process was affected mainly by generation quantity of smoke and less affected by heat-transfer process between smoke and building walls.

Keywords: Computational simulation, fire smoke, high-rise building, temperature

INTRODUCTION

In high-rise building fires, the most immediate threat to passengers' life is not the direct exposure to fire but the smoke inhalation because it contains hot air and toxic gases, so it has positive meaning to research on the smoke temperature. And as far as high-rise building fire was concerned, smoke damage and asphyxia were the most important factors which lead to personnel casualties. Smoke was visible motes which came from combustible matter in the condition of incomplete combustion and were held suspended in the air and was made up of superheated colorless gas (such as air, CO, CO_2, HCN, NO_2 and H_2S), tiny black carbon motes and ash which was from complete or incomplete combustion of fuel (Kenichi1, 2011). There were three major harm of smoke to people (Hagiwara, 2011). First, high density smoke could stimulate eyes intensely and depress visibility limit, so it interfered escape and rescue of evacuee. Second, all kinds of polymer chemical substances were widely applied in modern construction industry. So there were great deals of toxic and harmful gases endangering people life (Song *et al*., 2010). Third, a mass of nontoxic gases from combustion reduced the concentration of air and influence respiration function (Chow and Chow, 2010). Simultaneously toxic gas could make people asphyxiation to death. Therefore, the rules of smoke generation, movement and control mode have the most significance in reducing the national property loss and protecting people from danger in fire study (Hu *et al*., 2004).

According to the statistic data of fire, construction fire was 60% of the fire disasters and high-rise building was the famous one which caused the surprising huge expense and great fire probability (Qingwei *et al*., 2010). For instance, there were 41 fires in 115 high-rise buildings in the past three years in New York, USA. In our country, from 2008-2011 there were 64, 242 fires of high-rise buildings, 6, 302 casualties and 1, 016 million Yuan of direct economic losses, in which there were 38 catastrophic fires, 119 casualties and 104 million Yuan of direct economic losses and in which there were 412 heavy fires, 801 casualties and 182 million Yuan direct economic losses (Lu and Zhao, 2010).

The temperature calculation of smoke plume was the foundation of high-rise building design and provides theoretical base for firefighting project and the design of personnel evacuation system. There were many facts affected the smoke temperature in actual computation and massive work of modeling, calculation and analysis of smoke field was brought by considering

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every details thoroughly (Elghazouli *et al.*, 2008). Moreover, certain deviation was exist between the computational result and the practice dates thought this way because of the complex inner structure of the modern constructions. But many times smoke temperature was just considered generally instead of minor details. The heat smoke flow diffused in the passages in high-rise building fire (Black, 2011). And there were two main facts that influence the temperature field of heat smoke flow in this process (Yang and Zhu, 2006): first, the heat exchange between heat smoke flow and the wall. Second, the temperature change of the heat smoke flow mixed with the air in the passage. The variation rule of temperature of certain node could be calculated though partition grid using energy equation.

So in this study, the variable rule of smoke temperature field distribution in passages of high-rise building was researched. Heat-transfer process between smoke and building walls was analyzed by establishing difference equation of heat balance and diffusion process between smoke and transverse passage of high-rise building was analyzed by mathematical model of air mixed with smoke. The variable rule of smoke temperature, diffusion time and length of exit passageway was also analyzed.

MATHEMATIC MODEL OF HEAT TRANSFER OF SMOKE DIFFUSING IN RRANSVERSE PASSAGE

Heat transfer model of smoke flow and exterior-protected construction: The fire smoke mainly transferred heat depending on the wall when it spread in the structure. And the process of heat exchange could be divided into three parts: first, heat smoke flow exchanged heat with wall in the diffusing passage, the main heat exchange was the forced-convection heat transfer between the heat smoke flow and wall; second, the thermal conduction of wall; third, the wall exchanged heat with the air of the other side between the lateral wall of passage and the room without fire and the main heat exchange was natural-convection heat transfer. Some assumptions were made to simplify the computational model macroscopically, as illustrated in Fig. 1:

- The coefficient of heat conductivity, density, specific heat and so on of the wall could be considered as constant when the smoke flows in the passage.
- The temperature of wall and room was homology before the smoke flows.
- The radiation heat transfer of the smoke and wall was leaved out of account as long as of the wall and exterior air.

