

NUMERICAL AND EXPERIMENTAL STUDY ON OPTIMAL RUNNING MODE OF SMOKE EXTRACTION SYSTEM IN A SUBWAY STATION IN BEIJING

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ABSTRACT

Velocity fields on the platform area and flow rate of the smoke extraction system were experimentally measured under the different fan-operation modes in an actual subway station in Beijing. The velocity at the four tunnels connected with the station and velocity at the stairs between platform and concourses were obtained. Through simulation based on the measured results, the smoke velocity, temperature and concentration in case of station fire under the different fan-operation modes were analysed, and the optimal smoke extraction mode was proposed. Improved advices about the issues of the current extraction mode were put forward, to offer reference for the current running modes of the subway extraction system and the design of the future subway extraction system.

KEYWORDS

Subway station; Fire; Extraction mode; Experiment; Numerical analysis

INTRODUCTION

As the major public transportation and main passenger artery, subway is an effective tool to alleviate the intensive traffic in modern cities. But during the subway construction and working, there is a non-neglectful problem that is how to prevent and deal with subway fire effectively.

The subway, a type of underground structure, is different from ground buildings and always buried deeply in the underground from several meters to several decades meters. The connection with the outside is the several exits. When subway fire, the direction of the passenger evacuation is the same as the smoke movement, the exits become to extraction mouths. The hot smoke can limit the evacuation sight, furthermore, passenger will asphyxiate or die due to the poisonous gases in the smoke. A fire taking place at an urban subway station and a tunnel causes heavy casualties and tremendous loss of property as shown in the cases, such as Jungangno incendiary fire in Daegu, Korea (in 2003, 198 casualties), London Cross subway fire in Britain (in 1987, 32 casualties). Now the subway code prescribes that the train must run to next station to evacuate when train fire in tunnel, using fire control system to put out the fire and extract the smoke in the station. Therefore, the

smoke control in subway station is an important study in the subway construction.

Now there are three main study methods about subway fire: full scale experiment, scale model experiment and numerical simulation. Full scale experiment is the most ideal and persuasive method for fire study. But there are some disadvantages, such as expensive spending, limited cases and bad emersion in full scale experiment. The present study is the smoke movement characteristic and smoke extraction modes using scale model experiment and numerical simulation. For example, ZHONG and SHI (2006) built a deep-burying model station which scale is 1:10, and experimented for the train fire in subway platform. Hasemi et al. (2004) used pool pan fire limited heat release rate to examine the characteristics of heat behavior in case of a fire outbreak at a subway platform. MICLEA and MCKINNEY (2000) used CFD simulation software CFX to evaluate the ability of emergency vent system controlling smoke in platform fire in a station installed screen. Dong-Ho Rie (2005) studied three vent modes in a subway station through numerical simulation and scale experiment for train fire and gained the optimal vent mode.

In this study, we took measurements at a typical monolayer island stations on 1#and 2#lines in Beijing in December 2005, the flow rate of the extraction system and velocity on the platform were experimentally measured, the real measured values at four tunnels connected with the station and two stairs between the platform and concourses were obtained. These were used to estimate the heat and smoke behavior numerically in order to obtain the optimal running mode of smoke extraction system on fires. Finally advices were offered to improve and perfect the present running control methods of smoke extraction system.

MEASUREMENT IN THE ACTUAL SUBWAY STATION

Purpose

Through experiment for the running conditions of the smoke extraction system in a typical subway station in Beijing, the flow rate of extraction fan, velocity distribution of stairs and exit paths were obtained; the actual ability of the extraction

