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Numerical Study on Impulse Ventilation for Smoke Control in an Underground Car Park

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Abstract

This study examines smoke control capacity of impulse ventilation system (IVS) in an underground car park. An analysis is made in relation to important parameters including jet fan number, jet fan velocity, extract rate and system robustness on fire position. The comparison with ductwork system is also performed to determine the different effect of smoke control between two systems. Fire Dynamic Simulator version 5.30 is applied to simulate 10 scenarios in a 80 m long, 40 m wide and 3.2 m height domain with a fire source simulating a car fire with an peak heat release rate of 4 MW. Results show that impulse ventilation system not noly prohibit fire smoke spreading but also maintain a good visibility providing clear access for fighters. However it may cause temperature rise on the downwind zone of fire source with a maximum value between 80-100℃ and fire plume tilt. Smoke control capacity of impulse ventilation system is sensitive to jet fan numbers. Too high jet fan velocity may cause severe smoke recirculation. Increment in extract rate is conductive to relay jet flows. An impulse ventilation system can effectively control smoke movement and induce smoke to extract points under two typical different fire locations, which is of great practical importance. Impulse ventilation system seems superior to ductwork system in maintaining high visibility.

Keywords: Impulse ventilation, underground car park, smoke control, jet fan;

1. Introduction

As underground car park is characterized by restricted height, in case of a fire, smoke layer will drop rapidly leading to difficulty in evacuation, conducting search and rescue operation. If the area or volume of car park is greater than a value, such as 2000m^2 in China [1], smoke extraction system is required. Smoke extraction system is often combined with ductwork ventilation system, providing prevention of the build-up contaminated air fumes during the normal use and smoke extraction in the event of a fire. This system performance has been reported by [2,3,4].

Impulse ventilation system(IVS) [5,6], based on jet fans mounted under the enclosed or underground car park ceiling, induces contaminated air or fire smoke towards pre-designated extract points, where a mechanical extract

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system can exhaust them. In general use, IVS removes contaminated air, such as carbon monoxide, produced by vehicles; during a fire, fire smoke is controlled and extracted within limited areas by IVS. IVS was developed from tunnel longitudinal ventilation system. Its function also partially likes positive pressure ventilation (PPV) studied by Kerber and Walton [7] at NIST. A typical IVS consists of four main components, i.e., jet fans, extract and supply fans, detection system and control system. The use of impulse ventilation system [8] has become increasingly popular due to easy installation and low building excavation cost, comparing with ductwork ventilation system.

Only limited research work has been done on IVS for smoke control in underground car parks. Viegas（2001）[9] simulated flow field in enclosed car park with jet fans, and the flow pattern was very complex. Viegas (2010) [10] mainly focused on the interaction between the fire ceiling jet and jet flow driven by jet fans and sensitivity analyses of IVS important parameters. Meanwhile, some IVS design companies have completed many projects. However, the design of IVS in underground car parks is mainly based on experience and computational fluid dynamics verification. To get the design procedure of IVS for smoke control in underground car parks, more detailed researches on the influence of IVS design parameters in smoke control effect should be carried out. In case of a tunnel fire, it is found [11] fire source position influences critical wind velocity for arresting upwind gas and smoke dispersion.

2. Car park model and CFD details

2.1 Car park and computational domain

An underground car park with 80m long, 40m wide, and 3.2m high, as shown in Fig.1, is considered. A car inlet, 11.5°slope, 11m wide, 3.2m high at the lowest point, is at the western boundary of car park. Two staircases, for people evacuation, are located on the western and eastern side of car park respectively.

The computational domain used for this study is a space with 80 m long, 40 m wide and 3.2 m height and is averagely broken into 8 grids in the wide direction. Each grid is composed of 0.2 m on a side grid cells. The domain contained a total of 1.28 million grid cells. This mesh is fine with respect to studies by Viegas [5, 10]. The ceiling and floor are grid boundaries. The entrance boundary is passive opening to the outside.

Two staircases are enclosed by wall. All of the walls and columns are specified as concrete, and jet fan shrouds are specified as inert material that is non-reacting solid boundary fixed at 20℃.

