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Numerical Security Assessment in Case of Fire in Underground Transport Spaces

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Abstract

In case of fire in a subway station and if the fire smoke extraction is not handled properly, passengers may be trapped and thus would be in a life-threatening situation. The most immediate threat is not direct exposure to fire, but the smoke inhalation. The smoke contains hot air and toxic gases. The increasing rate of use of subway stations could lead to an increase in the frequency of serious fires, thus subway station designers and operators must consider all fire aspects, smoke propagation, and ventilation strategies within their facilities. In this paper, heat transfer through the spread of smoke in the event of a fire in a subway station is examined. It concerns the identification of ventilation strategies in the station so as to provide security for passengers and rescuers, based on numerical simulations using the FDS software. Smoke control strategies by traps located at the ceiling associated with different tunnel ventilation were investigated. The results show that the safest strategies are mainly those with air flow rate blown into the station from the tunnels less than the flow rate extracted by the traps. The least safe scenarios are those where the ventilation through the tunnels is accomplished with flow rate greater than the one extracted by the traps.

Keywords : Smoke ; propagation ; subway station ; strategy ; ventilation ; simulation

1. Introduction

With the rapid growth of cities and consequently a rapid increase in population, subway has become a major public transportation. It is an effective way to solve traffic problems. Algeria, and particularly the capital Algiers has put into operation its first commercial Metro line in 2011.

During subway construction, there is a substantial problem that is how to prevent and deal with subway fire effectively. Fires are major risks in underground spaces. They have claimed lives of several passengers throughout the world. Subway station is prone to fire due to its structural characteristic of confined space where ventilation depends mostly on mechanical systems. Thick Smoke produced by a fire reduces visibility and creates dangerous situations to the users and the fire fighters, hindering prompt emergency evacuation.

It has been recently shown that an optimized ventilation system for fire safety in underground stations may not necessary be associated with a strong ventilation flow. Under strong ventilation, the hot smoke front tends to mix with surrounding fresh air flow induced through openings and exit doors, thus endangering the users [1]. Forced ventilation will affect different types and sizes of fire loads in different ways. It will bring with it a plentiful supply of oxygen which might tend to increase the severity of the blaze, but it might also have a cooling effect which may tend to reduce the severity of the phenomenon. It may also cause fire to spread across at a significantly faster or slower rate. It may even put the fire out entirely. The relative importance of each of these factors has not been adequately investigated [2]. Therefore, a well-designed emergency ventilation system can save many people's lives and belongings.

The Prediction of smoke movement in buildings and underground stations and the design of smoke control systems are essential to lead to safe strategy evacuation in case of fire. To be able to design a control strategy, an expert in fire safety needs to establish several parameters that describe the dynamic of the smoke movement and its impact on the occupants. To predict the movement of smoke, fire safety engineers rely on modelling tools, such as simple empirical models or complex CFD models depending on the objective of the study. CFD programs are capable of simulating a wide variety of problems related to fluids [3-4]. Moreover, in recent years, several mathematical models have been used to quantify parameters of smoke in confined and semi-confined spaces. The effects of phenomena, such as stack effect which occurs during the exploitation of transport network were examined [5]. Smoke extraction by roof vent in a tunnel was numerically simulated, using CFX program and compared with experimental results [6]. Willemann and Sanchez, [7] discussed some of the computational modeling techniques and analysis carried out to design a tunnel ventilation fan plant for the New York City subway in order to improve the safety level in the system. The study showed how computer modeling techniques and analysis helped the design of tunnel ventilation fan plants.

Shahcheraghi et al., [8] investigated the effect of fan starting time on the performance of a subway station emergency ventilation system. The method included a time dependent fire growth within a transient computational fluid dynamic simulation of a train fire in the subway station.

Andersson et al., [9] investigated the single exit underground station of Zinkensdamm in Sweden in order to improve the evacuation in case of fire on the platform. A smoke spreading in case of fire in a train on the platform was visualized with the help of the CFX 4.3 program. Kang, [10] provided models for smoke propagation and investigated the natural and forced ventilation through tunnels in case of fire in a subway station. Deficiency in determining the visibility through their approach was reported. Rie et al., [11] evaluated experimentally and numerically the effectiveness of smoke management systems by fans whose role is to ensure a sustainable environment for the evacuation of users. Park et al., [12] carried out a numerical analysis with the FDS [13] software to examine the ventilation characteristics and the movement of smoke in line 4 of the Suyou station in Korea. They reported that a large extraction of smoke increases the escape time and the level of fire safety. The effect of platform screen doors (PSD) and ventilation on the safety of occupants of the Seoul subway system has been discussed through simulations with the FDS software by Roh et al., [14]. Their conclusion reveals that when PSD technology is used, passengers will have more time to escape.

Despite all these studies, smoke and fire are always the worst enemies of man in underground stations. More studies are needed, especially in the aim to bring the underground stations security to standards of new technological advances. A preliminary study on the subject was initiated. The results were quite satisfactory [15].

The purpose of the present study is to assess the level of security in a typical subway station using FDS software for more selected scenarios. The analysis of temperature and velocity fields in the station is accomplished in order to determine the most critical fire scenarios.

The strategy for evacuating fire fumes from underground stations uses two extraction traps located in the ceiling at both ends of the station as shown in Figure 1. The tunnels on both sides of the station are employed to extract smoke from the station or to blow in fresh air. The four passenger entrances on both sides of the station are kept at atmospheric pressure.

