A NETWORK MODEL OF SIMULATING SMOKE MOVEMENT IN BUILDINGS

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ABSTRACT

Fire model is a key element in the design and assessment of building fire safety with performance-based approach. There are at least three types of fire models: zone models, field models and air flow network models. Network model can examine the effects of a fire occurring at a particular location inside a building on the distribution of parameters in the whole building. However, the application of network models is mainly in mine shaft ventilation. It is increasingly popular to study fire smoke movement in high-rise buildings with the development of its technique.

In this paper, an air flow network model is developed for studying smoke movement in a building fire. This model mainly covers the analysis of fire smoke movement, the distribution of each room temperature and the calculation of heat transfer of structure. The mass balance equations, heat balance equations and heat transfer equations corresponding to every sub-model were described briefly. The calculation methods based on principles of graphics theory and their computer programs were also described. Results predicted by the model are compared with the experimental results.

1. INTRODUCTION

Studies on smoke movement patterns and smoke control systems [e.g. 1-4] are commonly conducted by experiments with real fires in physical models, and by computer modelling. Smoke movement in building fires is affected by the shape and volume of the building, compartment patterns, geographic and atmospheric conditions. It is unrealistic to carry out fire and smoke tests on all kinds of buildings with different fire conditions. Predicting smoke movement in building fires by computer models, or mathematical fire models [e.g. 5-10], takes the advantages of setting up the parameters freely, and can get the predicted results rather easily. Therefore, computer modelling would be more practical and so is a critical element in the design of building fire safety through performance-based codes [e.g. 11]. This is also attracting more and more attention in China.

Computer fire model [e.g. 1,5-10] is a powerful design tool for the building designers. It can provide certain criteria on hazard assessment and on making decisions under different scenarios. Relevant design data can be provided for fire safety design. Efforts are focused on improving the performance and accuracy of prediction of those fire models. Basically, there are three types of fire models at the moment: zone models [6,7], field models [8] and air flow network models [1,9,10]. Both field models and zone models are commonly used to simulate building fires. However, the application of network models is mainly in mine shaft ventilation. But this has the potential of becoming a more popular design tool, ASCOS [1] and CONTAM [e.g. 9,10] are the obvious examples.

In using air flow network model to predict fire and smoke movement, the space concerned is regarded as node points. The parameters inside the nodes are uniform. The parameters are also uniform on the passage plane connecting all the finite space, and the node points are the convergent points of all the passages. Based on the assumptions made in the network model, the effects of a fire occurring at a particular location inside a building on the distribution of parameters in the whole building can be examined. This modelling approach is applicable in simulating building fires at the development stage of a fire.

This article puts forward the network model of smoke movement in building fires and its calculation methods. Results would give some insight into this area on modelling a building fire.

This is useful in developing performance-based fire codes.

2. NETWORK MODEL

Analysing smoke movement in an air flow network model is to establish the mass balance equation of the room by taking the mass production rate of a room equal to the sum of mass flow rate through all the openings of that room. By referring to Fig. 1, the following equation can be established in terms of the volume of smoke flow from Room i to Room j through the opening M_{ij} (kgs^{-1}) with M^+ leaving and M^- entering Room i respectively; the volume of smoke flow from Room j to Room i through the opening m_{ji} (kgs^{-1}); the mass production rate of Room i M_i ($M_i = M_{com,i} + M_{sup,i}$); the burning rate of Room i during the fire $M_{com,i}$ (kgs^{-1}); the rate of air flow to Room i $M_{sup,i}$ (kgs^{-1}); the smoke density ρ_i and the volume of Room i V_i:

$$V_i \frac{\partial \rho_i}{\partial t} + \sum_j \left(m_{ij} - m_{ji} \right) = M_i \qquad (1)$$

The mass flow rate through each of the opening depends on the temperature difference, pressure difference and the position of the neutral plane between the two adjacent rooms of the opening:

$$m_{ij} = f(P_{ij}, T_i, T_j, B, \mu)$$

$$m_{ji} = f(P_{ji}, T_i, T_j, B, \mu) \qquad (2)$$

where μ is the flow coefficient of the opening; B is the width of the opening (m); P_{ij} and P_{ji} are the pressure difference at the two sides of the openings of Room i and Room j respectively (Pa); and T_i, T_j are the temperature of Room i and Room j respectively (K).