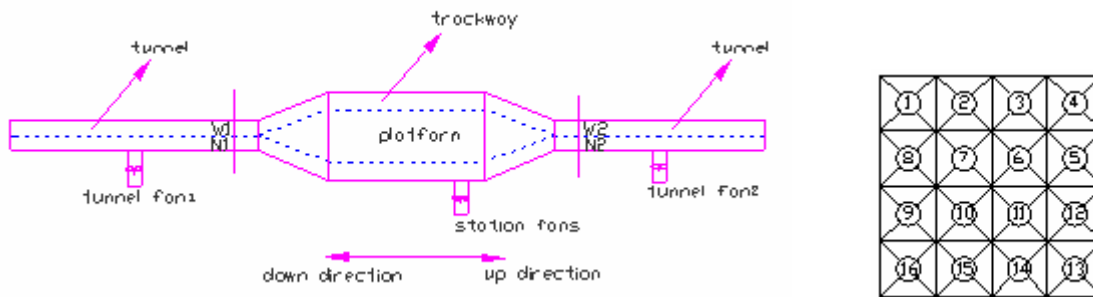


Figure 1 Fans in the measured station and distribution of the measurement points

was examined; at the same time, the velocity distribution at the key position in station and tunnels, as well as the air movement in cold status(no fire) were provided as the boundary condition for the numerical simulation to verify the reliability of the numerical analysis.

Description of the subway station

The measured subway station is located on 1#and 2#lines in Beijing which is the object of this study. The dimension of the station is approximately 148.8m × 20.3m × 6.7m. There are two concourses located at each side of the station. The concourses are connected with the platform through the east and west stairs and 3.65m higher than the platform. The vertical height between the concourses and the outside ground is 13.6m. The west concourse has two exits (A and C) connected with the outside. The way of exit A is 23.2m long, and the width of stairs is 6.1m; the way of exit C is 52.35m long, and the width of stairs is 5.9m. The east concourse has one exit (B) connected with the outside. The way of exit B is 39.45m long, and the width of stairs is 5.9m. The equipment and employee houses are located at the under and above the two concourses respectively.

Smoke extraction system

The building time of the station is relatively early compared with the modern subway station. The vent and extraction system are the same fan system which is composed of fan, muffler, draught and gloriette. The fan system ventilates or extracts for the station through positive and reverse running. There is no special vent and extraction duct. In normal status, the fans run positively in the ventilation mode. On the fire case, the fans turn to reverse running in the extraction mode; and at the same time, the fans in the tunnels connected with the station start up to assistant the ventilation or extraction, the direction of the smoke movement in platform is horizontal (Figure 1).

Conditions and methods of measurement

Time: Measurement was conducted after a daily subway service was over on the December 15, 2005

night.

Place: Subway station and tunnels connected with the station

Method: Cold smoke

Contents: Velocity at station, velocity at tunnel connected with the station, flow rate of fans

Instruments: hand hot ball anemoscope

The measured spots of the tunnels and the distribution of the measured points are shown in Figure 2: the four tunnels connected with the station W1, N1, W2, N2, and the measured section is 100m long from the station; the dimension of the tunnel section is 4.1m × 4.35m. The average measured velocity of the tunnel sections is shown in table 1. The “supply” in table1 means that the fans in tunnels operate in opposite and supply to station, the direction is from tunnels to station.

Comparison of computational results with measured values

Mathematical model

The commercial CFD software PHOENICS is used to solve the problem. The turbulence model used in the numerical model is the widely used standard $K - \epsilon$ model. The buoyancy model is a nonlinear Boussinesq suppose. The measured average velocity of the tunnel sections is adopted as the velocity boundary conditions in numerical analysis.

The control equation includes mass, momentum, energy equation , $K - \epsilon$ equation and η_t equation.

The common control equation is

$$\frac{\partial(\rho\phi)}{\partial t} + \text{div}(\rho U\phi - \Gamma_\phi \text{grad}\phi) = S_\phi$$

In the equation, ϕ is the common variable which is the solved variable of u, v, w, k, ϵ, T etc. ρ is the density; U is the velocity vector; Γ_ϕ is the generalized diffused coefficient; S_ϕ is the generalized source.

The viscous coefficient $\eta_t = c_\mu \rho k^2 / \epsilon$

Table 1 Fan modes and measured velocity of the tunnel sections

MODES	FAN MODES			VELOCITY OF THE TUNNEL SECTIONS			
	Tunnel fan 1	Station fan	Tunnel fan 2	W1	N1	W2	N2
Case1	Stop	Extract 96m ³ /s	Stop	0.94m/s Supply	0.77m/s Supply	0.55m/s Supply	0.59m/s Supply
Case2	Stop	Extract 97 m ³ /s	Supply	0.40m/s Supply	0.43m/s Supply	1.84m/s Supply	1.82m/s Supply
Case3	Extract	Extract 99 m ³ /s	Supply	0.34m/s Extract	0.30m/s Extract	1.84m/s Supply	1.92m/s Supply
Case4	Supply	Extract100m ³ /s	Supply	0.88m/s Supply	0.52m/s Supply	1.78m/s Supply	1.92m/s Supply

All of these equations are discretized in finite volume method, the momentum equation is discretized in stagger grid, the diffused item is discretized in hybrid scheme which is the combination of windward and center, the solve method is SIMPLE algorithm, structural grid is adopted for computation.