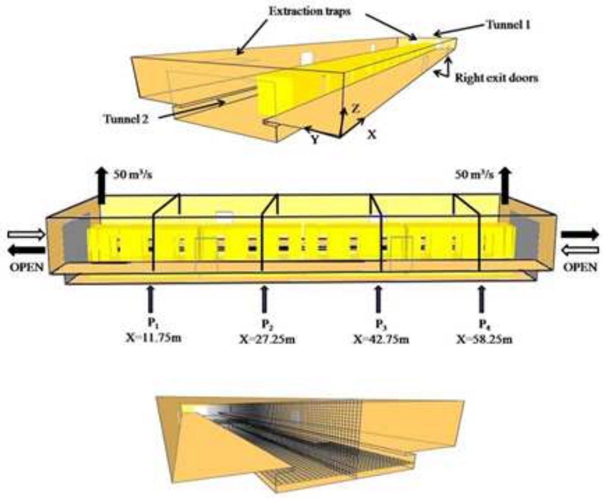

Fig.1. Sketched configuration of the station and boundary conditions

2. Numerical Approach

Mathematical modelling of fire growth and smoke movement in any building presents a major challenge. Not only it is difficult to simulate physical phenomena such as turbulence, radiation heat transfer, combustion…, but also parameters such as location of fire, external wind conditions, available ventilation. All have an impact on the behavior of the fire and the smoke.

FDS is a computational fluid dynamic model of fire-driven fluid flow. The software solves numerically a form of the Navier-Stokes equations appropriate to low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. Smokeview is a visualization program that is used to display the results of the FDS simulation. FDS has been aimed at solving practical fire problems in fire protection engineering. It uses a mixture fraction combustion model. The model assumes that combustion is mixing-controlled, and that the reaction of fuel and oxygen is infinitely fast. Turbulence is treated using Large Eddy Simulation (LES) model.

The equations are solved in order to obtain the evolution of the distribution of averaged flow quantities. Additional information can be found in McGrattan, [13].

2.1. Description of the physical domain

The station which is the subject of this study is a typical one level station of an underground transport network. It is 70 m long, 14 m wide and 4 m in height from the platform ground. The train parked on the right of the station is composed of four carriages. Each carriage has three doors on both sides. The total length of the train is 64 m. The station with one platform on each side has four passenger entrances and two bi-directional tunnels at each end. To ensure the smoke is well controlled during fire, the station is equipped with two mechanical ventilation systems to evacuate smoke, located on the ceiling, (Fig. 1). The rate of blowing fresh air or extracting fumes by the tunnels is fixed depending on the smoke evacuation scenario considered.

2.2. Boundary conditions and specifications

The boundary conditions are defined at the tunnels and at the ceiling extraction traps. The various fire locations mean that many scenarios can be investigated. A case of fire, occurring at one of the carriages of a train, generating a constant thermal power of 15 MW is considered. The source of fire on the train is located at different points according to the scenarios considered. Temperature is evaluated along the middle of the right platform at height z = 1.5 m and depth y = 2 m.

CFD numerical simulations require hours or even days to run on the latest personal computers. One of the most significant factors influencing the computation time is the size of the computational grid specified. It is important to determine an appropriate grid size for a given computational domain.

FDS simulations for selected grid sizes were performed to highlight the effect of grid size on the estimations of the temperature. Obtained temperature distributions were compared. In the vicinity and the centerline of the fire the temperature is higher when the grid sizes are fine. The choice of the grid resolution is important for the prediction of the temperature in the fire area.

To validate the chosen grid size with respect to the fire area, the plume centerline temperature is determined using a well established Heskestad's empirical correlation [16] and compared to FDS predicted temperatures. The Heskestad correlation provides an estimation that is closer to that obtained for the adopted grid size of 0.25m x 0.25m x 0.25m.

The physical domain is then divided into three sub-zones, meshed equally in the three directions Figure1. The first zone, represented by the volume of the two platforms has 250,880 cells. The second zone, represented by the volume of the train space, has 6,720 cells, and the last zone, the railways has 42,000 cells. The total number of meshes is 299,600. The numerical simulation was carried out for the whole domain. Simulation was performed up to 300s. This is the time required to evacuate passengers safely [17]. When a mechanical smoke control is engaged, a 50 m^3/s flow rate is prescribed at each trap at the ceiling. On the solid walls, a non-slip condition, constant temperature (taken equal to 20 °C) and zero smoke flux are assumed. Because the train is parked, no pulsating air movement is considered. More data are given in Table 1.

Table 1

Boundary conditions

	Size (m x m)	Boundary conditions
Traps	2 x 2.5	Const. output flow rate (Q=50 m^3/s)
Pass.Entr.	3 x 2.5	OPEN [1]
Tunnels	7.5 x 4.5	Extracting and blowing flow rates [2]

[1] OPEN means that there is no condition imposed. Velocity, temperature and pressure are those of the domain.

[2] Flow rates calculated at velocity of 1, 1.5, 2, and 3 m/s.

The main objective in smoke control system analysis is the assessment of the ability of the emergency ventilation system to provide safe zones in the event of fire. For a tenable environment within short periods, the air temperature below minimum height of 1.5 m should not exceed 40°C. NFPA 130 [17] requires less than four-minute for platform evacuation time period and six-minute time period for all passengers to reach safe point.

For this aim, we used in this investigation two criteria, the area 1.5 m above the platform should be clear of smoke and its temperature should not exceed 40°C.

To assess the smoke propagation in the station, we simulated four scenarios. The fresh air flow rate that can be blown in or the smoke which can be extracted out from each tunnel is taken equal to 0, 33.375, 50, and 100 m^3/s, respectively, while the extraction from the traps is maintained constant at 50 m^3/s per trap. These correspond to four emergency ventilation cases: (1) no ventilation through tunnels (NVT); (2) total ventilation through tunnels is less than that from the traps (LVT); (3) total ventilation through tunnels is equal to that from the traps (MVT); (4) total ventilation through tunnels is higher than that from the traps (HVT). The ventilation imposed on tunnels can be either extraction of smoke or blowing of fresh air.

2.3. Scenarios and nomenclature

In order to better enhance the advantages of one ventilation strategy over another, and because of the large number of cases simulated, we only introduce the most representative cases. These are obtained for four main strategies: 1) No Ventilation (NVT), 2) Low Ventilation (LVT), 3) Moderate Ventilation (MVT), and 4) High Ventilation (HVT).

