https://doi.org/10.1051/matecconf/202237300076

Influence of current direction in longitudinal ventilated road tunnels on the backflow of combustion Produits

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Abstract. The results of numerical modeling in longitudinal ventilated sloping road tunnels are given. The slope of the tunnels varies in the range of 0-6%. 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 seat of fire sized: 2.75x5.8x1.5 m is in the central part of the tunnel. The scenarios of development of 5, 10, 20, 30, 50 MW fires are studied in the case of positive and negative directional ventilation flows. The time of modelling was 120 seconds. The numerical problems were modelled with a volumetric grid method. The grid cell dimensions were: 0.5*0.5*0.5 m. Virtual point and volumetric measuring equipment was used to record the modeling results. The modelling used 4 groups of measuring devices that measured and recorded air velocity, temperature, and air and smoke densities. The paper discusses cases of algebraically summarizing the ventilation and fire-induced flows. Based on the results of numerical modeling, we can point out that the widely accepted indices of critical velocity and back-layering length in inclined road tunnels often give erroneous results. Therefore, in strategies for emergency ventilation, indicators such are critical velocity and back-separation should be used with caution.

1 Introduction

Road tunnels are designed, built and used along the most complex road sections with the aim to overcome them easily. They accelerate cargo turnover, which is a very important economic component. Depending on the location, orography and topology, some tunnels have a great inclination. Long tunnels, particularly the ones through mountain passes, typically present alternating sections of different directions and gradients. The spatial orientation of tunnels and their sections in fact always helps the occurrence of permanent

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ventilation flows of positive and negative directions depending on the location of fresh air inlets and polluted air outlets.

Consequently, reaching the design solution of standard and emergency ventilation systems in closely alternating horizontal and inclined tunnel sections is a complex problem. It is especially difficult to design emergency ventilation to eliminate flue gas back-layering in sloping tunnels, as the fire development scenarios fundamentally differ for horizontal and sloping tunnels.

The peculiarities of the development of underground fires in horizontal tunnels were first focused on by the famous scientist Thomas, who studied the issue using physical models [1] and introduced important technological parameters of tunnel ventilation in science. These parameters are: critical speed and back-layering length. He noticed that the lower the velocity of the ventilation flow, the greater the distance of opposite distribution of the flows of smoke and other toxic gases in a fresh air stream was. This is caused by high temperature of the combustion products, and the resultant little density and volatility at the expense of buoyancy, while the temperature depended on many factors, including fire strength and boundary conditions. Other things equal, as the velocity increased, the back-layering decreased and was zero at a certain, so-called critical velocity [2].

The critical velocity and back-layering length in different cases and conditions have been studied through theoretical, experimental and numerical modeling. There are a number of papers describing different fire development scenarios have been written and published to address this issue. In particular, the peculiarities of underground fires, the smoke propagation under the ground [2-7], the temperature distribution in tunnels, the effect of tunnel inclination on back-layering length in case of natural ventilation [8-10], and fire development dynamics and scenarios under the ground have been studied, the theoretical and experimental studies of critical velocity have been performed, and the effect of the distribution of smoke and combustion products in the opposite direction of the ventilation flow movement has been identified [11-17].

In [2], Thomas noted that critical velocity of 3 m/s for most tunnels should be sufficient to avoid back-layering. The appropriateness and adequacy of this numerical value of critical velocity to avoid back-layering is proved in papers [15, 16]. Consequently, the validity of this numerical value of critical velocity does not seem to arise any questions, but the results of our numerical modeling have convincingly shown that it is invalid in case of positive ventilation flows, i.e., when a fresh air inlet portal is hypsometrically higher than the seat of fire. At first glance, the critical velocity should decrease during the ascending motion of the ventilation air in inclined tunnels, and should increase in case of ascending motion of the ventilation flow. However, the numerical modeling has clearly shown that for the ventilation flows of a positive direction, back-layering occurs permanently even at much higher velocities, and consequently, both important parameters: the critical velocity and the back-layering length lose their meaning as parameters and must be used with extreme caution during the design and exploitation of relevant ventilation systems.

2 Results and discussion

2.1 Calculating fire-induced dynamic pressure

The dynamic pressure induced by fires in the tunnels with great slopes reaches significant numerical values, and has a particularly negative effect on a descending ventilation flow, i.e., when fresh air enters the tunnel from a high hypsometric level and the seat of fire is located lower it. In this case, the ventilation flows are algebraically summed, and the ventilation flow is expected to overturn. The dynamic pressure induced by fire can be theoretically calculated by the Clapeyron equation, which is as follows:

$$pv=RT \tag{1}$$

The notations used in formulas are explained in Table 1.

Table 1. Explanations and units of measurement of the notations used in formulas.

p - Pressure (kPa);
v – Specific air volume $v = {}^{1}/_{\rho}$ (m^3/kg);
ρ – Air density (kg/m^3);
R – Specific air constant, R =287 J/(kg.K); (J/(kg.K))
m – Mass of flue gas (kg);
V – Air volume participating in the combustion process (m^3);
dV – Volume increment (m^3);
dl – Distance travelled by the flow (m);
du – Flow velocity increment at the given moment (m/sec);
A - Tunnel cross-sectional area (m^2);
τ – Time (s);
p_2 – Fire-induced pressure value (kPa);
c_p - Specific heat of air (kJ/(kg.K);
Fr_c - Critical Froude Number;
g - Gravitational acceleration (m/s^2);
H - Tunnel height (m);
k - Constant of proportionality;
k_g- A grade correction factor;
l – Tunnel length (m);
$\dot{Q}$ - Total heat release rate (kW);
$\dot{Q}_c$ - Convective heat release rate (kW);
s - Tunnel slope (%);
T - Average smoke temperature (K);
T_0 - Ambient temperature (K);
ΔT - Temperature difference (K);
u_c - Critical velocity in a horizontal tunnel (m/s);
u_{cs} - Critical velocity in a sloping tunnel (m/s);
u_0 - Longitudinal velocity (m/s);
$\Delta\rho$ - Density difference between the ambient air and the smoke (kg/m^3);
ρ_0 - Ambient density (kg/m^3);
φ - The ratio of tunnel width to height;
L_b - Back-layering length (m);