2.2 Fans

Two types of fans, supply/exhaust fan and jet fan, are adopted in this study. Supply/exhaust fans, installed on the western and eastern wall of car park, are used to provide make-up air and remove smoke. Since this type fan is truly reversible, one fan can perform supply or exhaust function at one time. So in this paper, supply/exhaust fans are simulated by 2m wide, 1m high supply and exhaust vents [12] located 2.7m from ground. The average velocity of the exhaust flow or supply flow through each vent is variable for providing different volumetric flow rate that is approximately equal some air changes per hour (ACH) of this car park.

Jet fan is truly reversible as well; for this car park, its activation direction is east or west. In FDS, jet fans are simulated by 0.4m square jet fan surfers, center of which are positioned 2.8m from the ground. The average velocity of jet flow through jet surfers is also variable. To form a short passageway that draws gases in one side and expels them out the other, four flat plates are used to construct a shroud around the jet fan surfer. Velocities of exhaust/supply vents and jet fan surfer in every simulation are reported in simulation cases section.

Both supply/exhaust fans and jet fans are activated by a heat detector installed at a height 3m in simulation. The activation temperature of the heat detector is 73℃, and time response index is 100 $(m\cdot s)^{1/2}$. Based on simulation result, heat detector activation times in all 10 cases essentially are equal to 390s.

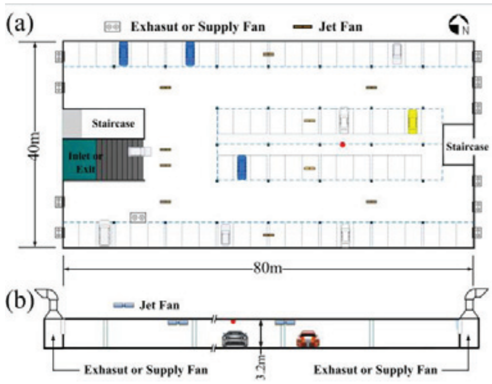

Fig.1. Schematic diagram of car park IVS, (a) plan view, (b) side view.

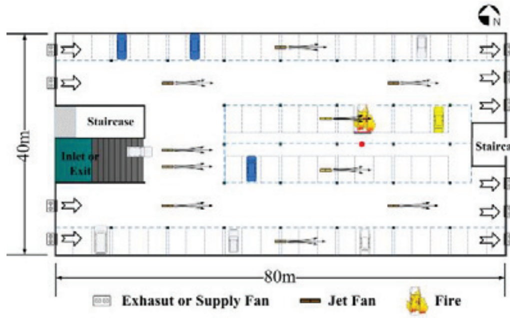

Fig. 2. Schematic diagram of case S3, plan view.

2.3 Car fire

Heat release rate (HRR) of cars can prescribe the severity component in risk assessment. According to Li Y. [13], a medium growth t-squared fire with a peak value of 8MW seems to be appropriate for a worst passenger vehicle fire scenario. Katsuhiro Okamoto [14] carried out sedan passenger car fire experiments, and the peak HRR was close to 3MW. Viegas [10] used 4MW heat source to simulate a car fire. Considering the installation of sprinkler system in this car park, we assume that the car fire development is confined to a steady phase with a medium growth t-squared fire and a peak value of 4MW. Fire source is modeled by the upper surfer of a 5 m long, 3 m wide and 1.2 m high block with design HRR above.

The visibility [15] in the car park has significant effect on human evacuation. A good visibility helps fire fighters to access car park and locate fire position. On the other hand, smoke soot directly influences visibility, smoke movement can be investigated by analyzing visibility condition. This study will focus on visibility condition in different simulation. In FDS model, soot yield is one of the three parameters that control visibility. In this study, the other two parameters are constant. Soot formation [16] is a very complex process affected by many factors, for example, fuel type, fuel size and fire environment. In this paper, soot yield is given as 0.05, a medium value.

2.4 Simulation cases

Jet fan number, jet fan velocity and extract rate are important parameters in IVS design. Meanwhile, engineers also have questions about the differences between IVS and ductwork system, and robustness of IVS. With a view to investigating parameters and questions above, 10 simulation cases were carried out. Table 1 is a summary of cases. Case S3 is a based case, because except case 10, the other cases can be seemed as modified cases from case S3 by changing one parameter. Results of S3 are then used as the basis for comparing. According to research purposes, 10 cases can be divided into 5 sets that are described in result and discussion section.