Physical model

A full-size three-dimensional model was built according to the actual size of the station in Cartesian coordinate (Figure 2). The origin of the coordinate is the origin of calculation region, the X axis is parallel to the length of the station, the Y axis is parallel to the width of the station, and the Z axis is parallel to the height of the station. The attributes of the objects and the wall friction in the station are not considered. The walls are set in adiabatic boundary. The velocity

of the tunnel sections of case 3 in table 1 was used as the velocity boundary to simulate the cold (no fire) status.

Velocity results comparison

The velocity on the stairs located in the platform to the west concourse was obtained by numerical analysis. The comparison of the results obtained by numerical analysis with the velocity measured on the stairs was conducted in Figure 3: the velocity in different height of the stairs had layers in height, the velocity in z=3.675m height was higher than in z=4.675m; and in stairs width direction, the velocity in center was the highest, and decreased in two sides gradually, the range of the velocity change was in 1.5m/s~1.0m/s. The velocity meets the requirement of the subway design code in China.

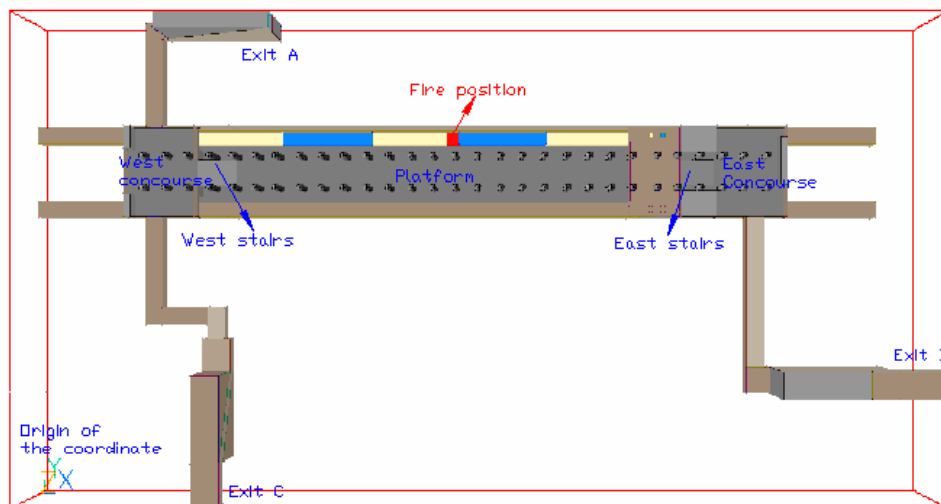
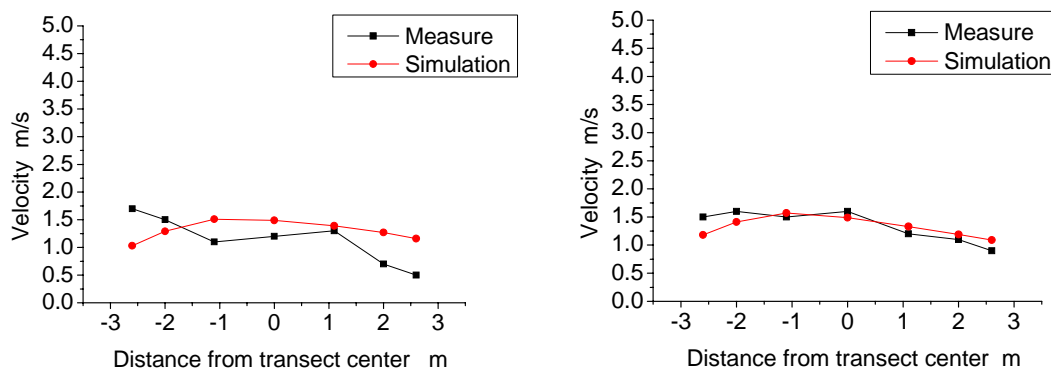
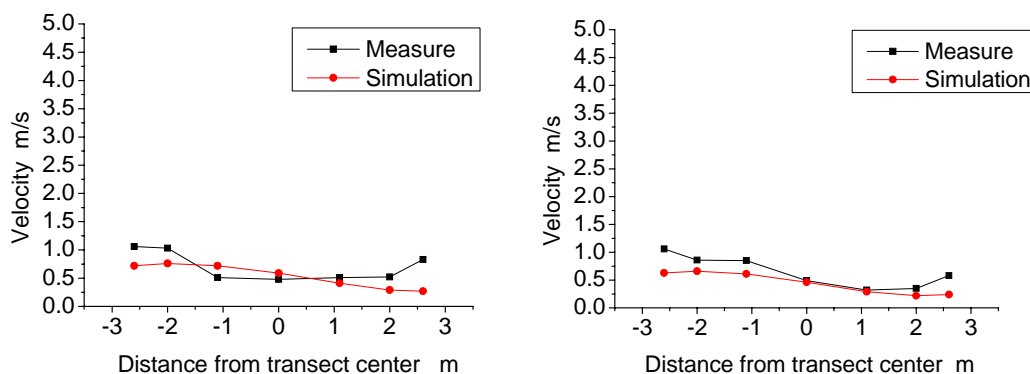


