Study of the Throttling Effect in Tunnel Fires

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Abstract

As per the emergency ventilation strategy, air velocity of 3 m/s in case of the longitudinal ventilation is sufficient for smoke control in all fire conditions. Numerical experiments were carried out with FDS software to estimate the numerical value of the critical velocity. Numerical models were realized in 0-6% slope tunnels with a 1% step for 5, 10, 20, 30 and 50 MW fires for four types of fuel: gasoline, diesel fuel, oil and firewood. The paper notes that the dynamic pressure induced by a strong fire is much higher than the static pressure of tunnel jet fans. As a result, following the algebraic summation of positively-directed ventilation flows and the negatively-directed flows induced by fire, an intense back layering occurs, which casts doubt on the suitability of the specified emergency ventilation strategy when designing the fire ventilation. The critical ventilation speed of 3 m/s cannot cope with the traction caused by fire, expressed by the ascending movement of the high-temperature and low-density combustion products. The paper discusses the numerical modelling results with an adiabatic underground heat exchange model and presents typical tunnel fire modelling plans, which correspond to an inclined tunnel for ascending and descending ventilation flows as well as a horizontal tunnel. The article gives the regularities obtained by the numerical models of changes in the variables of average air temperature and density, average carbon monoxide, average carbon dioxide and soot concentrations. According to the emergency ventilation strategy, critical velocity is an important value and a major determinant of back layering prevention in sloping tunnels. Although many papers have been devoted to this problem, the obtained results differ much. The present paper shows that strong fires induce much greater dynamic pressures than the static pressures of the tunnel jet fans are. Consequently, the flows caused by these forces, as they move in different directions, following their algebraic summation, cause a strong back-layering in case of positive ventilation flows, i.e., when the ventilation flow is descending and the fire seat is found at a lower point compared to the air supply portal. The new results can be used to develop fire ventilation plans as well as life-saving and emergency control solutions in the operating tunnels for personnel and rescuers.

Keywords: throttling effect, tunnel fires, emergency ventilation strategy, ventilation flow

Introduction

The road tunnel ventilation projects use two kinds of ventilation scenarios. The first is the tunnel exploitation under normal conditions, while another considers the impact of fire and develops fire ventilation plans to save people and infrastructure. It is clear that the former design must assure the safe operation of the tunnel in the face of future increase in traffic, whereas the emergency control projects must allow human self-evacuation as well as fire liquidation by the firefighters. The critical velocity and back layering length are important parameters of tunnel ventilation during the fire.

Back layering is an opposite propagation of combustion products in the clean air flow. The opposite propagation of combustion products is due to their high temperature resulting in lower density and ascending movement at the expense of buoyancy forces in relevant conditions. This is particularly evident when an air current moves from a high level to a lower level, and the seat of fire is at a low level.

Critical velocity is the minimum velocity excluding back layering, which must be given to the ventilation flow. In terms of a longitudinal ventilation system, a flow with a critical velocity, as an idea suggests, shall expel the smoke and other harmful combustion products from the seat of fire only from one side of the tunnel, in particular, polluted air portal. There should be an underground space free of harmful combustion products at the section of the tunnel on the other side of the fire seat and at the portal, from which fresh air is supplied to the tunnel.

The concept of critical velocity has become a key factor in the designing of fire ventilation [1-3]. It is fair to note that the important fire ventilation parameters mentioned above were introduced into science by Thomas for a horizontal tunnel [4], using the Froude scaling theory [5]. Taking Thomas's formula and Froude's approach into account, it is possible to determine the critical velocity for tunnels of natural sizes based on the results obtained from the models. A dimensionless formula to calculate the critical velocity is proposed in [6], in which the velocity is a function of the heat release rate and tunnel height. The said formula to calculate the critical velocity for tunnels with different cross sections is studied by experimental observations in [7]. This last work is used to estimate the accuracy in many works [8-14] done with numerical calculations.