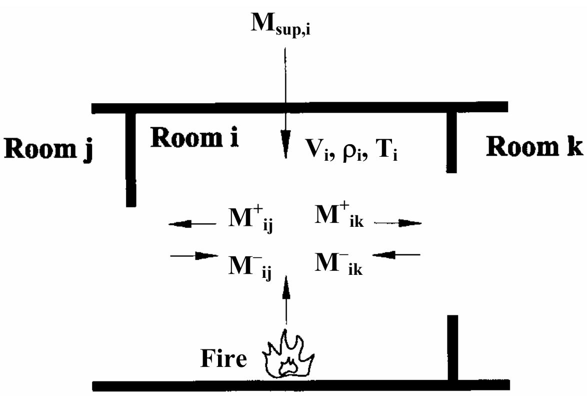

Fig. 1: Mass balancing

Therefore, the flow rate of each opening can be obtained by solving for the mass flow rate and the pressure difference of each opening from the set of equations for all the rooms in the building established from equation (1). To solve the equation, a building air flow network can be written by Graphics Theory through air exchange trees and path matrix. With this method, the pressure and flow rate [12] of different rooms and passages of a building at different time can be calculated.

To analyse the room temperature, a heat balance equation is set up with the heat production rate and heat flow rate. As shown in Fig. 2, based on the relationship between the heat flow rate and room temperature, the set of heat balance equations can be transformed into a set of equations on room temperature. The heat balance equation of fire room i is:

$$I_{Ci} = I_{Li} + I_{Ri} + I_{Wi} + I_{Ai} \qquad (3)$$

where I_{Ci} is the heat release rate of combustibles in the fire room per unit time (kW); I_{Li} is the heat carried by the fire plume through the opening per unit time (kW); I_{Ri} is the radiative heat loss through the opening per unit time (kW); I_{Wi} is the heat absorbed by wall surfaces per unit time (kW); and I_{Ai} is the heat absorbed by indoor gases per unit time (kW).

Note that I_{Ci} can be expressed in terms of the ventilation factor $A\sqrt{H}$ as:

$$I_{Ci} = KA\sqrt{H}q_{co} \qquad (4)$$

where K is the ratio coefficient; A is the area of the opening (m^2); H is the average height of the opening (m); and q_{co} is the heat release of burning 1 kg combustibles ($MJkg^{-1}$).

I_{Li} and I_{Ri} are the sum of heat loss through all of the openings, which can be expressed in terms of the specific heat capacity of air C_p; the area of the opening A_{Rij} (m^2); the radiation penetration rate τ_{ij}; and the Stefan-Boltzman constant σ as:

$$I_{Li} = \sum_j I_{Lij} = \sum_j \left(C_{pi} m_{ij} T_i - C_{pj} m_{ji} T_j \right) \qquad (5)$$

$$I_{Ri} = \sum_j I_{Rij} = \sum_j A_{Rij} \tau_{ij} \sigma \left(T_i^4 - T_j^4 \right) \qquad (6)$$

I_{Wi} is the sum of heat absorbed by all of the wall surfaces which can be expressed in terms of the area of the k^{th} wall surface of Room i $A_{Wi(k)}$ (m^2); the surface heat exchange coefficient of the k^{th} wall surface of Room i $\alpha_{i(k)}$ ($Wm^{-2}K^{-1}$); and the surface temperature of the k^{th} wall surface of Room i $T_{Wi(k)}$ (K) as:

$$I_{Wi} = \sum_k I_{Wi(k)} = \sum_k A_{Wi(k)} \alpha_{i(k)} \left(T_i - T_{Wi(k)}\right) \quad (7)$$

Heat absorbed by indoor gases is expressed in terms of the gas density ρ_i, specific heat C_{pi}, volume V_i and temperature T_i of Room i as:

$$I_{Ai} = \rho_i C_{pi} V_i \frac{\partial T_i}{\partial t} \quad (8)$$

Substituting equations (4) to (8) into equation (3) would give an equation with temperature T_i being the unknown. A set of equations can be established similarly for other rooms. By integrating the set of equations, the temperature of each room at different time can be obtained [13].