Figure 2 Physical model of the measured station



(a) velocity on z=4.675m height (b) velocity on z=3.675m height

Figure 3 Velocity distribution on different height in the west stair



(a) velocity on z=4.675m height (b) velocity on z=3.675m height

Figure 4 Velocity distribution on the different height in the east stairs

The velocity on the stairs located in the platform to the east concourse was also obtained by numerical analysis. The comparison of the results obtained by numerical analysis with the velocity measured on the stairs was conducted in Figure4: the velocity in the stairs was less than 1.0m/s and could not meet the velocity of 1.5m/s in the platform fire required in the subway design code in China. It is proposed that there should set baffles in the two sides of the stairs, which can increase the velocity of the stairs to meet the requirement of the code.

The velocity on the west stairs was higher than on the east stairs, which has a great relation with the station construction. The west concourse has two exits (A and C) connected with the outside. The air flow from outside to the station in the two exits ways and flow to the platform through the west stairs, which make the supply air bigger and the velocity higher. However the east concourse has only one exit (B) connected with the outside. The supply air is smaller and the velocity is lower.

In addition, as shown in Figure3 and Figure 4, the

results obtained by numerical analysis are very similar to measured velocity at the measurement points on the stairs, which show the correction of the model and the reliability of the numerical results. Though the results obtained by measurement and numerical analysis are probably affected by 1)measurement error, 2)the exit way is shorter and affected by the outside airflow greatly, 3)the unsteady of the fan running, 4) the simplified physical model and the idealized calculation condition etc., which lead to the error between the numerical analysis and measured results. But the error is in the limited range, the results can verify the correct of the numerical simulation.

OPTIMAL EXTRACTION MODE ANALYSIS FOR TRAIN FIRE ON THE MEASURED STATION

When train fire on station, the running modes of the extraction system play very important role for the smoke control. In this paper, when the train fire on the station, the characteristic of the smoke movement in different fan-operation modes were studied

through numerical analysis which use the measured values as the boundary. The optimal running mode of the smoke extraction system was obtained through the numerical analyses; and the improvement advices were put forward for the modern extraction system.

Extraction modes

The modes of the extraction system were considered four modes from Case 1 to Case 4 in table 1. The direction of the airflow was from tunnel to station in case1, case 2 and case4, but reverse in case 3.

Boundary sets

Temperature boundary: summer condition was considered, the temperature in the three exits and four tunnel connections was set to the summer average temperature 26.2°C, according to the weather information of Beijing in “Environment Annuals of Beijing Subway”. It was also assumed that all of the walls in the subway station were adiabatic.

Velocity boundary: As was shown in table 1.

Pressure boundary: the relative pressure of the exits and four tunnel connections was 0.0Pa (atmospheric pressure was 100000Pa)

Fans in the station: the two fans run in parallel, extract. The flow rate of the fans in the four cases was shown in table 1.