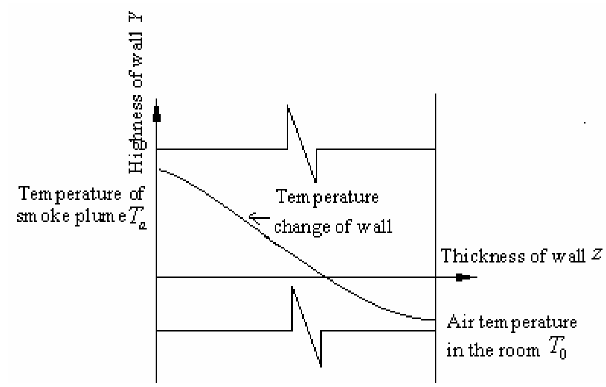

Fig. 1: Temperature curves of wall

The heat exchange formula of wall could be gained in use of Fourier formula according with the analysis and assumption:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{1}$$

Boundary condition: t = 0; $T_a = T_0$; $T = T_0$

$$x = 0, -\lambda \left.\frac{\partial T}{\partial x}\right|_{x=0} = \alpha_0 (T_\alpha - T)\big|_{x=0} \tag{2}$$

$$x = \delta, -\lambda \left.\frac{\partial T}{\partial x}\right|_{x=\delta} = \alpha_1 (T - T_o)\big|_{x=\delta} \tag{3}$$

where,

λ = The heat conductivity of wall w/ (m.k)
α = The thermal diffusivity, m^2/s
T_α = The temperature of smoke in the passage, K
T_0 = The temperature of air in the other side of wall, K
δ = The thickness of wall, m
T = The temperature of wall, K
t = The time, s

The wall thickness set as x-coordinate Z and the wall high was y-coordinate Y, the time and wall thickness were the parameters.

The computational model was established with taking the time and the thickness of wall as the parameter and the thickness was the abscissa Z, the highness was the ordinates. The temperature of smoke which will change with the time in the passage was T_0 when the time was 0.

Discretization formula: The difference method was used to analysis the temperature change of smoke in the passage.

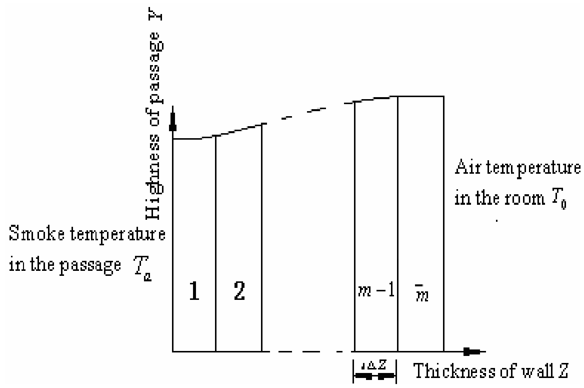

Fig. 2: Mesh map curves of wall

The wall was divided into m segment and the interval of adjacent node was $\Delta Z(\Delta Z = \delta/m)$ on the assumption that the temperature was identical in each cell inner, as shown in Fig. 2:

Formulas (4), (5) and (6) could be gained from Formulas (1), (2) and (3) with dispersing the space and the time:

$$T_i^{p+1} = \frac{\alpha \Delta t}{(\Delta z)^2}\left(T_{i+1}^p + T_{i-1}^p\right) + \left|1 - \frac{2\alpha \Delta t}{(\Delta z)^2}\right| T_i^p \quad (4)$$

$$T_1^P = \frac{T_2^p + (\alpha_0 \Delta z / \lambda) T_f^p}{1 + \alpha_0 \Delta z / \lambda} \quad (5)$$

$$T_n^P = \frac{T_{n-1}^p + (\alpha_0 \Delta z / \lambda) T_{a1}}{1 + \alpha_1 \Delta z / \lambda} \quad (6)$$

Boundary condition:

$$T_i^0 = T_0 (i = 1,2,3,..., m) \quad (7)$$

where,
T_n^p = Temperature of n node at p, K
ΔZ = The length of unit node on the wall, m

the value of Δt could be calculated by Δx in the formula $N = (\Delta x^2)/\alpha \Delta t$ and N was 3 or 4. (none but N was greater than or equal to 2, the solution could be stable and N could not be too large, otherwise the working capacity could increase enormously.) the temperature of any cell in time p in the wall could be gain by simultaneous Eq. (4), (5), (6) and (7). But in real process, the temperature of infinitesimal I of T_i^{p+1} in time p+1 and infinitesimal I+1 of T_{i+1}^p in time p was solved. At last the temperature of node on lateral wall in the passage could be obtained though repetitive calculation.