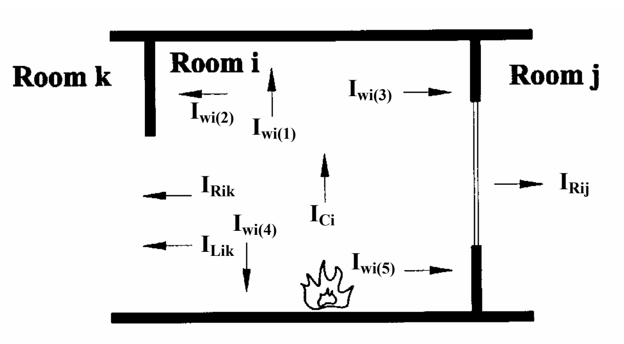

Fig. 2: Heat balancing

The heat transfer of protective structure should be analysed before establishing the heat balance equations for the rooms. Theoretically, heat transfer is a three-dimensional process. But for buildings with the height and width of all wall surfaces much greater than the thickness, heat transfer will be treated as a one-dimensional conduction problem with the heat transfer equation expressed as:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) \quad (9)$$

where T is the temperature (K); t is the time (s); λ is the thermal conductivity coefficient ($Wm^{-1}K^{-1}$); ρ is the density (kgm^{-3}); and c is the specific heat ($Jkg^{-1}K^{-1}$). The equation can be solved by finite difference methods [14].

3. THE COMPUTER PROGRAM

A proposed program was developed for studying smoke movement in large buildings based on the above equations. In that program, there is one main program and 42 sub-programs which can be summarized by a flowchart as shown in Fig. 3 for calculating the temperature, thermal conduction through the walls and smoke movement. The main functions of the program are:

- The temperature, pressure, smoke concentration and mass flow rate of the opening at any part of the building at any time can be calculated. This gives dynamic simulation of smoke movement. Based on these results, other data such as the temperature and smoke concentration along the evacuation routes during a fire can be predicted for assessing the evacuation pattern.
- During the calculations, effects of the fire on the building structure can be handled easily. For example, the flow rate coefficient through the openings and surface area of walls according to the extent of damage of the doors and windows can be varied to describe opening or closing a door during evacuation.
- Pressurization or smoke exhaust in a room can be described easily by changing the parameters concerned. Therefore, different smoke management systems can be evaluated to get better design.

4. FULL-SCALE BURNING TESTS

Physical full-scale burning tests [15] were carried out in a high-rise tower at the Sichuan Fire Research Institute, Public Security Ministry, China for validating the predicted results. A plan of the tower of length 23 m and width 20 m is shown in Fig. 4. Tests were conducted in the rooms at the centre of the second floor. At the moment, use of wood as building materials in China is not so much than in countries such as Japan and Sweden. Literature reported that the fire load of a house in Japan and Sweden was 10 kgm^{-2}. In this study, 125 kg wood (equal to a fire load of 7 kgm^{-2}) was used as the burning fuel. The wood was piled up neatly on an electronic balance, which was used to record the mass loss during the burning process for calculating the heat release rate of the combustibles. During the fire, all the smoke exhaust facilities were closed.

The equipment used in the fire tests was listed in Table 1.

Ten of the 20 thermocouples were placed inside the fire room of length 7.2 m and width 3.9 m in five measuring points (A, B, C, D, E) on a horizontal plane as shown in Fig. 5. Another two thermocouples were positioned vertically at 1.2 m and 0.4 m from the ground and the ceiling respectively. One thermocouple was placed at each room adjacent to the fire room; three in the corridor; two in the front room; and one in the front room and one in the staircase of the tenth floor.