Fire model

The fire model can be steady or unsteady, but it can be assumed the fire is steady in the lack of heat release, which can make the design system more reliable. In this paper, 10MW of heat power was employed according to the design parameters of subway in abroad. It was also assumed the fire source is a heat and smoke source, the dimension of the fire is 2.7m×2.65m×2m as shown in Figure 2 ($x=92.9m, y=79.7m, z=1.5m$). The combustion process in the calculation was not considered, nor the radiation. The fire was unsteady and the period of numerical analysis was set to be 10 minutes.

Results and discussion

In station fire, it must meet the requirement in the following to ensure the passenger evacuate to safety area.

Velocity: When fire in the subway station, the extraction system should make the subway form negative pressure. The flow direction of air in the exit ways should flow from outside to station and ensure a definite velocity to control the smoke diffusion, and ensure passengers evacuate in the reverse direction of new airflow. The subway design code in China (2003) prescribes: when fire on platform in station, there must have a velocity no less than 1.5m/s towards down the stairs located in the concourse to platform.

Temperature: the NFPA130(2003) prescribes: The

temperature of evacuation route should be no more than 60°C. And according previous research (HUO 2003), when the smoke layer is higher than passengers eyes(1.5m), if the smoke temperature in the upper reaches to 180°C, there will be burn threat to passengers.

Concentration: When the smoke layer is below passenger eyes (1.5m), the volume percent of the CO in the smoke reaches to 0.25%, there will be toxic hazard to passengers. According to other research results (ZHENG et al. 2005), the volume percent 5% of the smoke is used as the smoke layer boundary.

Velocity distribution

As shown in Figure 5, in the four cases, the 1.5m/s velocity in the west stairs could be formed, which meet the requirement of the velocity in stairs in the subway code in China. The velocity was higher in center than two sides. Whereas, the velocity in east stairs was lower than 1.5m/s, and could not meet the regulation in the subway code in China. It was proposed that the enclosure baffles were set in the exit of the stairs to improve the velocity in the stairs, to make passengers evacuate in the reverse direction of the airflow.

In addition, the velocity in the west stairs was the highest in case1, and the velocity in the east stairs was the highest in case3.

It obviously that the difference of the station construction, fire position and extraction modes will lead to the difference of the velocity. According to the above, the air resistances in the two sides of the station are imbalance because there are two exits (A and C) connected with the outside in the western concourse and one exit (B) in the eastern concourse, which lead to the difference distribution of the velocity.

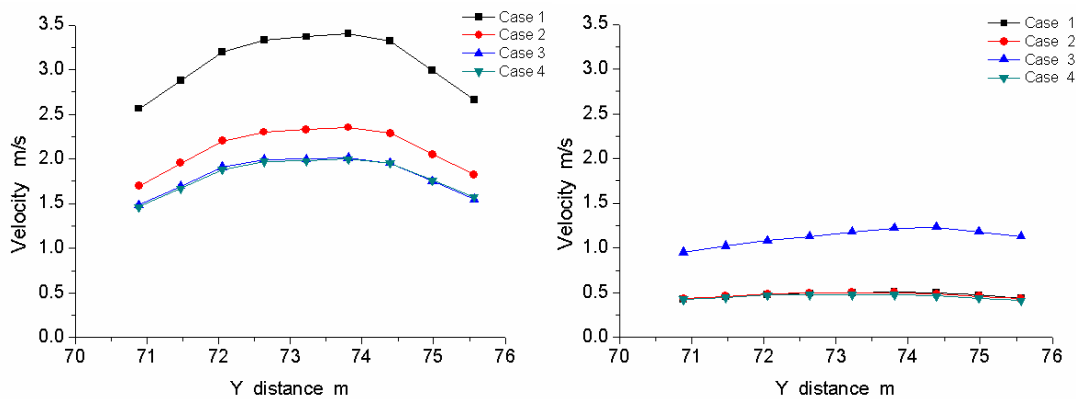
Temperature distribution

The Figure 6 shows that smoke temperature change according to time along the platform length (The position, P cross section is shown in figure 5(c)) at passenger eye height (1.5m from the platform surface).

As shown in Figure 6, smoke dropped rapidly in the front 360s and dropped slowly later. At last, smoke became steady gradually.