To identify the safest fire scenarios for passengers, we classify the results of the simulations with respect to the average temperature measured at the transverse planes P_1, P_2, P_3 and P_4, over a time of 300s. In order to make easier the pinpointing of cases, we have established the following nomenclature: each case is named case ABC, where A represents the location of the fire in the train (A=1 means the fire is on the surface of the carriage, A=2 means the fire is at the tires), B represents the carriage on fire (B=1 means the fire is located in the first carriage, B=2 means the fire is located in the second carriage), C represents the ventilation strategy engaged in tunnels (C=0 means no ventilation through tunnels, C=1 means the air flow is blown in through the two tunnels, C=2 means the air flow is blown in through the left tunnel and smoke is extracted out through the right tunnel, C=3 means the air flow is blown in through the right tunnel and smoke is extracted out through the left tunnel, C=4 means smoke is extracted out through the two tunnels).

3. Results and Discussion

For the design of a ventilation system, for which the worst case situation will be that of the fully developed fire, steady simulations are performed.

Steady state regime varies according to the strategy conditions applied. For scenarios in which the fire is the primary source of energy, after the gas temperatures within the computational domain reach a nearly steady state, imposed constant heat release rate HRR should approximately be equal to the convective heat rates, as radiative rate is neglected. This is merely a check of the global energy balance. For the selected scenarios, this heat balance occurs at approximately 100s depending on the conditions imposed. Beyond this time, smoke behavior and gas temperature vary very slightly. The predicted results of the temperature field and smoke propagation for 300s are summarized for the four ventilation strategies.

3.1. Strategy 1: No ventilation (NVT)

Table 2 shows the average temperature obtained in the middle of the right platform at 1.5 m height for four cases investigated. The condition imposed on tunnels is (OPEN) (i.e. no charge is specified).

Table 2

Average temperature for the strategy without ventilation by tunnels

Case	Average temperature of the right platform at depth y=2m and height h = 1.5 m (° C)			
ABC	P_1	P_2	P_3	P_4
110	**27.0**	**20.7**	**22.0**	**21.4**
120	**21.9**	**32.7**	**28.6**	**21.3**
210	**50.8**	**24.9**	**27.2**	**22.4**
220	**29.8**	**41.1**	**41.9**	**22.1**

In these four cases, extraction of air and smoke is made only through traps at the ceiling with a 100 m^3/s total flow rate. The conservation of momentum in the station involves an extra air flow through tunnels and passenger openings, with average velocities over the range 0.5 and 1 m/s on tunnels while it is between 1 and 1.5 m/s on passenger openings. It can be observed from table 2 that cases 210 and 220 represent a moderate risk for passengers, because the temperature of the smoke exceeds just slightly the critical temperature of 40 °C. The air induced through passenger doors, like the location of the fire at the tires (presence of more organic material), contributes to the strengthening of the fire which results in an increase of temperature.

The heat generated by a fire increases the ambient air temperature. As a result, it expands and increases in volume. It is generally assumed that in most fires, the volume of hot gases should at least triple compared to the initial volume. This significant increase causes the expulsion of other gases present at onset of the fire. This trend continues so long as the increase of temperature is maintained. The phenomenon of thermal expansion explains partly the rapid spread of smoke, as well as the lowering of the smoke layer in the station. This is followed by a rise of the medium temperature which exceeds the reference temperature of 40 °C. It is worth noting that, although we imposed a smoke extraction trough traps on the ceiling with a total output of 100 m^3/ s, the reference smoke temperature was exceeded (case 210 - P_1) and (case 220 – P_2 and P_3).

Figure 2 illustrates smoke temperature fields after 200 s in steady state regime for cases 110 and 220. We remark that, there is no smoke stratification at the first carriage for case 110, and also at the 2nd and the 3rd carriage for case 220. This can be explained by the fact that, there is an important buoyancy force and a call of fresh air through passenger entrances. Smoke temperature fluctuations are more marked at P_1 for case 110 and at P_2 for case 220.

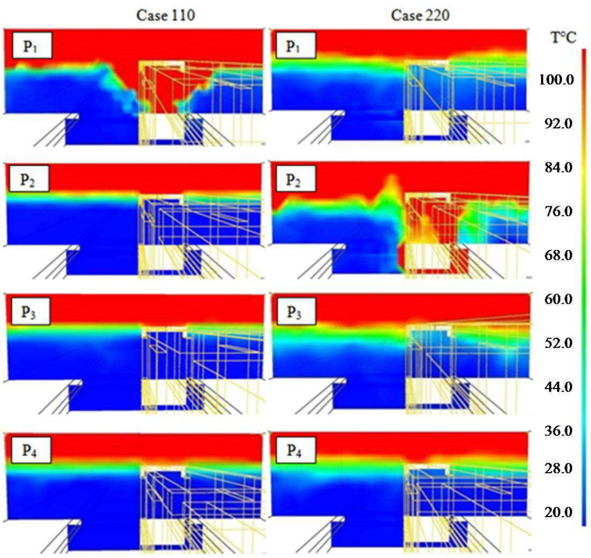

Fig. 2. Temperature field at cross-sections P_1, P_2, P_3 and P_4

The results show that when you are far from the fire source, smoke stratifies and remains more or less stuck to the ceiling.

Figure 3 shows instantaneous temperature distribution at 1.5m height from the platform surface for cases 110 and 220. The temperature fluctuations are sizeable in the transverse planes where fire occurs; namely, P_1 for case 110 and P_2 for case 220. For case 220, this also occurs at P_3. For this latter case, the fire sets in half way with respect to the length of the train and the position of exhaust fans. The non stratification of smoke is due mainly to the combination of two sources: the fire and the fans, which generates a disturbance through heat release and dynamics of extraction, respectively. The temperature fluctuates over the range 20 - 47 °C for case 110 and between 25 and 60°C for case 220 approximately.