Later, the concept of critical velocity was developed for inclined tunnels when the gradient-factor, i.e., a correction factor of the numerical value of critical velocity depending on the gradient, was introduced. The gradient-factor can be viewed as the third technological parameter of fire ventilation. The regularities of the changes of the mentioned technological parameters with the account of the tunnel geometry, fire power and the traffic nature were determined. In particular, the influence of tunnel slope, the ratio of tunnel width and height, and aerodynamic blockages caused by traffic interference in the tunnel and other reasons on the specified parameters was studied [6-9].

Fires in transport tunnels were studied in various aspects: characterization of underground fires and smoke propagation scenarios [9-18], issues of temperature distribution and propagation in tunnels, as well as non-stationary and quasi-stationary heat exchange processes between the rock mass and ventilation flow [19-23], influence of the tunnel gradient on back layering length in terms of natural ventilation [11, 24, 25], propagation of smoke and toxic combustion products in the direction opposite to the movement of ventilation flow [18, 24-26], dynamics and scenarios of fire development under the ground [26-28], theoretical and experimental studies of critical velocity [29-36], and impact of piston effect of moving transport on ventilation [37].

The technological parameters of ventilation given above: critical velocity, back layering length and gradient factor were used in the recommendations to design tunnel ventilation, taking into account the design value of fire power. The latter differed significantly in different recommendations [1-3]. For example, under standard NFPA 502, heat release rate (HRR) varied within the range of 30-200 [3]. The implication here is that heavy trucks and gasoline tankers have a maximum heat release rate.

From the review of the above-mentioned literary sources, it can be seen that the throttling effect of fire, as well as the aerodynamic impact of smoke and toxic products of fire on the ventilation flow and the ventilation system was paid less attention. It should be noted in advance that we consider the impact of fire on ventilation not so much as an imaginary "narrowing" of the tunnel and a resultant increase in aerodynamic resistance, but additionally, and more importantly, as a result of algebraic summation of flows. This is followed by reduced ventilation, which occurs when the seat of fire is located hypsometrically lower than the air supply portal, i.e., when the descending ventilation flows are of a positive direction.

For many typical vehicular traffic tunnels, the emergency ventilation strategy accepts that in terms of longitudinal ventilation, an air velocity of 3 m/s is sufficient for smoke control under all fire conditions. As for the idea of smoke control, as mentioned above, there will be an area free of smoke and other toxic combustion products from the seat of fire to the tunnel air inlet portal.

To examine this view, we carried out a numerical simulation with FDS software using the finite volume method. The modelling technique is discussed below.

It was found that the critical air velocity of V_{cr}=3 m/s is valid only for small fires, whereas 30 MW or stronger underground fire scenarios are not subject to this regularity. In particular, in case of a descending ventilation flow, smoke and other combustion products are intensely mixed in fresh air flow and often a higher average concentration of pollutants is released into the atmosphere from the tunnel air inlet portal as compared to the dirt air outlet portal. Figure 1 shows the results of variability of the ventilation flow average velocity for a 50 MW fire.

As Figure 1 shows, in case of a zero-tunnel inclination, it can be seen that the fire is a resistance to the ventilation flow (curve 2). Jet ventilation started at 0.00 s and the ventilation flow reached a velocity of about 3.4 m/s. A 50 MW fire activated in the central part of the tunnel at 20 s reduces the air velocity by 0.4 m/s because of the throttling effect. In this case, the traction caused by the fire is zero.

In case of a descending ventilation flow (curve 3), the ventilation flow has a positive direction, and the fire still acts as a resistance to ventilation and in this case too, reduces the air velocity by about 0.4 m/s, while the remaining speed reduction by about 1.4 m/s is the algebraic sum of the negative direction flow induced by fire and the ventilation flow of a positive direction.

In case of an ascending ventilation flow (curve 1), the algebraic sum of the ventilation flow and the flow induced by fire increases the total flow by approximately 1.3 m/s, as both flows have the same (negative) direction. In this case too, fire is an aerodynamic resistance to the ventilation flow and the total velocity is reduced by the relevant value, by approximately 0.4-0.5 m/s.