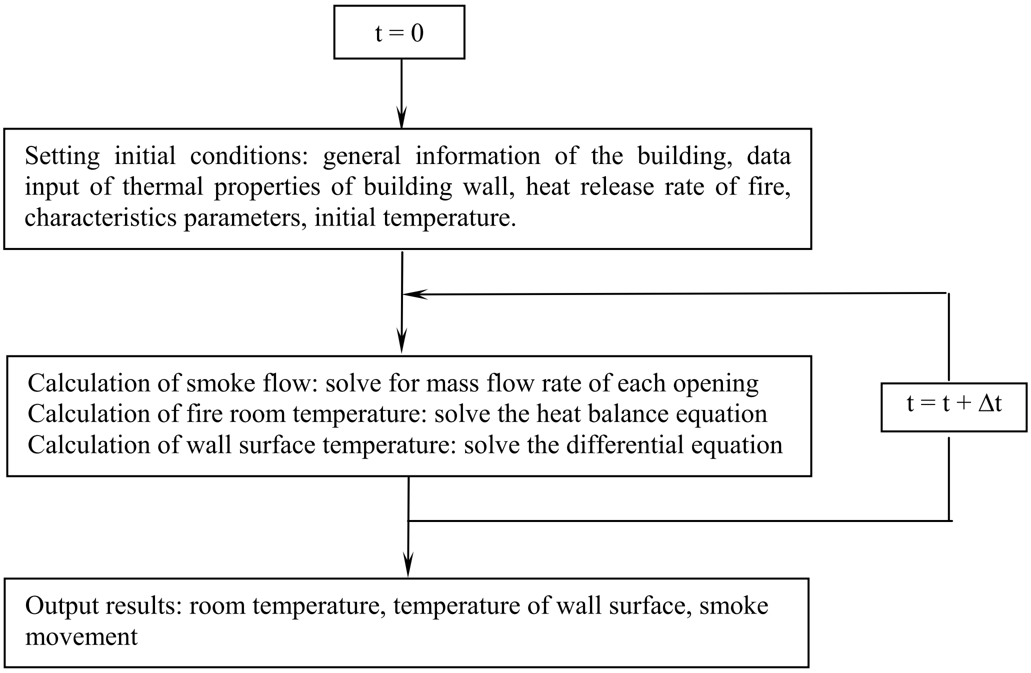

Fig. 3: Flowchart of the computer program

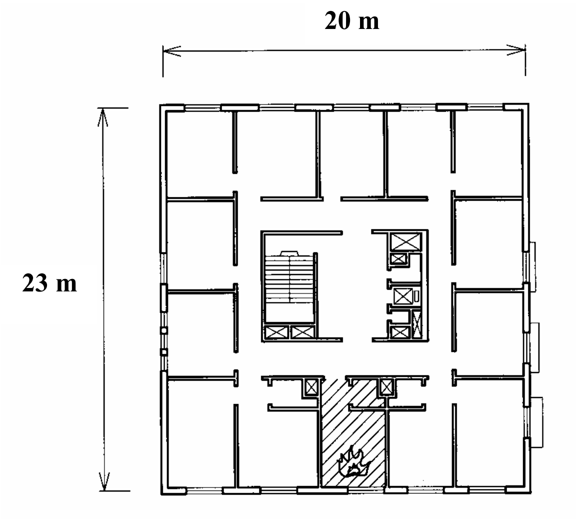

Fig. 4: Plan of tower

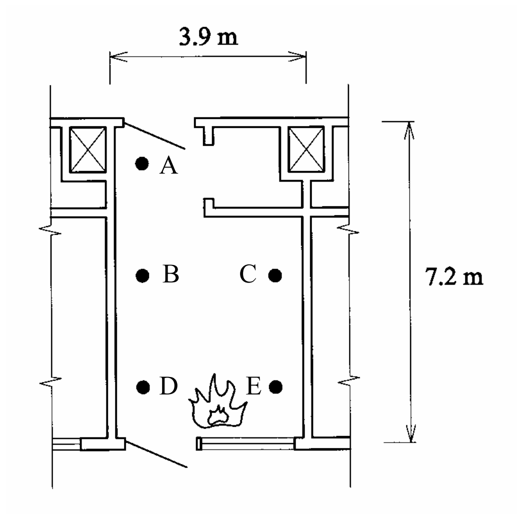

Fig. 5: Plan on the measuring points in the fire room

Table 1: List of equipment

Equipment	Quantity	Remarks
Nickel chromium – nickel silicon thermocouple	20	Range 0°C to 1300°C
Micro pressure gauge	2	Range 0 Pa to 6000 Pa
Digital differential pressure transducer	2	Range -50 Pa to +50 Pa
Pressure transducer and data logger	11	Range -120 Pa to +120 Pa
Hot sphere anemometer	2	Range 0 ms^{-1} to 10 ms^{-1}
Electronic balance	1	—

There were 11 pressure probes connected to the data logger. They were located at the staircase, front room, corridor and fire room of the second floor; the staircase, front room and corridor of the third and ninth floor; and the staircase of the tenth floor.