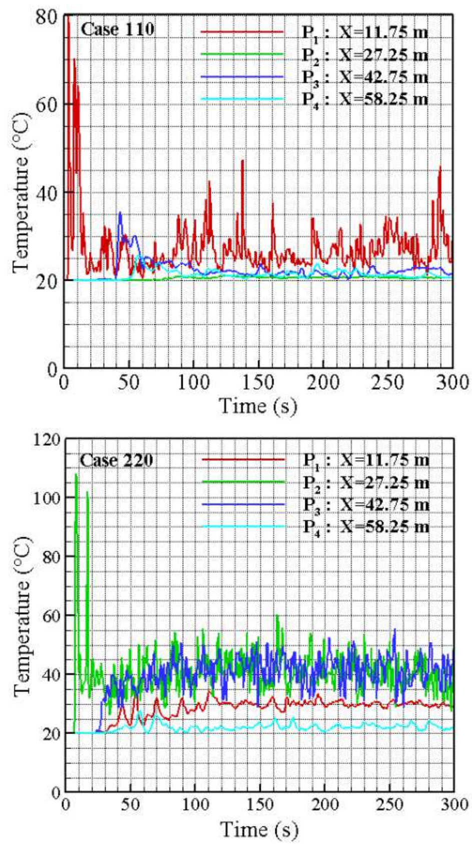

Fig. 3. Instantaneous temperature of fumes at 1.5m height from the platform surface

It can be seen from figure 4, which shows smoke fields in the station after 300s for the cases 110 and 220, that the lower part of the platform is unobstructed by fumes along most of its length.

Fig. 4. Smoke distribution in the station after 300s for cases 110 and 220

The above results of the smoke temperature indicate that the temperature is low; except in the vicinity of the fire source. The fields of smoke (Fig. 4) agree with the temperature levels (Fig. 2).

Moreover, as shown in Figure 4, the presence of smoke in the vicinity of the third carriage (case 220) justifies the elevation of the average temperature up to 41.1 and 41.9 °C respectively for P_2 and P_3. When the fire is located in the middle of the station or in its vicinity, there is a competition between the right and the left extraction; creating an area where smoke cannot make a prevailing path to either the left or the right. Therefore, it builds up and goes down on the lower level of platform below the 1.5m eye height.

3.2. Strategy 2: Low ventilation (LVT)

In order to cover maximum configurations, we explored 16 cases. The results for the average smoke temperature are presented in Table 3. It appears that a number of cases in the strategy of low ventilation (LVT) present a risky situation for passengers. The most dangerous ones are cases 124, 222 and 224, because the corresponding average smoke temperature exceeded the critical reference temperature in at least three measurement points.

The "LVT" strategy with extraction through the two tunnels and the two traps in the ceiling (case 124), generates a very important air intake through exit doors. This strongly induced air stirs the fire and leads to the production of more smoke. This smoke quickly reaches high temperatures (between 46.7 and 60.3°C on average); thus enhancing its rapid motion and its spreading throughout the whole station. Temperatures recorded at the four measurement points are far beyond the critical reference temperature. This situation is un-tenable for people.

In the setup of case 222 for the 'LVT' strategy, part of the air blown inward through the left tunnel is immediately sucked by the fan mounted in the left trap, while the other part pushes smoke produced towards the right of the station. The suction capacity of the right trap and the right tunnel seems to be no sufficient to remove all fumes. There is an accumulation of gas within three-quarters of the station that leads to a temperature increase slightly beyond the critical reference temperature.

The smoke behaviour resulting from configuration 224 for the "LVT" strategy, led to smoke invasion of the whole station and a temperature increase far exceeding the critical reference temperature, as clearly evidenced in table 3. The higher temperature at the measuring left points (P_1, P_2) compared to the temperature at the right points (P_3, P_4) is explained by the fact that the heat source is closer to the left side. The measured temperature levels characterize well therein a very dangerous situation for users and first rescuers.

Table 3

Average smoke temperature for the “low ventilation by the tunnels strategy (LVT)

Case	Average temperature of the right platform at depth y=2m and height h = 1.5 m (° C)			
ABC	P_1 x=11.75m	P_2 x=27.25m	P_3 x=42.75m	P_4 x=58.25m
111	**27.7**	**20.9**	**21.8**	**20.7**
112	**47.9**	**26.6**	**22.5**	**30.5**
113	**66.5**	**25.3**	**32.5**	**20.4**
114	**82.1**	**25.2**	**27.3**	**31.1**
121	**21.6**	**28.1**	**22.5**	**20.8**
122	**21.7**	**38.6**	**31.9**	**43.0**
123	**42.3**	**32.5**	**42.0**	**20.3**
124	**58.2**	**59.9**	**60.3**	**46.7**
211	**52.0**	**23.9**	**27.9**	**21.1**
212	**58.6**	**32.3**	**24.9**	**36.0**
213	**42.1**	**23.7**	**28.3**	**22.5**
214	**63.1**	**24.9**	**22.7**	**21.9**
221	**26.9**	**37.1**	**37.5**	**22.2**
222	**28.6**	**43.9**	**45.5**	**48.9**
223	**60.3**	**35.1**	**52.8**	**20.7**
224	**49.5**	**79.1**	**69.3**	**46.6**

The scenarios where the fire occurs either on the platform surface of the train or on the tires, in the first carriage, generate temperature distribution almost identical regardless of the ventilation adopted. The average temperature at the cross-section P_1 is greater than the reference temperature; except for case 111. The smoke temperature reached 80 °C for the ventilation strategy “C = 4”. The “C = 4” ventilation strategy means an extraction rate of the air-smoke quite important. In this strategy, the smoke is sucked through the tunnels as well as the traps. To this end, air is sucked through the exit doors, following a depression created within the station. The velocity of the sucked air can reach 5m/s. In addition to its involvement in the stirring up of the fire, this air flow disrupts the smoke layers. The accumulated toxic gas comes down to lower levels and encumbers the passenger area; thus creating a dangerous situation for users. Note that this situation is focused only at the first wagon on the left of the station.

As it can be remarked, case 111 generates levels of temperature below the critical reference temperature at all cross-sections (fig. 5 and 6). The air flow rate driven inwardly through each tunnel is less than that drawn out through each trap. The fire on the platform of the first carriage produces smoke that is immediately drawn out by the fan of the left trap. Blowing air inwardly by the left tunnel helps containment of fumes and promotes aspiration through the left trap. The contribution of air flow through the tunnel on the right partially maintains pressure on the fumes that can spread to the right of the station. In addition, part of this air is drawn out through the right trap located near the right tunnel. This mechanism of suction and pressure of the LVT strategy can be recommended.