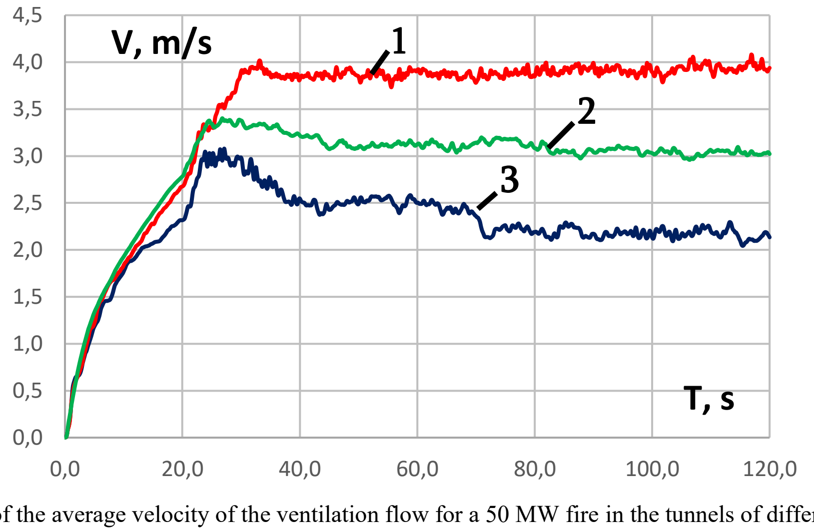

Fig. 1. Variability of the average velocity of the ventilation flow for a 50 MW fire in the tunnels of different inclinations: 1 – Inclination 6 % (ascending flow); 2 - Inclination 0 %; 3 - Inclination 6 % (descending flow)

The first preliminary conclusion is that the flow of a negative direction induced by fire caused by a decrease in air density has a

3.0-3.5 times stronger effect on the numerical value of the ventilation flow than the fire as a local aerodynamic resistance.

This also necessitated a more thorough study of the impact of fire on the ventilation flow.

Materials and Methods

Identifying traction induced by fire

The dynamic pressure induced by fire can be theoretically determined by the Clapeyron Equation of ideal gases, which establishes the relation between the pressure of gases, specific volume and temperature.

Standard density of air of 1.2 kg/m^3 is used in the calculation, manufacture, testing and operation of fans, obtained by the Clapeyron Equation in terms of p = 101.3 kPa atmospheric pressure at sea level and 20°C, i.e., the ventilation flow is practically considered as the ideal air by proven technology. The ventilation jet meets the properties of ideal gas during the fire better than gas of 20°C at normal atmospheric pressure at sea level.

As the Clapeyron Equation shows, it is clear that the dynamic pressure induced by fire with a temperature of 1000°C in tunnels is 121.6 kPa, which is greater than the atmospheric pressure, and is 8 times more the maximum static pressure of the most powerful fans. This time, the air density is reduced to 0.277 kg/m^3 [31]. Consequently, in case of a strong fire, it will be virtually impossible to control the ventilation flow by means of fans, and the air direction and discharge will be due to the depression caused by the fire.

Numerical modeling methods

The scenarios of development of 5, 10, 20, 30, 50 MW fires in tunnels with 0, 1, 3, 4, 6% gradients were investigated. The geometry of the tunnel is as follows: length: 100 m; width: 8 m; height: 6 m; area of the seat of fire: 16 m^2; the coefficient of the tunnel walls ratio is 1,33. The seat of fire sized: 2.75x5.8x1.5 m is in the central part of the tunnel. In fire modeling, mostly gasoline was used as the combustion reagent. Individual numerical observations were also conducted with such combustion reagents as: diesel fuel, oil and firewood. The time of modeling was 120 seconds.

The numerical problems were modeled with a volumetric grid method. The grid cell dimensions were: 0.5*0.5*0.5 m. Each model had about 55 thousand cells.

For modeling the descending ventilation flows, at τ = 0 s, two jet fans with a capacity of 28 m^3/s and a pressure of 2000 Pa will start at the upper portal. The fans will inject the air flow, whose average speed in the tunnel always exceeds the critical value (3 m/s). At the moment of time τ = 20 s, the fire will start on the model and the observation will continue in terms of fire. For modeling the ascending ventilation flows, the fans would start at the lower portal, while the rest of the experiment would be carried out similarly to the course described above.