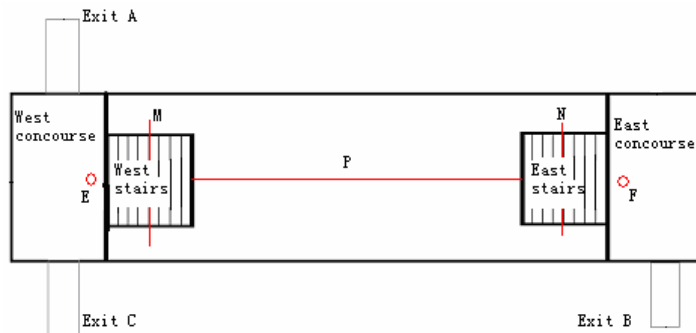
In case1, the smoke temperature was the lowest in the height of passenger eyes and under 60°C, which meet the requirements of passenger safety evacuation.

The temperature drop rate was approximately same as in the case2 and case4. The reason is that the tunnel velocity is the same in the two cases, which leads to the same air resistance and the same velocity and smoke distribution.



(a) West stairs

(b) East stairs



(c) Calculation points distribution

Figure 5 Velocity distribution on $z=4.675m$ height in the two stairs in the four fan-operation modes

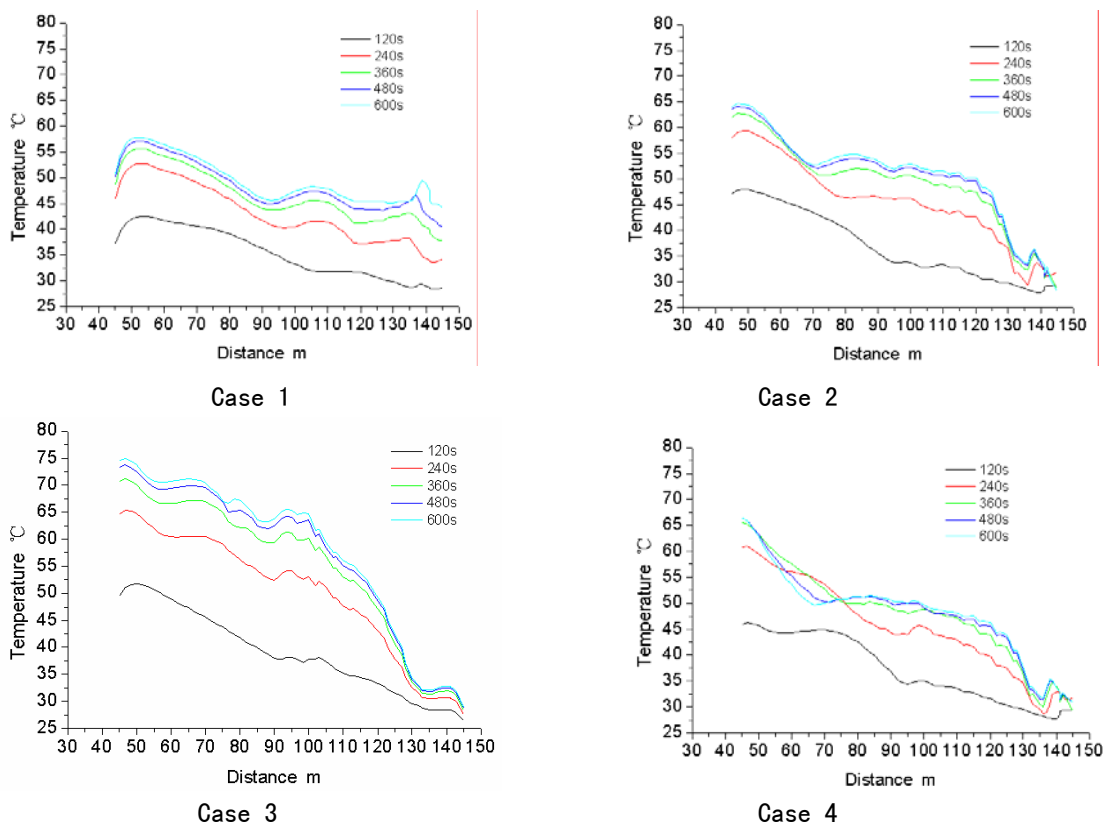


Figure 6 Temperature distribution on the various points in the middle of platform in the four cases