3. Result and discussion

Every case was simulated for 1200s. As smoke movement approximately reaches a quasi-stable state after 800s, results presented in what follows are mean results from 875s to 925s. Results are mainly portrayed in figures as horizontal slices of U component of velocity along X axis (z = 2.8 m), visibility (z = 2 m) and temperature field (z = 2 m). Horizontal slices of U component velocity at z = 2.8 m, across jet fans axial line, portray the interaction between jet flow and backlayering flow. The height of 2 m is seemed as an interface between smoke movement and human action, so results at this height can partially illustrate the harmful impact of smoke on people. It is known that fire plume will tilt when jet flow reaches it with a high velocity, and this phenomenon may accelerate fire spread between cars. Hence, with the aim to investigating the effect of jet flow on fire plume and smoke layer, vertical slices of temperature field (y = 24.4, y = 4 m) and temperature distribution against height are presented in figures as well. For the sake of contrast, the result of several cases are presented in one figure.

Table 1. Simulation cases matrix

Case	Jet fan number	Jet fan velocity (m/s)	Extract rate (ACH)	Supply rate (ACH)	Jet fan activation direction	Fire center location （x; y）(m)
S1	0	0	18	12		
S2	8	12	18	12		
S3	10	12	18	12		
S4	11	12	18	12	east	54.5; 24.5
S5	10	8	18	12		
S6	10	16	18	12		
S7	10	12	8	12		
S8	10	12	24	12		
S9	10	12	12	18	west	25.5, 2.9
S10	-	-	18	-	-	54.5, 24.5

3.1 Jet fan number

The first set case contains S1, S2, S3 and S4. The comparison S1-S4 shows how jet fan number takes effect in smoke control of IVS. In simulation S1, S2, S3 and S4, 0, 8, 10 and 11 jet fans are adopted respectively. Table 2 shows the jet fan label and jet fan surface center X, Y location. The other parameters in 4 cases above are the same. Velocity of jet fan surface is 12 m/s; jet fans active direction is east; the extract rate and the supply rate are 18 ACH and 12 ACH respectively. Fig.2 simply shows the location of jet fans and fire, jet fan activation direction and exhaust/supply fans working model in S3. It should be pointed out that not only the number of jet fans but also the location of jet fans can affect the capacity of smoke control and the influence of jet fans location is not eliminated in this section study.

Table 2. Jet fans array [a]

Label	X coordinate (m)	Y coordinate (m)	S1	S2	S3	S4
a-1		9.0	× [b]			
a-2	20.0	16.0	×	×		
a-3		19.0	×	×		
a-4		31.0	×			
b-1	28.0	24.6	×	×	×	
c-1	40.0	2.6	×			
c-2		37.4	×			
d-1	48.0	15.4	×			
d-2		24.6	×			
e-1	60.0	9.0	×			
e-2		31.0	×			

[a] The jet fan numbers of S5 - S9 are equal to S3.
[b] Cross (×) denotes no jet fan.

Fig.3 (a)-(d) depict U component of the velocity fields of S1-S4 at 2.8 m height. There is no jet fan in S1. By referring to Fig.3 (a), it is shown that the backlayering flow spreads to the west boundary of car park over Y = 0 to Y = 40, and car park entrancethe backlayering flow is not arrested by the make-up air from supply fans and car park entrance It can be seen form Fig.3 (b) that the make-up air is relayed by jet fans, but backlayering flow also progresses to the western part of car park through gaps between jet fans. Meanwhile, in both S1 and S2, the velocity of make-up air from car park entrance is too low to prevent backlayering flow at place where x is greater than 15 m. In S3, two new jet fans, a2 and a3, are added and mounted on the ceiling close to car park entrance. Upon comparison of Fig.3 (b) and Fig.3 (c), the relay effect of jet fans in S3 is more prominent than that in S2; the make-up air is relayed to the east boundary of car park and arrests backlayering flows. Fig.3 (c) also shows two new jet fans induce fresh air into car park from car park entrance. Compared to S3, S4 has a new jet fan, b1, thus the number of jet fans increases to 11. The main function of jet fan b1 is to fill up the gap of plus U component velocity between a-3 and a-4. As is clear from Fig. 3 (d), the backlayering flow between jet fan a-3 and a-4 is separated by jet flow driven by jet fan b-1.