Virtual measuring devices were installed in two rows in the middle of the tunnel, at 10 m intervals in the longitudinal direction. The first row was located at a height of 1.7 m from the tunnel carriageway, and the second row - at a height of 5.7 m. The modeling used 4 groups of measuring devices that measured and recorded the air velocity, temperature, and air and soot densities at the point of location. In addition to point measurements, the model used virtual measuring devices to determine the mean values of air, carbon monoxide, carbon dioxide, and soot densities at 10 m intervals in the elementary section of the tunnel.

The purpose of the experiments was not to design a specific realistic tunnel, but to show that the specified numerical value of the critical velocity is not suitable to prevent back layering in case of strong fires. Therefore, a simple rectangular cross section of the tunnel was selected. Fire Dynamics Simulator (FDS) was used for all models.

A separate model was provided with 3 and 4 fans connected in parallel. This was done to significantly increase the numerical value of the modeled critical velocity.

Heat exchange between the surrounding mountain massif and the ventilation flow was considered adiabatic in numerical models. However, it was clear from the beginning that a clearly non-stationary heat exchange occurs in the given instance, while the process itself is polytropic and in reality, more heat losses will occur. Following this assumption, the numerical values of the temperatures obtained by numerical modeling will be somewhat higher, but this is acceptable, as temperature prediction is not the subject of major interest of the present study. The pressure near the portals in the underground space equaled the atmospheric pressure in the numerical experiments.

We present the typical plans of fire modeling in the tunnel, which correspond to the inclined tunnel for ascending and descending ventilation flows, as well as the horizontal tunnel with the ventilation flow moving through it. In all cases, there is a seat of fire in the central part of the tunnel. In case of an ascending flow, air is supplied from portal A, and polluted air is diverted from portal B. just opposite, for the descending flow, the air supply is portal B. For a horizontal tunnel, it does not matter which portal will supply the air, because in this case, we are dealing with a horizontal ventilation flow.

The tunnel is 100 m long, and the calculation of length in all subsequent figure starts from portal A.

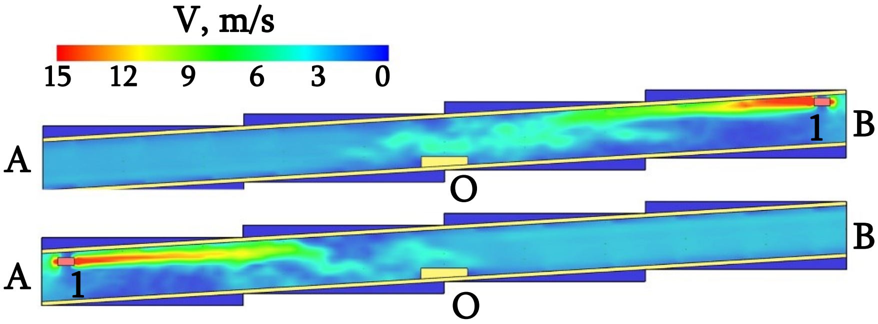

Fig. 2. Basic plans of ascending and descending flows: 1 – jet fan, which will start at τ = 0 s; O – seat of fire, which will start at τ = 20 s (as the fresh air jet front reaches the seat of fire and goes beyond it). Up – a descending ventilation flow of a positive direction; below – an ascending ventilation flow of a negative direction

Results And Discusion

Temperature and density variability according to the numerical model

The temperature variability in the descending ventilation flow is presented in Figure 3 as per the numerical model, which corresponds to the upper plan in Figure 2. The fire strength is 50 MW and the air current velocity is 3.0 m/s, which, in line with the critical velocity idea, must ensure the passage of the air polluted with combustion products along OA tunnel section, while section OB must be free from the polluted air.

According to the modeling results, the flow induced by fire is so strong that after summing up with the ventilation flow, the total flow is practically directed towards Portal B. Thus, if the ventilation flow moves at a speed of 3 m/s, there is an abnormal distribution of temperature developed as a result of fire in the air supply tunnel.