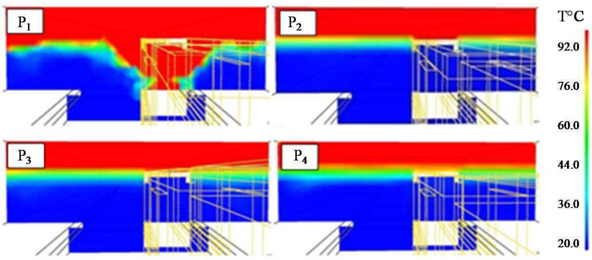

Fig. 5. Temperature field in cross-sections P_1, P_2, P_3 and P_4 for case 111

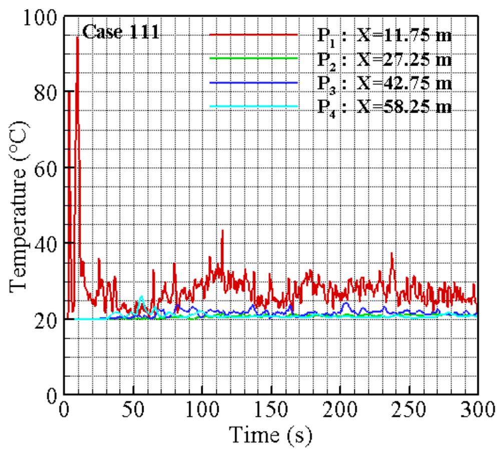

Fig. 6. Instantaneous temperature at 1.5m from platform surface

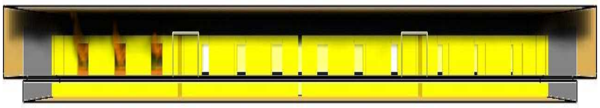

Fig. 7. Smoke fields for 300s of duration for case 111

For the case 121, the same flow behaviour seems to happen; the only difference is that the highest temperature recorded is in the vicinity of the carriage on fire (27.7 °C for case 111 and 28.1°C for case 121). For case 221, the fire is located almost in the middle of the station and on the tires. The extraction path, from the source location to the traps in ceiling, is longer. The movement of the fumes is slowed down by that of the air arriving from the tunnels in the opposite direction. This air causes their accumulation and consequently their temperature increases. The rise of the gas temperature remains below the critical reference temperature; this is due mainly to the strategy "LVT" adopted. The mixing of air with fumes keeps low the temperature.

The effect of sucked air from passenger entrances can be clearly seen through temperature field and instantaneous temperature distribution for case 224 (fig. 8 and 9).

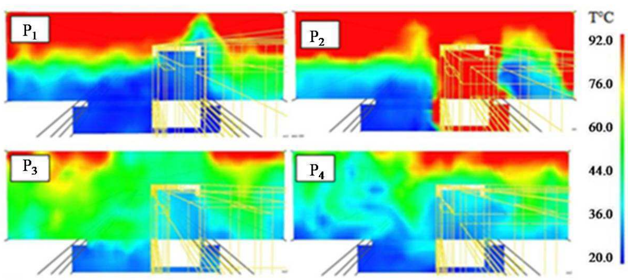

Fig. 8. Temperature field in cross-sections P_1, P_2, P_3 and P_4 for case 224

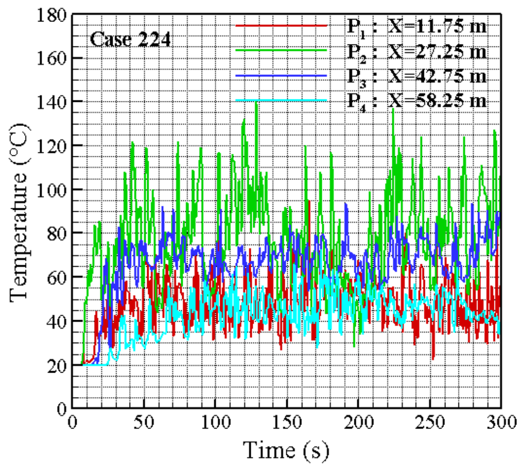

Fig. 9. Instantaneous temperature at 1.5m from the platform surface

The observations that can be made on the average temperatures recorded for cases 123 and 223, where the fire broke out on the platform or at the carriage tires, are: (1) the average temperature at P_2 does not exceed the critical reference temperature because this does not coincide with the mid-plan of the smoke source, (2) smoke spreads on both sides of the carriage on fire as shown by the elevation of the average temperature at P_1 and P_3, (3) when the fire broke out at the tire, it generates a higher average temperature (Table 3).

The temperatures shown in Table 3 are the average temperatures recorded over 300 s of simulation. When the analysis is based on the average temperature, dangerous cases cannot be highlighted accurately. However, for more accurate analysis, we draw the temperature field and the measured instantaneous temperature of the fumes during the simulation time at selected cross-sections for case 123, (Figs. 10 and 11).

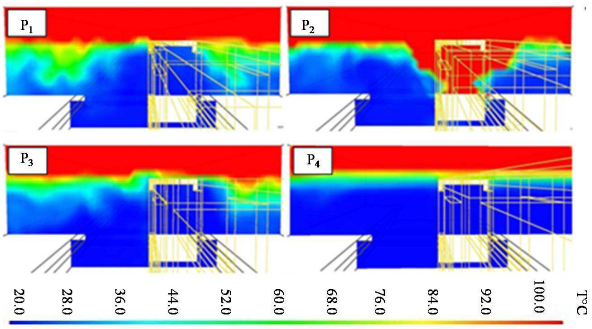

Fig. 10. Temperature field in cross-sections P_1, P_2, P_3 and P_4 for case 123

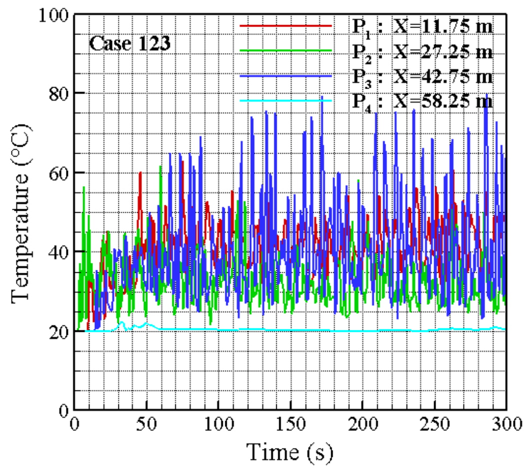

Fig.11. Instantaneous temperature at 1.5m from the platform surface

The smoke distribution obtained for t = 300s is also shown for case 123 (Fig. 12). The plot of instantaneous fume temperatures shows that alarming maximum levels can be reached. They exceed by far the critical reference temperature at the measurement cross-section P_3, as they reach 70 and 80 °C. These high temperatures are also very common. The region that does not endanger users is at the right side of the station, starting from the carriage number four.