An electronic balance was placed at the centre of the fire room to record the mass loss during the fire for calculating the burning rate. A data acquisition system was installed at the bottom floor of the test tower for monitoring the test temperature and pressure, etc.

The procedure of the fire test was:

- Data acquisition system was started before ignition until the initial values of all measuring points became stabilized. Temperature and pressure of each measuring point were recorded.
- Data was recorded by the data acquisition system once every 30 s upon ignition.
- Evacuation of people during a fire was simulated by: Opening the door of the fire room 30 s after the fire had started. The door was kept open throughout. The door of the front room was opened 40 s after the fire had started and closed 3 minutes later. The door of the staircase was opened at 50 s and closed 3 minutes later. The duration of the fire was 30 minutes.
- Firemen entered the fire site 30 minutes after igniting the fire to put out the fire.

The heat release rate determined the fire size and development, and depended on the burning rate as:

$$Ic = 10638\ W_{mass} \tag{10}$$

where W_{mass} is the mass loss of wood per unit time. The curves of heat release against time are shown in Fig. 6. The average heat release during steady burning was 360 kW.

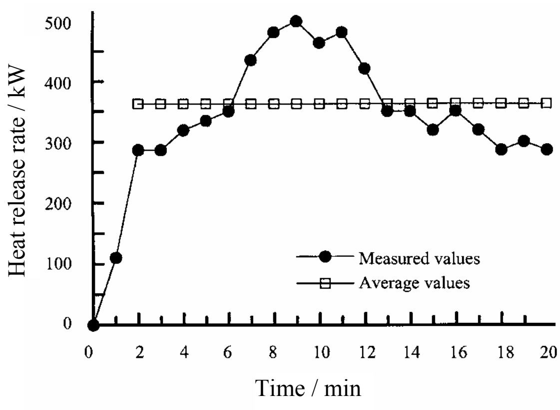

Fig. 6: Heat release rate

Taking the smoke temperature of the fire room to be the average value of temperatures measured by the ten thermocouples inside the fire room, the variations of room temperature during the fire are plotted in Fig. 7.

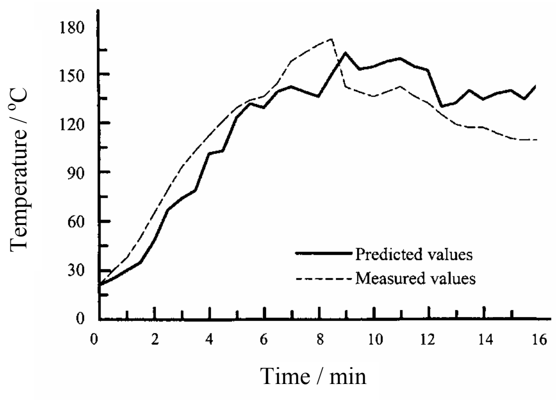

Fig. 7: Fire temperature in the fire room

The mass flow rate through an opening depends on the pressure difference between the two sides. Therefore, the mass flow rate through a particular opening can be obtained by measuring the pressure difference at the door between the front room and the staircase. The variations of mass flow rate at the door between the front room and the staircase of the first floor are shown in Fig. 8.

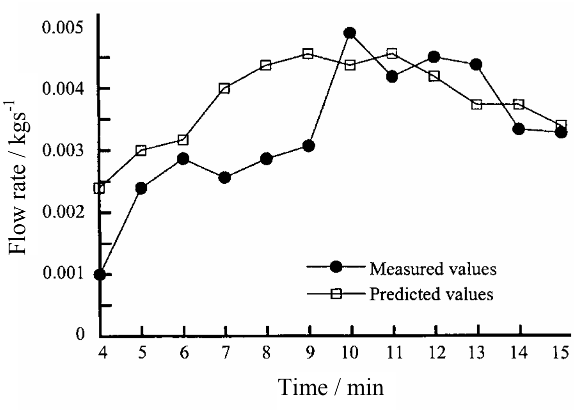

Fig. 8: Mass flow rate

Note that the arrangements of the fire experiments were based on the field measurement of evacuation tests, with reference to the calculated results of evacuation models in other countries. Actual evacuation is very complicated and depends on the design of the building, the number of people and their age, the position of fire origin, whether the doors are open or closed along the passages from the rooms to the escape route, etc. There are also devices in the smoke management systems to prevent spreading of smoke. In this study, all the smoke blocking devices were closed since the fire test was on validating the developed air flow network model. It was also assumed that the occupants took action 30 s after the fire had started by opening the door of the fire room to escape. After about 5 to 10 s, the occupants were at the corridors and opened the door to the front room. They opened the door to the staircase and escaped at a further 5 to 10 s later.