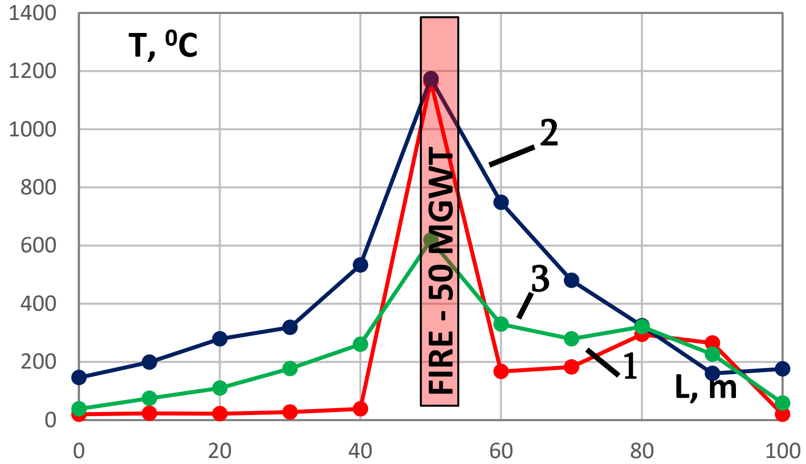

Fig. 3. Air temperature variability in the descending ventilation flow: Tunnel inclination: 6 %; fire strength 50 MW; 1 – Temperature at a height of 1.7 m from the tunnel floor; 2 - Temperature at a height of 5.7 m from the tunnel floor; 3 – Average temperature in the tunnel cross section

As the air density significantly depends on its temperature, it is expected that the air density distribution will be of the type similar to the regularity shown in Figure 3 for the descending ventilation flow what is shown in Figure 4. Indeed, the course of the curves in Figure 4 almost repeats the course of the corresponding curves in Figure 3.

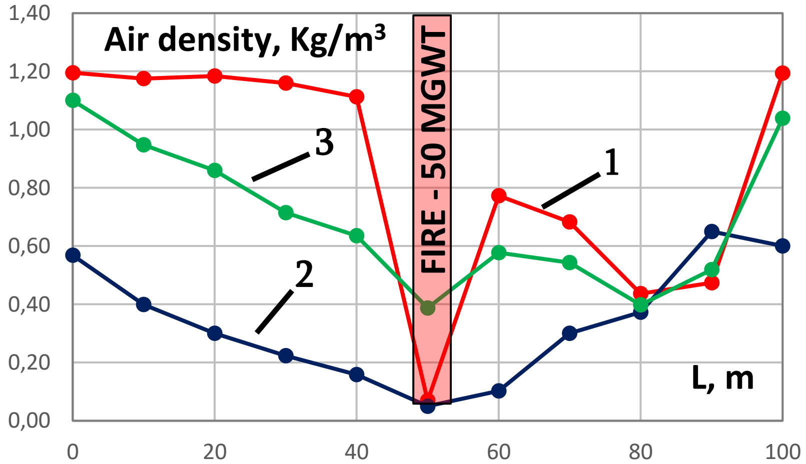

Fig. 4. Variability of air density in the descending ventilation flow:
Tunnel inclination: 6 %; Fire strength: 50 MW; 1 – Density at a height of 1.7 m from the tunnel floor; 2 - Density at a height of 5.7 m from the tunnel floor; 3 – Average density in the tunnel cross section

Figures 3 and 4 show that we are dealing with an abnormal situation: on a clean air flow, right of the fire seat, the air has a higher temperature. Consequently, the impact of fire is more noticeable in the direction of a high level from the seat of fire than in the opposite direction from the same seat. The reason for this is the predominance of traction induced by fire over the power of the jet fans.

Variability of soot density depending on the modeled fire

In line with the plan in Figure 2, the variability of average soot density was determined for the modeled fires depending on the tunnel length. The results are given in Figure 5.