The comparison of Fig.4 (a)-(d) shows the influence of jet fan number in visibility improvement. For numerical simulation, the zone with visibility more than 28 m is seemed as clear zone. In S1, since smoke spread freely within car park most of the visibility , at 2 m height, less than 5 m. In S2, the area of clear zone, close to supply vents and car park entrance, is slightly larger than a quarter of car park; visibility between x = 20 to x = 60 is improved because smoke is diluted by jet flows. In S3, visibility at 2 m height is significantly improved because of two jet fans (a-2, a-3), and the area with visibility more than 20 m is obviously enlarged. This means that visibility is sensitive to jet fans number. The dividing line between clear zone and smoke filled zone is contiguous to fire source, which is contribute to locating fire position. The comparison between Fig.4 (c)-(d) shows visibility on the northwest corner is improved by jet fan b-1, however the dividing line on the south part of car park retreats to the east.

Fig.5 (a)-(d) show simulation result of temperature field at a height of 2m. In S1, there is no zone where temperature is dramatically increased at 2 m above the car park floor. However, in S2 and S3, 2 m temperature obviously rises downwind of fire source, because jet fans push hot smoke to the west side of fire source. In S3, the temperature on the downwind zone of fire source is higher than that in S2, as the induce effect of jet fans in S3 is greater. The maximum temperature on the downwind zone of fire source is between 80 to 100℃. As jet fan b-1 is far from fire source, it only makes a little effect on temperature distribution. As a result, temperature field in S3 and S4 is similar in general.

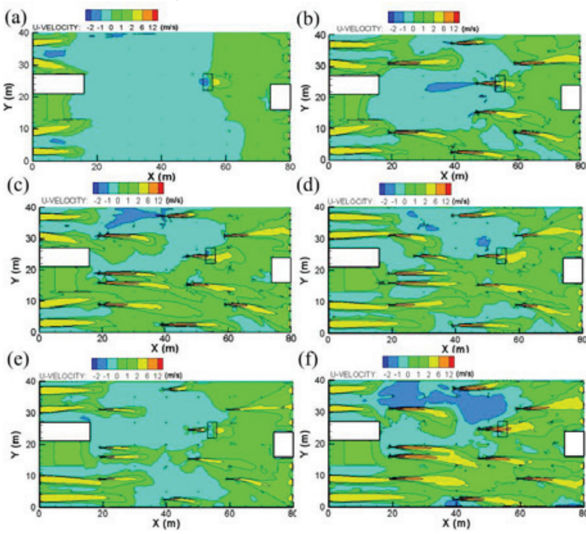

Fig. 3. U component of velocity fields at z = 2.8 m,
(a) S1, (b) S2, (c) S3, (d) S4 (e) S5 and (f) S6.

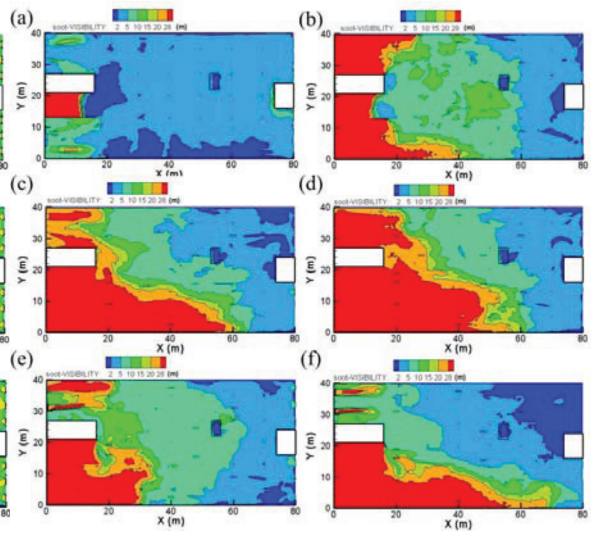

Fig. 4. Visibility distributions at z = 2.0 m,
(a) S1, (b) S2, (c) S3, (d) S4 (e) S5 and (f) S6.

The comparison of Fig.6 (a)-(d) shows the influence of jet fan number in fire plume tilt and smoke layer thickness. In S1, there is only a small hollow on the west side of fire plume. The thickness of smoke layer on both sides (east and west) of fire source is equal. In S2, there is a shape hollow on the west side of fire plume because it is disturbed by jet flow driven by jet fan d-2; smoke layer thickness on the east side is evidently thicker than that on the western side. For S3, the phenomenon of fire plume tilt and smoke layer thickness difference is more obvious. and the whole fire plume tilts from burning surface instead of slightly deflecting at the tip of fire plume in S2. Undoubtedly, severe fire plume tilt will accelerate fire spread between cars. For S4, the degree of fire plume tilt is similar to S3; smoke layer on the west side of fire source is thinner and incontinuous.