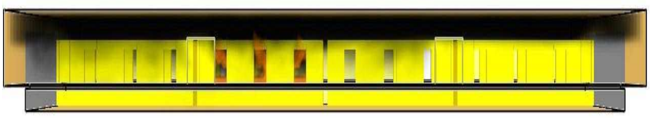

Fig. 12: Smoke distribution in the station at t=300s for case 123

Figure 13 depicts the velocity field overlaid by the temperature field in the horizontal cross-section, at 2 m above the platform surface. The induced air currents are also illustrated. We show that the nearer the fire source is to the exit door, the hotter is the induced air. The escape routes located to the right of the platform station are safer for evacuation.

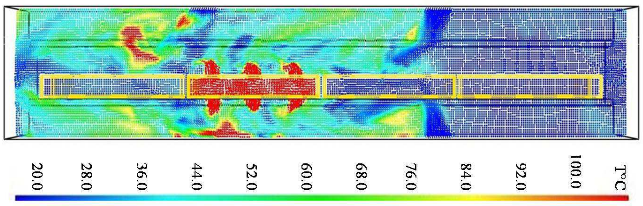

Fig. 13: Velocity and temperature fields at a horizontal cross-section 2 m height from the surface of the platform for case 123

3.3. Strategy 3: Moderate ventilation (MVT)

The simulations for the "MVT" ventilation strategy were performed for 50 m^3/s of air flow rate through each tunnel. Since a variety of cases can be simulated, we selected four configurations; classified with respect to the carriage of the train and to the location of the fire in the carriage. Table 4 gives results of the average temperature at 1.5 m height above the platform ground at four cross-sections points P_1, P_2, P_3, and P_4, for four cases.

Table 4

Average temperature results for the moderate air flow rate on tunnels

Case	Average temperature of the right platform at depth y=2 m and height h = 1.5 m (° C)			
ABC	P_1 x=11.75m	P_2 x=27.25m	P_3 x=42.75m	P_4 x=58.25m
111	**33.5**	**22.4**	**23.0**	**26.9**
121	**24.5**	**26.7**	**22.4**	**25.3**
211	**41.6**	**29.6**	**27.4**	**32.0**
221	**30.2**	**33.8**	**27.9**	**31.8**

The obtained results show that MVT strategy can maintain at comfortable average temperature, the zone 1.5 m above the platform surface. All studied cases are secure except case 211 where a slight average temperature excess can be observed at cross-section P_1.

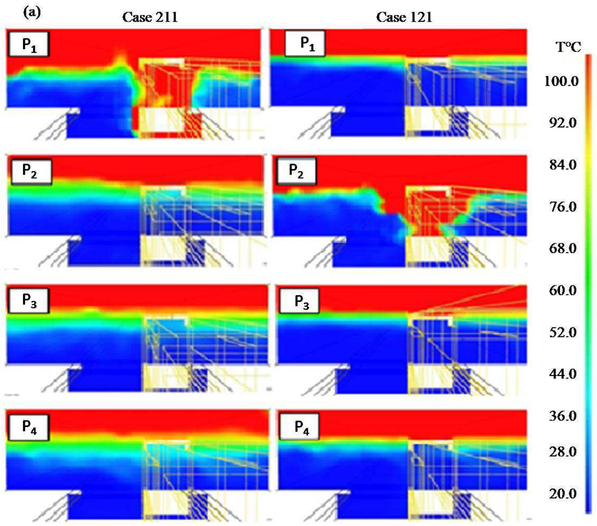

Fig. 14a. Temperature field in cross-sections P_1, P_2, P_3 and P_4.

To better comment simulation results obtained for the MVT strategy, we have shown on Figure 14a, the temperature field in cross-sections P_1 to P_4 for cases 211 and 121.

In case 211, the fire is in the first carriage but at the tires. For case 121, the fire is always located in the first carriage but on the carriage platform surface. One can observe that the temperature field for case 211 does not show a clear interface between the hot zone and the cold zone. The flow seems to be more disturbed but remains at the temperature level below the critical reference temperature. For the 121 case, there is a clear separation between the hot and the cold zones Smoke air mixture is stuck to the top wall especially at cross-sections P_1 and P_3. The higher temperatures for case 211 are justified by the fact that the fire happens in the tires which generates more smoke that accumulates despite the ventilation strategy adopted. The comments made on temperature fields can be confirmed through the smoke field obtained after 300s for both cases (Fig. 14b). Note that smoke invades mainly the areas where fire is located.

Fig. 14b. Smoke field in the station at t=300s

During a fire, generally, there is a rush of passengers towards the openings in order to escape. Passenger entries located on both sides of the station communicate with the external environment. These openings are a source of air supply to the interior or a discharge of air fume mixture outwardly when a given ventilation flow is conveyed. They can present a significant hazard if they are smoky. To highlight the flow through these openings, we assume that they are open. The corresponding velocity and temperature distributions of the flow along the 2.5 m door height are drawn, (Fig. 14c and 14d). Figure 14c shows the variation of the flow velocity of the right and the left doors of the left side station for cases 211 and 121.

Note that negative and positive velocities at the right and left doors indicate that mixture of air and smoke is outgoing through these openings. On the right door, the absolute velocity value increases up to 1 m/s at the height of 2.25m. This increase is explained by the fact that the mixture reaching this height is hotter. On the left door, the maximum velocity is reached at about 2.25m height for case 211. For case 121, the leaving mixture flow appears to be greater than that for case 211. On almost the entire height of the door (2 m), the velocity is uniform and equals 0.5m/s for the right door and 0.75 m/s for the left door. The results of the velocity distribution are confirmed by those of the temperature distribution, (Fig. 14d).