5. NUMERICAL EXPERIMENTS

Based on the actual fire conditions and the data of the building, predictions were made using the developed smoke movement program. Predicted results were compared with the measured results. The shape and trend of both curves of the measured and predicted room temperature are the same as shown in Fig. 7. Both the measured and predicted values reached their maximum at between 8 to 9 minutes, and then became steady gradually. Such observations satisfied the fire development patterns. At the initial stage, because there was sufficient amount of oxygen, the materials were burning completely, and the temperature inside the fire room rose obviously. As the burning continued, the available amount of oxygen decreased, the temperature of the fire room started to decrease gradually with slight fluctuations after being relatively stable for a certain period of time.

The development of a fire can be divided into at least two stages. In the first stage, the fire development mainly depends on the fuel, which is called the fuel-controlled stage. The fire development in the second stage is mainly governed by the availability of oxygen in indoor air, which is referred to as the ventilation-controlled stage. The absolute difference between the measured and calculated values at 8 minutes was 32.3°C, and the relative difference was 19.3%. The absolute difference at 16 minutes was 34.1°C and the relative difference was 31.4%. The average relative difference between the measured and calculated values was 15.4%.

The shape and trend of the curves of the measured and predicted flow rate are the same as shown in Fig. 8. Similar to the temperature curves, the variations in flow rate also satisfied the patterns of fire development. The maximum difference of 0.015 kgs^{-1} between the predicted and measured value was observed at 9 minutes. The average relative difference was 20.9%.

The above comparison of the measured and predicted results of room temperature and flow rate suggested that although the measured values and the predicted values are not identical, relatively speaking, the curves of predicted values are smoother. It is because in the calculations, some factors may be ignored or idealized; but the real situations are much more complicated, with many unexpected factors and larger fluctuations. Also, there are measurement errors. However, the two curves showed the same trend and the difference was not very large, which also satisfied the patterns of fire development.

To further validate the reliability of the model, calculation methods and program, a set of test data was selected from the National Institute of Standard and Technology of USA [16] for comparison as shown in Fig. 9. Note that the fire source was located at the centre of the fire room with heat release rate of 100 kW. It can be seen from the figure that the predicted values agreed with the measured values.

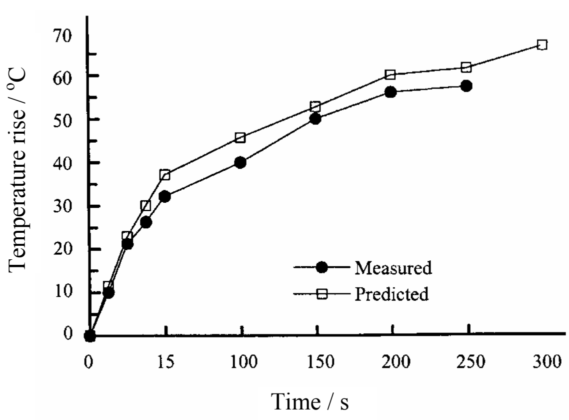

Fig. 9: Average temperature in the fire room for the NIST experiment

6. CONCLUSION

Currently, computer fire models [e.g. 5] are basically divided into field models [e.g. 8], zone models [e.g. 6,7] and network models [e.g. 1,8]. Field and zone models are widely used in many countries on projects involving engineering performance-based fire codes [e.g. 11] for studying building fires. Air flow network models are useful and should be seriously considered by the Authority [e.g. 10]. The feasibility of applying network models in building fires was preliminarily explored in this article.

The basic theory of a self-developed network model of smoke movement in building fires were described in this article. The software developed for predicting the smoke movement was briefly outlined. Fire tests were carried out which proved that the predicted results are reasonable and reliable. These demonstrated that the model and the associated equations suggested in this article are accurate, feasible and practical. The software developed can be used as a tool for assessing the design of smoke exhaust systems in buildings. The next step of research would be to further improve the model and the application software, to make the application procedures become more popular and practical; while on the other hand, to research on the prediction of evacuation characteristics of buildings.

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