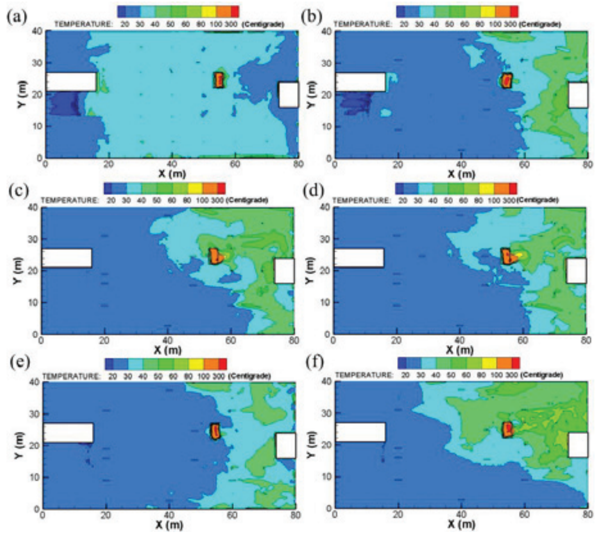

Fig. 5. Temperature fields at z = 2.0 m, (a) S1, (b) S2, (c) S3, (d) S4 (e) S5 and (f) S6.

Fig.7 shows the temperature versus height distributions at 1 m downwind fire source, (x; y) = (57.0 m; 24.4 m). As those temperature distributions are impacted by adjacent fire plume, Fig.7 also depicts the degree of fire plume tilt. Temperature curves of S1 and S2 bent up at height = 2.0 m, but the curve of S2 has a gentler slope because smoke is cooled down by jet flow driven by jet fans. For S3 and S4, temperature curves start to bent up prior to height = 1.0 m and appear relatively similar. Meanwhile for S2-S4, three curves approximately peak at the same temperature, 225℃. Consequently, with increment of jet fan number the extent of fire plume tilt is intensified.

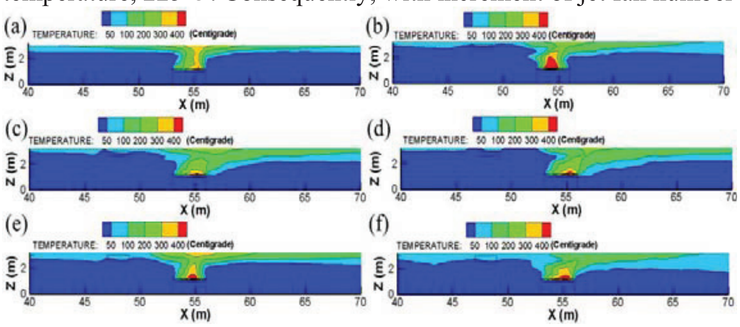

Fig. 6. Temperature fields on fire source cross section plane, at y = 24.4 m, (a) S1, (b) S2, (c) S3, (d) S4 (e) S5 and (f) S6.

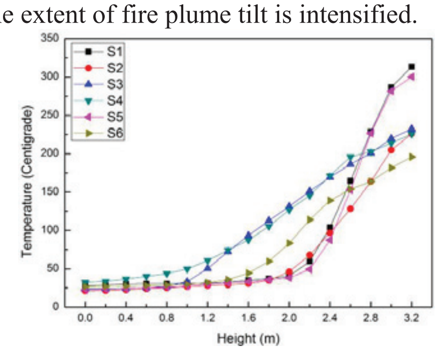

Fig. 7. Curves of temperature against height, located 1 m downwind of fire source long edge.

3.2 Influence of jet fans velocity

Besides the number of jet fans, jet fan velocity is another important parameter in IVS design. For S5, S3 and S6, jet fan velocity are 8 m/s, 12 m/s and 16 m/s respectively, and corresponding simulation results are also presented in Fig.3 - Fig.7.