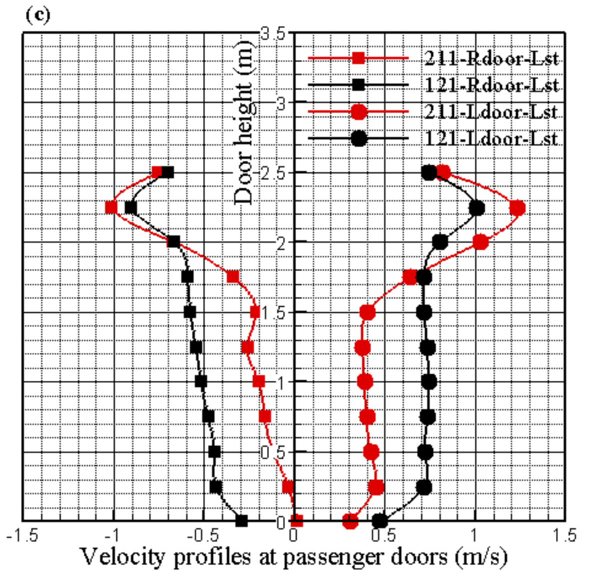

Fig. 14c. Velocity profiles at passenger doors

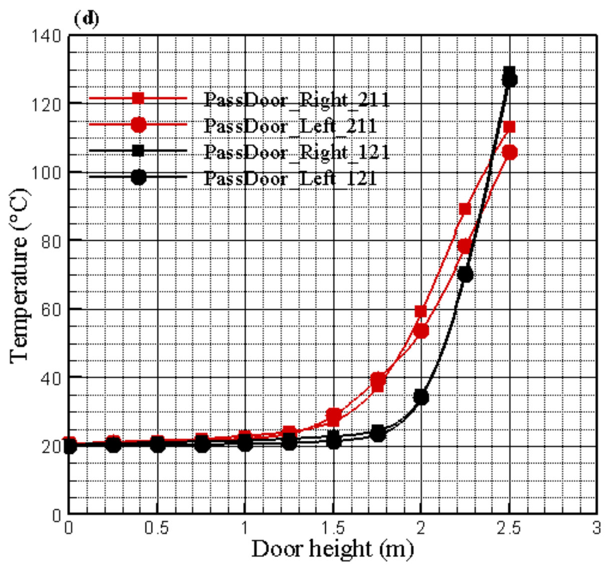

Fig. 14d. Fumes temperature as a function of the door height

In Figure 14d, it is shown that up to the threshold height of 2 m, temperature does not exceed 40 °C. Beyond this height, the temperature gets higher which indicates that some of the smoke produced exhausts through the doors.

3.4. Strategy 4: High ventilation (HVT)

Simulations for different cases are conducted with imposed air flow rates of 66.75 and 100 m^3/s. blowing from each tunnel of respectively. The blown total air flow rates are greater than the total flow rate extracted trough the traps. On the basis of the conservation of momentum the extra air and fumes must evacuate through passenger entrances.

Table 5 gives results of the average temperature of the flow measured at cross-sections P_1, P_2, P_3 and P_4, for each flow rate case.

Table 5

Average temperature results for two differents high air flow rate on tunnels

Average temperature at right platform at depth y = 2 m and height h = 1.5 m (°C)				
Q_{tunnel} = 66.75m^3/s				
ABC	**P_1 x=11.75m**	**P_2 x=27.25m**	**P_3 x=42.75m**	**P_4 x=58.25m**
111	**55.5**	**24.5**	**26.0**	**33.3**
121	**29.8**	**29.4**	**27.9**	**31.7**
211	**57.1**	**28.5**	**26.5**	**38.7**
221	**36.1**	**41.4**	**28.2**	**40.6**
Q_{tunnel} = 100 m^3/s				
111	**67.0**	**29.2**	**30.9**	**46.0**
121	**39.1**	**56.0**	**30.6**	**49.4**
211	**95.5**	**34.2**	**30.6**	**41.6**
221	**39.1**	**54.6**	**29.6**	**40.8**

When the total flow rate through the tunnels is about 30% higher than that extracted through the traps, average temperatures obtained at P_1, P_2, P_3 and P_4 for HVT strategy are almost below the critical temperature, except for cases 111 and 211 particularly at cross-section P_1. In the first case, three quarters of the station, on the right is not invaded by smoke, which is thus a secure area for users and rescuers. Fumes seem to be confined to the left side of the station. It is suggested that the critical flow rate blown through the tunnels must be set between rates over the range 0 to 30% above the rate extracted.

When the flow rate is doubled, the averaged temperatures are well above the critical reference temperature, which involves unbearable situations.

To further refine interpretations of the different simulated cases, we draw the temperature field at t = 300s for case 121 for two flow rates through tunnels, Fig. 15a.

The temperature field indicates that smoke remains stuck to the ceiling and is more or less layered in the four cross-sections, (case 121 - 66.75 m^3/s flow rate). It presents some disturbance in the cross-section close to the fire. For case 121, with 100 m^3/s flow rate, the temperature field shows disturbed air fume mixture at all cross-sections.