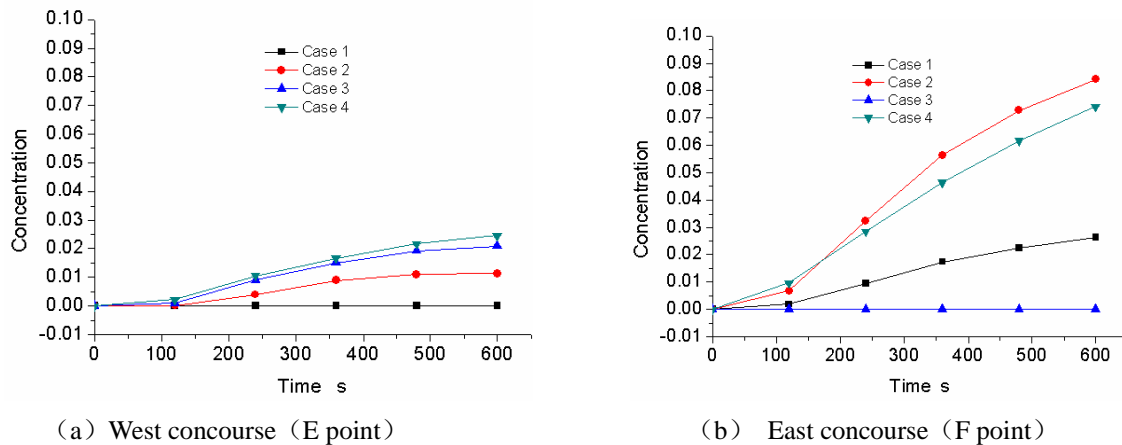


Figure 7 Smoke concentration change in time in four vent modes in concourses

Case3 was the worst case. The air in the west tunnel flowed from station to tunnel. In addition to the small supply rate in the west stairs and the large supply rate in the east stairs, the fan-operation mode could not control the smoke spreading to the west part of the platform, which make the smoke temperature higher there. At 360s end, the smoke temperature in the west part of the platform was higher than 60°C, which could not meet the safety evacuation conditions; Moreover, as is shown in Figure 6, when fire in the middle of the train, the fan in the east side could not control the smoke flow to the west part of the platform. Smoke spread from fire source to two sides of the platform and could not form the organizational extraction in the platform.

Concentration distribution

In the connection of the two concourses towards the platform, 1.5m from the concourse surface (E and F points in Figure5(c)), smoke changed in time in the four fan-operation modes is shown in Figure 7. As shown in Figure 7(a), in the west concourse, the smoke concentration in the 1.5m from the concourse surface was lower than 5%, which showed that the smoke drop had not threatened passengers, passengers could evacuate through the west concourse. As shown in Figure 7(b), in east concourse, the smoke concentration in case1 and case3 was relative low (below 5%), passengers could evacuate safely through east concourse to B exit. Moreover, the smoke concentration was relative high in case2 and case4. Case2 at the 360s end and case4 at the 480s end, the smoke concentration had reached to 5%. Passengers could not evacuate safety through the east concourse.

In general, velocity, smoke temperature and concentration are considered, when the station train fire, the case1 is the best running mode of evacuation system which can provide a safety evacuation route through platform to ground exits, to ensure passengers evacuate to outside against the airflow

direction. The optimal running mode of extraction system is that the station fans run in extraction mode and the other fans stop.

CONCLUSION

- 1) The measured results in the island station on 1# and 2# lines in Beijing validated the correctness and reliability of the numerical simulation.
- 2) The computational results showed that, when the station train fire, the optimal running mode of the extraction system is that the station fan run in extraction mode and the other fans stop. This can make passengers evacuate to outside against the airflow direction.
- 3) The measured station has not special vent and extraction duct, the extraction fans are located in the east side of the station. When fire in the station, the extraction mode cannot control the smoke spread to the west part of the platform and cannot form the organizational extraction in the platform, which is unfavorably for the evacuation. It was proposed that there should set special extraction duct in the future extraction system design to form organizational extraction.
- 4) The station structure (including exits) has a great impact on the velocity distribution and smoke flow characteristic. Therefore, in the future subway station design, we should not only consider the capacity of evacuation, but also consider the construction layout impact on the ventilation organization

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