The comparison of Fig.3 (e), Fig.3 (c) and Fig.3 (f) shows that the continuity of plus U component velocity improves as the velocity of jet fan increases, but the area of backlayering flow with velocity less than -2 m/s is enlarged. This means a suitable increment in jet fan velocity canarrest backlayering progression, in contrast,an excessive increment accelerates the spread of backlayering flow and smoke recirculation. This phenomenon is explained as follows:On one hand, as the width of a single jet flow is a direct dependence on its velocity, a jet fan with a low velocity can not create a wide jet flow thatis able to fill up the gap between downwind jet fans. Then backlayering flow can move forward through those gaps and surround adjacent jet fans quickly. If Jet fans mounted on the upwind of fire source are swallowed by smoke, their capacity of arresting backlayering flow is partially lost. On the other hand, jet flow with high velocity will entrain a large volume of air, thus the total volume flow rate of air driven by jet fans may exceed the extract rate of exhaust fans. In this condition, jet flows may change direction in such a confined place, and rotational flows are created. Therefore it is important to seek an appropriate jet fan velocity that meets not only arresting backlayering flow but also not promoting rotational flows This relationship between jet fan velocity and U component velocity has a directly impact on the following three types of simulation results.

By referring to Fig.4 (e), Fig. 4 (c) and Fig.4 (f), it is clear that 12m/s jet fan velocity performs the best performance in visibility improvement. This means that isolated increment in jet fan velocity, without considering other parameters, may depress the capacity for maintaining good visibility condition.

The influence of jet fan velocity in fire plume tilt and smoke layer thickness is analyzed. It can be seen from Fig.6(e), Fig.6(c) and Fig.6 (f) that jet fan velocity affects the degree of fire plume tilt, but the degree of tilt is not a direct measure of jet fan velocity. On the upwind side of fire source, the smoke layer thickness of S3 is thinnest; on the downwind side of fire source, the thickness of smoke layer varies as jet fan velocity. Fig.7 gives concise portray. S5 curve bents up at height = 2.0 m, and S6 curve bents up at 1.4 m, but the bent point of curve S3 is at height = 1.0 m. Thus the fire plume tilt degree of S6 is between S5 and S3.

3.3 Influence of extract rates

The comparison between S7, S3 and S8 shows the influence of extract rate in IVS smoke control performance. The extract rates of S7, S3 and S8 are 12 ACH, 18 ACH and 24 ACH respectively. The simulation results of S7, S8 are presented in Fig.8 - Fig.11.

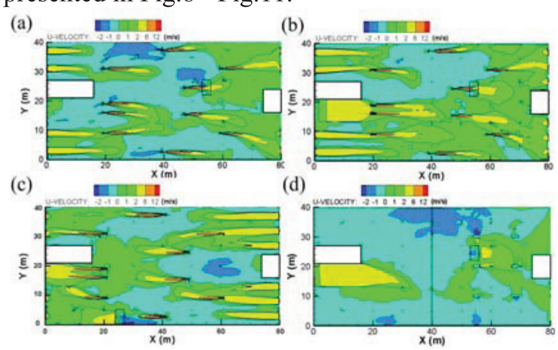

Fig. 8. U component of velocity fields at z = 2.8 m (a) S7, (b) S8, (c) S9 and (d) S10.

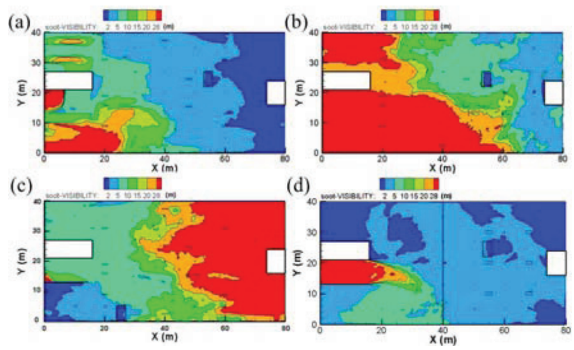

Fig. 9. Visibility distributions at z = 2.0 m, (a) S7, (b) S8, (c) S9 and (d) S10..

Comparing Fig.8 (a), Fig.3 (c) and Fig.8 (b), the increment in extract rate decreases the velocity of backlayering flow and improves the continuity of plus U component velocity. In other words, it contributes to the relay effect between jet fans.

As a result, smoke restriction effect is enhanced and visibility is improved with an increment of extract rate, which is shown in Fig.9 (a), Fig.4 (c) and Fig.9 (b).

Fig.10 (a), Fig.5 (c) and Fig.10 (b) reveal the influence of extract rate in temperature rise on the downwind zone of fire source. Hot smoke accumulation is the main reason of temperature rise, and it is exhausted by extraction fans. Therefore the increment of extract rate alleviates temperature rise on the downwind zone of fire source.