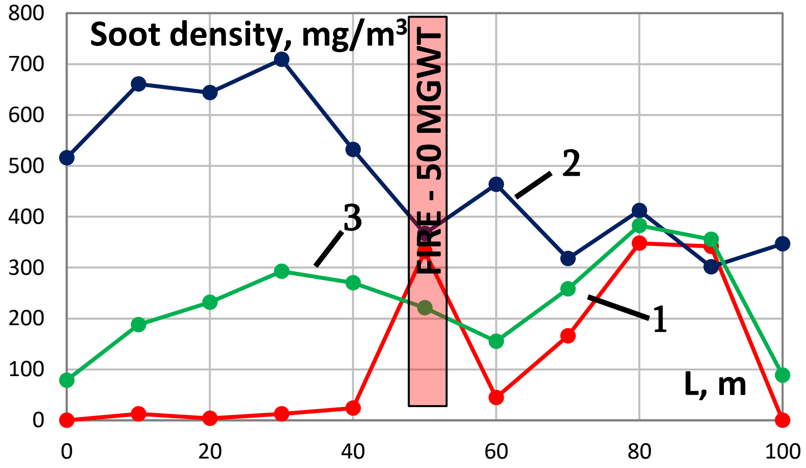

Fig. 5. Variability of soot density in the descending ventilation flow:
Tunnel inclination: 6 %; Fire strength: 50 MW; 1 - Density at a height of 1.7 m from the tunnel floor; 2 - Density at a height of 5.7 m from the tunnel floor; 3 - Average density in the tunnel cross section

The kind of variability of soot density according to the tunnel length given in Figure 5 corresponds to the conclusion made in the previous paragraph suggesting that the critical velocity of 3 m/s cannot cope with a fire-induced traction, and there occurs a flow overturning.

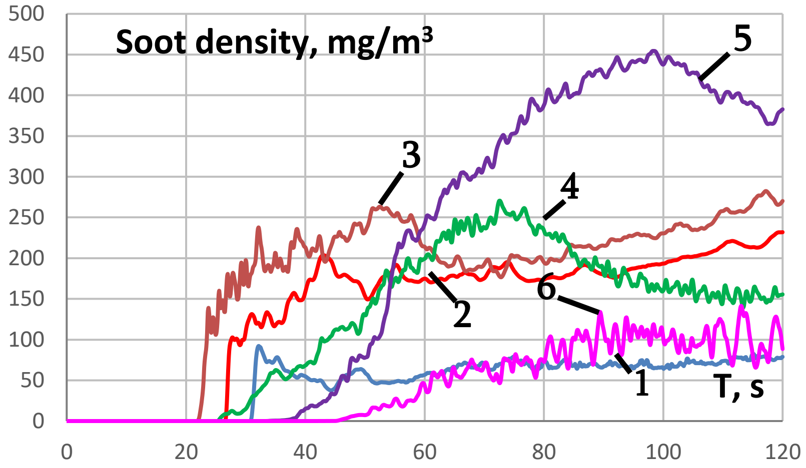

Fig. 6. Dynamics of soot density at different points for the descending ventilation flow. Distance from Portal A (see Figure 2):1 – 0 m; 2 – 20 m; 3 – 40 m; 4 – 60 m; 5 – 80 m; 6 – 100 m

The dynamics of soot density at different points is shown in Fig. 6 what once again proves the trustworthiness of the results and conclusion given in Figure 5. In particular, the soot density (curve 1) through the polluted air discharge Portal A (see Figure 2) is lower than the same value at fresh air supply Portal B (see Figure 2 and curve 6) for the whole process, i.e., for 120 s.

Conclusion

According to the emergency ventilation strategy, critical velocity is an important value and a major determinant of back layering prevention in sloping tunnels. Although many papers have been devoted to this problem, the obtained results differ much. The present paper shows that strong fires induce much greater dynamic pressures than the static pressures of the tunnel jet fans are. Consequently, the flows caused by these forces, as they move in different directions, following their algebraic summation, cause a strong back layering in case of positive ventilation flows, i.e., when the ventilation flow is descending and the fire seat is found at a lower point compared to the air supply portal. Therefore, the critical speed of 3 m/s in this case cannot prevent back layering what should be taken into account in developing the fire ventilation plans.

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