TEMPERATURE CALCULATON OF SMOKE PLUME IN THE PASSAGE

Simulation of smoke resource: The smoke with the temperature T_0 was considered as multi-component ideal gas and no longer had the chemical change. Heat smoke plume spread from the fire room which was main in the headspace with the influence of the buoyancy and concentrates in certain regions which the width was d and at that time the smoke was not mixed with air:

$$d = \frac{Q_0}{L \times \upsilon_0 \times \rho} \quad (8)$$

where,
L = The width of passage, m
ρ = The consistency of smoke, kg/m^3
Q_0 = The volume flow, m^3/s
υ_0 = The velocity of smoke, m/s

Diffusion mathematic model of heat smoke plum mixed with air: The smoke continuously mixed with the air as diffusing in the passage and there was the ideal boundary surface between the smoke plum layer and the air. The angle of flare was 30^0 according with the experimental findings. The smoke in the passage was divided into m nodes in the process of temperature calculation. In this study the smoke temperature was merely calculated in macroscopically without considering partial details. So the smoke was counted as one kind of gases flowing in X orientation and the temperature of same cross-section and the specific volume of same cell was homology. The grad of passage was divided into n units and the length was $\Delta x = Length/n$, as illustrated in Fig. 3.
The volume of each node was:

$$Vi = \Delta X\left[d + tg\theta \times \left(\frac{2i-1}{2}\right) \times \Delta X\right] \times L \quad i < \frac{\left(\frac{H-d}{tg\theta}\right)}{\Delta x} \quad (9)$$

$$Vi = \Delta X \times H \times L \quad i > \frac{\left(\frac{H-d}{tg\theta}\right)}{\Delta x} \quad (10)$$

where,
Vi = The volume of node i, m^3
ΔX = The length of node, m
H = The height of passage, m
L = The wideness of passage, m

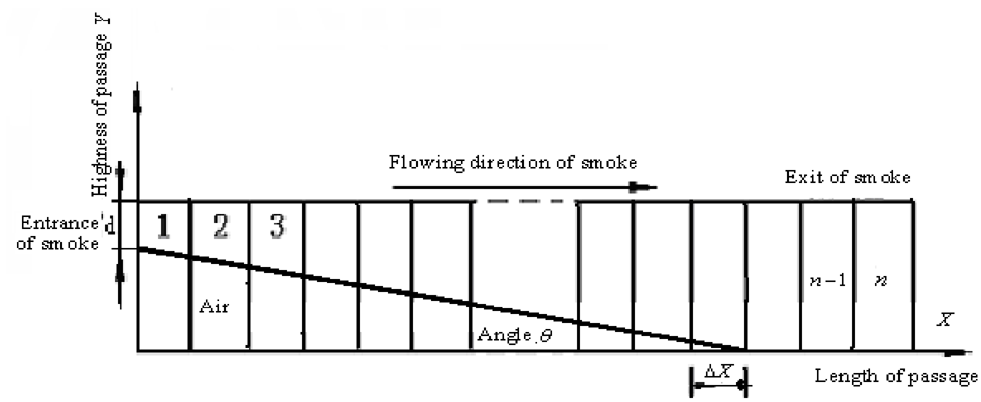

Fig. 3: Mesh map of passage

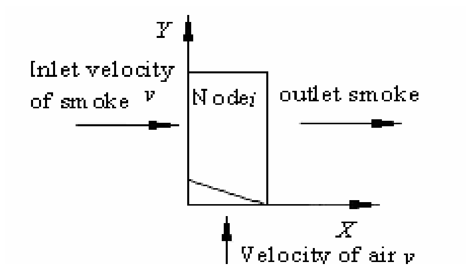

Fig. 4: Sketch map of smoke plume of node i

There were two factors that influence the temperature of each cell i: first, the heat smoke plume mixed with air and thermal flux of previous cell flowed into; second, the thermal flux flowed from cell i to the next cell and the temperature of itself changed., as illustrated in Fig. 4.
So the theoretical equation was built:

$$Cp \cdot \rho \cdot V_i \cdot \left(T_i^{p+1} - T_i^p\right) = Q_1 + Q_3 - Q_2 - Q_4$$

$$i < [(H-d)/tg\theta]/\Delta x \qquad (11)$$

$$Cp \cdot \rho \cdot V_i \cdot \left(T_i^{p+1} - T_i^p\right) = Q_1 - Q_2 - Q_4$$

$$i > [(H-d)/tg\theta]/\Delta x \qquad (12)$$

where,
C_P = The constant pressure specific heat of smoke plume, $J/_{kgk}$
ρ = The consistency of smoke plume, $kg/_{m^3}$

The thermal flux equation of smoke plume flowing into node i:

$$Q_1 = \rho_1 \times L \times [(i-1) \times \Delta X \times tg\theta + d] \times u \times Cp \times T_{i-1}^p \qquad (13)$$

The thermal flux equation of smoke plume flowing out of node i:

$$Q_2 = \rho_1 \times L \times [(i) \times \Delta X \times tg\theta + d] \times u \times Cp \times T_i^p \qquad (14)$$

The thermal flux equation of air flowing into node i:

$$Q_3 = \rho_0 \times L \times \Delta X \times tg\theta \times v \times Cp \times T_0 \qquad (15)$$

where,
ρ_0 = The consistency of air, $kg/_{m^3}$
ρ_1 = The consistency of air, $kg/_{m^3}$
u = The velocity of smoke plume, m/s
T_0 = The temperature of air, K

The heat capacity of smoke plume exchanging with wall:

$$Q_4 = \alpha(T_i^p - T_{i0}^p)A \qquad (16)$$

where,
α = The force-heat transfer coefficient of wall in smoke plume were a, $w/_{m^3k}$
T_i^p = The temperature of node i at time p, K
T_{10}^p = The temperature of wall contacting with node i
A = The surface area of heat exchange, m^2

And the temperature of each cell could be obtained of simultaneous Eq. (8) to (12).