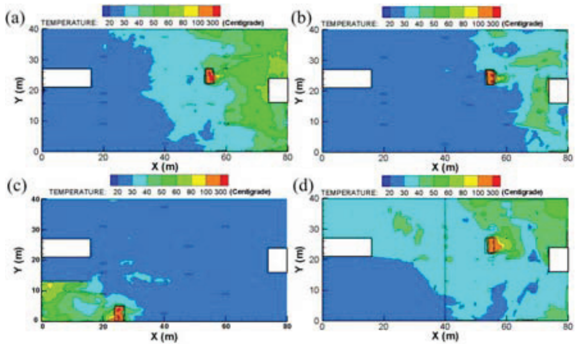

Fig. 10. Temperature fields at z = 2.0 m, (a) S7, (b) S8, (c) S9 and (d) S10

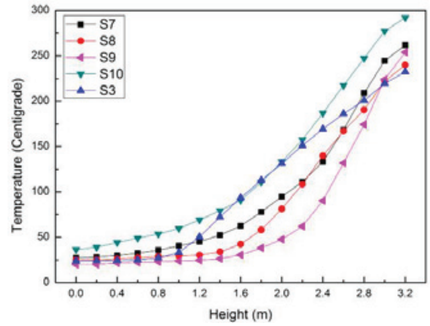

Fig. 11. Curves of temperature against height, located 1m downwind of fire source long edge.

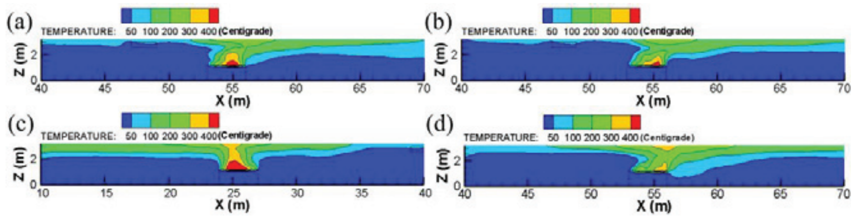

Fig. 12. Temperature fields on fire source cross section plane, at y = 24.4 m (S7, S8 and S9) or y = 4.0 m (S10), (a) S7, (b) S8, (c) S9 and (d) S10.

Referring to Fig.12 (a), Fig.6 (c) and Fig.12 (b), observations of fire plume tilt and smoke layer thickness are examined. In general the extent of fire plume tilt is similar under three extract rates. The smoke layer thickness on the upwind or downwind of fire source is decreased as extract rate increases. Fig.11 shows temperature distribution against height on the downwind side of fire source. For S7, S8 and S10, the position of measure point is (x; y) = (57.0 m; 24.4 m), and for S9, (x; y) = (23.0 m; 4.0 m). For the sake of contrast, temperature curve of S3 is presented in Fig.11 as well. It can be seen that the temperature curve in S3 is higher than that in S7 and S8 from height = 1.2 m to height = 2.6 m, and there is no significant difference between curve S7 and S8. This result confronts us with an intriguing problem that remains to be examined further.

3.4 Influence of fire location

A robust IVS should be able to control smoke under different fire locations. In simulations above, fire source center is placed at (x, y) = (54.5 m, 24.5 m). To examining the IVS robustness on fire location, simulation S9 is carried out. In S9, fire source center is placed at (x, y) = (25.5 m, 2.9 m), on the west part of car park. Jet fans are activated to west, shown in Fig.13. Supply fans and exhaust fans are reversed as well, so supply rate and extract rate are 18 ACH and 12 ACH respectively. As car park entrance automatically serves as a natural smoke exhaust vent, designed supply rate is more than extract rate.

Results of S9 are also shown in Fig.8 - Fig.11. According to Fig.8 (c), a continuous plus U component velocity flow field occurs, from supply vents to car park entrance and extract vents; main backlayering flow lies on the western car park, the vicinity of central northern and southern wall.

Fig.9 (c) depicts the visibility condition at 2 m height. Since the direction of designed main flow is west, fire smoke is confined to the southwest corner of car park. The zone with high visibility lies on the east part of car park. The area with visibility higher than 10m is nearly a half of car park. If fire fighters arrive in car park by the east staircase, high visibility will facilitate fire fighting and rescuing

Fig.10 (c) presents the temperature field at 2 m height. The zone with high temperature concentrates on the southwestern corner of car park, and temperature in other area rarely rises.