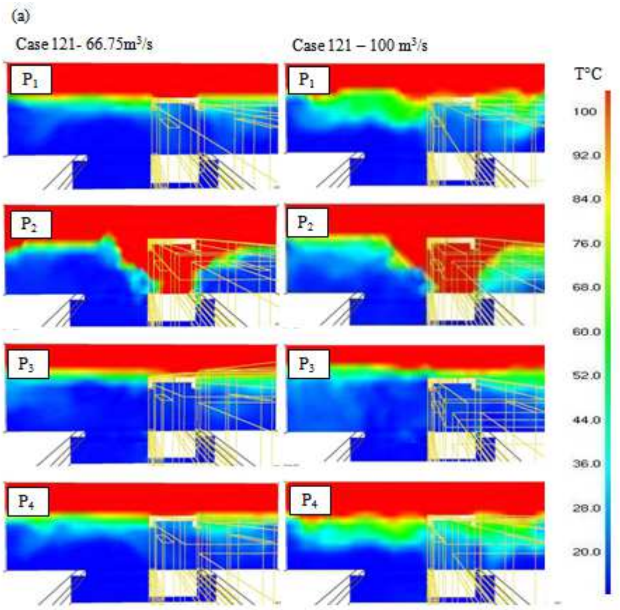

Fig. 15a. Temperature field in cross-sections P_1, P_2, P_3 and P_4

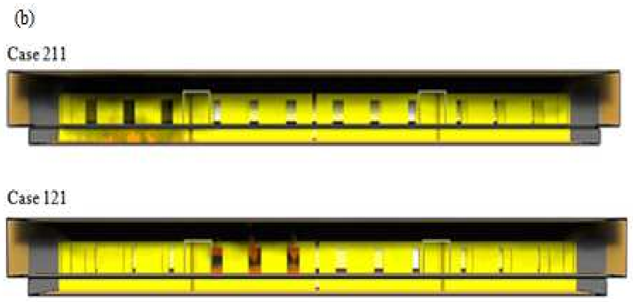

Fig. 15b. Smoke distribution in the station at t=300s;

Figure 15b shows the smoking out of the upper part of the station. The lower level is not invaded by fumes for case 121 at the blowing flow rate 66.75 m^3/s. Lower zones become smoky rapidly as flow rate is increased to a 100 m^3/s.

The fumes spread glued to the ceiling but when they reach the both ends of the station, they are subjected to a suction from the traps and a higher blow through the tunnels. When blowing through the tunnels is greater, the fumes are conveyed to levels below 1.5 m from the surface of the station platform.

In figure 15c are presented air-fumes velocity profiles as a function of the height of the doors for cases 121 and 211 for 'HVT'strategy. Air flow rate blown through tunnels is 30 % and 50% greater than the sucked air-fumes flow rate through traps respectively.

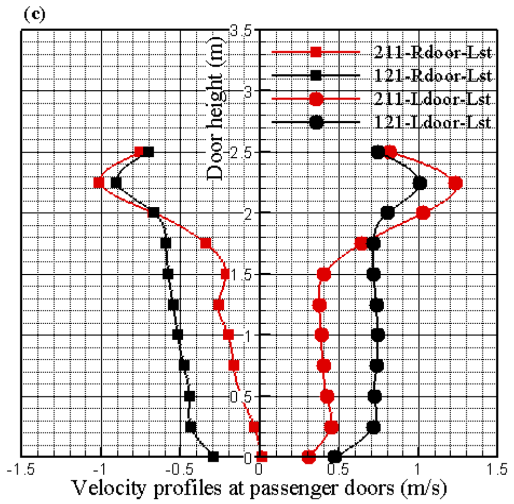

Fig. 15c. Velocity profiles at passenger doors

The negative velocities at the right doors and the positive velocities at the left doors indicates that air-fumes mixture escapes through these openings.

The high temperatures recorded at the passenger entrances, (Fig.15d) implies that some hot smoke escape through the doors.

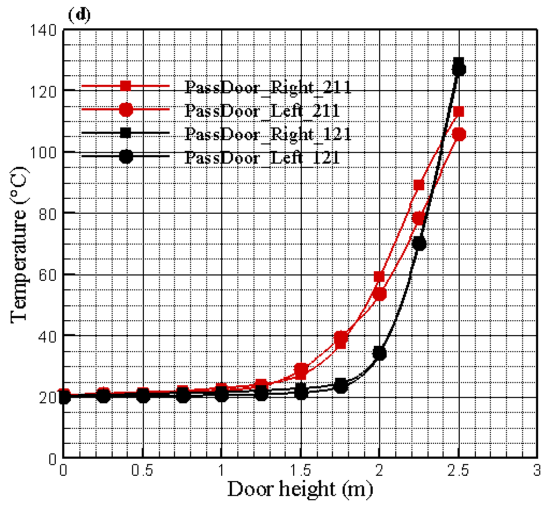

Fig. 15d. Fumes temperature as a function of heigh door

The safety of users is affected by smoke and high temperature at the doors. Temperatures are well above the critical value. Air-fume mixture comes down to low levels and reaches temperatures greater than 40 °C at average man's height. These are thus, classified among the category of very dangerous cases.

4. Concluding remarks

The purpose of this study is to assess numerically the degree of safety of users due to the spread of smoke during a fire in a subway station under different ventilation strategies. These strategies were simulated for two main fire locations on the train: on the carriage platform and on the tires. Results were obtained for four ventilation strategies according to the nomenclature defined previously. The following relevant conclusions can be drawn:

- In the no ventilation strategy, the lower part of the platform is unobstructed by fumes along most of its length. Smoke temperatures in these areas show that their values are low, except in the vicinity of the fire source. Temperature levels are confirmed by smoke fields. When the fire is in the middle of the station or in its vicinity, there is a competition between the right and the left flow extraction; creating an area where smoke cannot make a prevailing path to either the left or the right. Therefore, builds up and goes down the lower level of the platform below the average man's height.
- The obtained results show that "MVT" strategy can maintain at comfortable average temperature, the zone 1.5 m above the station platform surface. All studied cases are secure, except case 211 where a slight excess in average temperature is recorded at cross-section P_1. "MVT" strategy exhibits almost the same smoke behavior as "LVT' strategy.
- For high ventilation strategy "HVT", when the total flow rate through the tunnels is about 30% higher than that extracted, average temperatures are almost below critical temperature, except for cases 111 and 211 at cross-section P_1. In the first case, three quarters of the station on the right is not invaded by smoke, which constitutes secure area for users and rescuers. Fumes seem to be confined to the left side of the station. It can be concluded that a critical blowing air flow rates through tunnels in the range of 0 and 30% above the extracted air-fumes rate through the traps can be suggested.
- When the flow rate is doubled, average temperatures are well above the critical reference temperature, which involves unbearable situations for users.

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