INSTANCE

The smoke plume in the passage of a real building was calculated in use of this model and the passage was 35 m (x) ×1.5 m (y) ×2.8 m (z). The initial temperature of wall was 291 k, thermal diffusivity was 2.58×10^{-6}

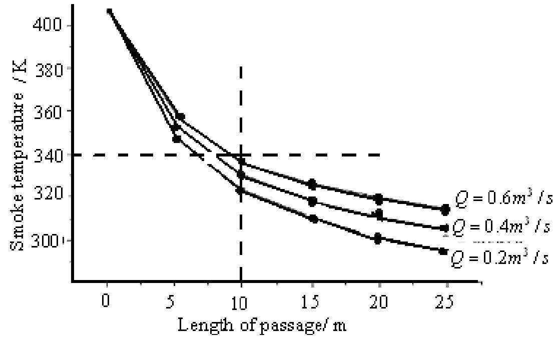

Fig. 5: Temperature curves of smoke plume changing with passage length

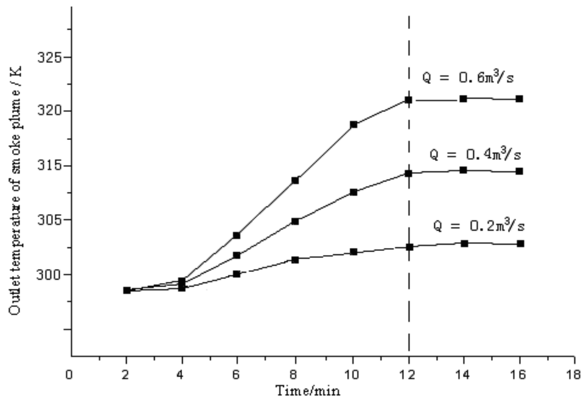

Fig. 6: Temperature curves of smoke plume changing with passage length

and thickness was 240 mm. The temperature of room was also 291 k.

Relationship between temperature of heat smoke plume and length of passage: On the assumption that the temperature of smoke in the entrance was 773 k and the smoke flux was 0.2, 0.4, 0.6 m^3/s, respectively and the temperature of smoke in the exit of passage was calculated for 30 min with the length of passage for X-direction and the temperature in the exit for Y-direction. The results were illustrated in Fig. 5:
Some conclusions could be obtained from Fig. 5:

- The smoke temperature continuously drops with the length of passage and it was closed to room-temperature in the exit.
- The temperature changing was related with the smoke flux, greater the smoke flux was, slower the change of temperature was, less the smoke flux was, faster the change of temperature was.
- The smoke temperature which was influenced of smoke mixed with air drops quickly in front of the 10 m as boundary according with the abscissa. But after boundary the downtrend was mitigated. So the major factor that influences the temperature change of smoke was that the smoke mixes with the air and the heat transfer between the smoke and the wall was the minor factor.

Relationship between temperature and time in exit of passage: The temperature of smoke in the exit of passage was calculated with the time for X-direction and the temperature in the exit for Y-direction, the smoke flux was 0.2, 0.4, 0.6 m^3/s, respectively. The results were illustrated in Fig. 6:

- The smoke temperature which was mainly influenced of smoke in the entrance was not stable and rise in the entrance in front of the 12 min as boundary according with the abscissa. But after boundary the smoke was stable and the temperature gradually fell down and the major influencing factor was the heat transfer on the wall.
- The smoke mixing with air was the major factor that influenced the temperature change according with the temperature curve, the heat transfer on the wall influenced little.
- From those curve of different flux, greater the smoke flux was, higher the temperature of smoke in the exit and less the smoke flux was, lower the smoke temperature in the exit was.

CONCLUSION

- It is known that this mathematic model is effective on analyzing the temperature diffusion of high-rise building fire smoke from previous analysis.
- The variation in temperature of heat smoke plume is mostly influenced by the smoke flux in the entrance and not too influenced by the heat exchange with the wall.
- The smoke capacity is powerful influenced on the smoke temperature diffusion in high-rise building fire, therefore there were not suitable for being excessively fires load to reduce the smoke capacity in high-rise building.

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