By referring to Fig.12 (d), the thickness of smoke layer on both sides of fire source are similar. With respect to S3, fire plume in S9 only slightly tilts to west, which may not cause fire spreading to downwind zone easily. Fig.11

portrays the same result. In S3, horizontal distance in the direction of X from fire source edge to the nozzle of jet fan d2 is 4 m; in S9, the distance from fire source edge to the nozzle of jet fan c1 is 12 m. Therefore the degree of fire plume tilt may be affected greatly by the distance between fire source and the nearest jet fan mounted on the upwind side. In the view of avoiding fire spread this problem is worthy of further work.

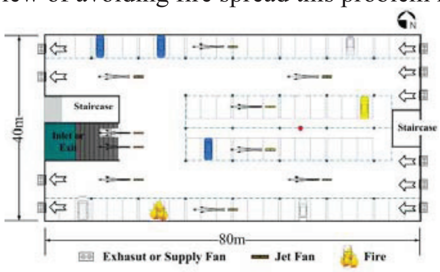

Fig. 13. Schematic diagram of case S9, plan view.

Fig. 14. Schematic diagram of case S10, plan view.

3.5 Comparison between IVS and ductwork system

In mechanical smoke control applications of underground car park, ductwork smoke extract system plays as a dominant role. After IVS is used in underground car parks, there has been considerable interest in the differences of smoke control effect between IVS and ductwork system To investigating the difference the comparison between S3 and S10 was performed. .

In S10, 6 extract vents are placed on the ceiling, as shown in Fig.14. Sheet metal ductwork is ignored in simulation. The extract rate is equal to S3, 18ACH, and the car park entrance automatically serves as a make-up air vent when extract vents are activated. A 0.6 m high smoke barrier is installed on the ceiling in the middle of the car park.

It can be seen from Fig.8 (d) that U component velocity is disordered at a height of 2.8 m. Smoke barrier and exhaust vents can not confine smoke within the west side of car park. Upon comparison of Fig.4 (c) and Fig.9 (d), It's found that IVS is superior to ductwork system in maintaining high visibility. For ductwork system, its smoke reservoir is a space between designed smoke layer height, 2 m in common, and car park ceiling. Unfortunately the height of underground car park is relatively low, 3 m for instance. If the smoke diffusion effect is not ignored in a long way from fire source, the volume of smoke reservoir is not very large. In contrast, for IVS, a part of car park that is on the downwind of a designed driving line between clear zone and smoke zone is the smoke reservoir Hence IVS may have a larger smoke reservoir than ductwork system and maintain the other part of car park as clear zone.

Furthermore, IVS has an advantage over ductwork system in controlling temperature according to Fig.5(c) and Fig.10 (d). In S10, the zone with temperature above 30℃ extends to the west boundary of car park, however it only extents to x = 40 m from fire source in S3. The extent of temperature rise on the east side of fire source in two cases above is similar.

IVS causes fire plume tilt based on results of S3, S4 and S8, which is seemed as the main limitation of IVS. Ductwork system also leads to this phenomenon and has the worst performance among 10 cases by referring to Fig.12 (d) and Fig.11. The main reason is that make-up air velocity is relatively high as it reaches the burning surface of fire source. Given that S10 is conducted with the fire source on the west part of car park, the velocity of incoming air is relative low. If fire source is placed on the east of car park, except corners, the make-up air would reach fire source at a greater velocity, then the degree of fire plume tilt is severer. If the height of this car park increases, the performance of ductwork system may be improved.

4. Conclusions

This work focused on the smoke control capacity of impulse ventilation system (IVS). Five properties of IVS, i.e., jet fan number, jet fan velocity, extract rate, system robustness on fire position and comparison with ductwork system, have studied in an underground car park with one inlet by 10 FDS simulation cases. U component velocity field, visibility condition, temperature field and distribution downwind of fire source are presented. These simulation cases illustrate that IVS is able to prohibit smoke spreading and maintain an acceptable visibility at a large area inside the car park. Whereas IVS may cause fire plume tilt and hot smoke accumulation on the downwind zone of fire source, which increases the risk of fire spread between cars.

These results may give insight to IVS design procedures. This study suffered from the lack of qualitative analysis of physical mechanism responsible for the change in IVS smoke control capacity. The results of this research apply to a very simple underground car park and not representative of many actual large car parks design. These limitations will hopefully be addressed in future research.

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