It should be noted that Clapeyron equation yields reliable results to estimate the fires in tunnels - firstly, because the combustion process in tunnels takes place in terms of atmospheric pressure and high temperature, without an increase in static pressure, and Clapeyron equation clearly describes the state of real gases [17]. On the other hand, as per the proven technology, ventilated air is virtually considered as ideal gas, as the standard air density at sea level ρ = 1.2 kg/m^3, and is calculated with the given equation when atmospheric pressure p = 101.3 kPa and the temperature is 20 ℃.

Based on above-mentioned, as per Formula (1), the dynamic pressure induced by a fire with temperature of over 1000°C in tunnels is approximately 8 times the maximum static pressure of the most powerful fans. In such a case, the air density is reduced to 0.277 kg/m^3.

Therefore, the ventilation flow induced by the fan and the flue gas flow induced by the reduced density, after summed algebraically, will change both, the magnitude and the direction of the ventilation flow.

It is clear that fire strength depends on the mass of fuel, which is related to the flue gas mass (m) with a certain dependence. By multiplying both sides of equation (1) by the given value, we obtain:

$$pV=mRT \tag{2}$$

where $V = mv$ is the air volume participating in the combustion process (m^3), with its value directly proportional to air velocity, i.e.:

$$dV=Adl=Adu \tag{3}$$

For 1.5-2 km long tunnels, following the vehicle speeds, the evacuation must end in 2 minutes. The pressure variation for this time is of concern. So, the time variation interval of independent variable τ is: $0 \leq \tau \leq 120$, where τ is given in seconds, and formula (3) will be as follows:

$$V = A\int_0^{120}[u_0 + u(\tau)]d\tau \tag{4}$$

where u_0 is the initial air flow velocity (m/s); $u(\tau)$ is the air flow velocity presented by time function (m/s).

By considering Formula (4), the value of pressure induced by fire at the seat of fire is obtained from Formula (1):

$$p_2 = \frac{mRT}{A\int_0^{120}[u_0+u(\tau)]d\tau} \tag{5}$$

The primary solution of the subintergal function in this formula is not known. An approximate solution can be obtained based on experimental data. It is known that 58.80 m^3 of air is needed to burn 1 m^3 of gasoline vapor, with the gasoline vapor density of 0.73 kg/m^3. Thus 1545000 m^3 air volume is needed to burn approximately 18 tons of gasoline vapor, in which case approximately 42.6 kPa excess pressure is induced. It is clear that in a fire in Nihon-zika tunnel [18], which burned 173 vehicles, the combustible materials, together with fuel, would have been of a more equivalent mass. In any case, the first approximation shows that the pressure induced by the fire is much greater than the maximum static pressure (2.0-4.0 kPa) of the fans used in transport tunnels. Accordingly, the induction of 2.0-4.0 kPa pressure in tunnels typical to jet fans is possible even if the fuel mass is much less, around 0.9-1.8 tons.

2.2 Numerical values of critical velocity in horizontal tunnels

In order to specify the concepts, let us consider some of the main fire indicators [19, 20].

The convective heat emitted by fire is calculated by formula:

$$\dot{Q}_c = \rho_0 c_p u_0 A \Delta T \tag{6}$$

Below is the relationship between the convective and the total heat:

$$\dot{Q}_c = 0.7\dot{Q} \tag{7}$$

Average smoke temperature is calculated by formula:

$$T = T_0 + \frac{\dot{Q}_c}{\rho_0 c_p A u_c} \tag{8}$$

Thomas [2] assumed that the combustion products are evenly distributed in the air at the seat of fire and the ventilation rate should exceed the distribution rate of combustion products to prevent back-layering. This assumption is known as the Critical Froud Model, and is the most well-known model for this matter, widely used in engineering, using the Critical Froud Number equal to 4.5:

$$Fr_c = \frac{\Delta\rho g H}{\rho_0 u_c^2} \tag{9}$$

The most important parameter of fire, the critical velocity for horizontal tunnels, is generally defined by formula:

$$u_c = k\left(\frac{g\dot{Q}_c H}{\rho_0 c_p T A}\right)^{1/3} \tag{10}$$

The proportionality constant in Formula (5) is defined by the Critical Froud Number:

$$k = Fr_c^{-1/3} \tag{11}$$

Based on the results of numerical experiments, the numerical values of a gradient factor, another important parameter typical to fires and dependent on the tunnel inclination, can be determined by formula:

$$k_g = \frac{u_{cs}}{u_c} \tag{12}$$

The third important parameter, the back-layering length, is determined by the following formula

$$\frac{L_b}{H} = 18.5\ln\left({u_{cs}}/{u_c}\right) \tag{13}$$

Based on the results of numerical modeling, it is also possible to calculate the numerical value of critical velocity according to the maximum instantaneous propagation velocity of the front of the combustion products in terms of natural ventilation corresponding to 20 s of modeling time (Fig. 1).

Over time, the front velocity of the combustion products decreases significantly along the tunnel due to the tunnel aerodynamic resistance. Therefore, the maximum numerical velocities given in Fig. 1 are critical velocities for horizontal tunneling with the fire heat release value. On the other hand, to indirectly determine the validity of numerical modeling, we also used a comparison of the theoretically calculated numerical values of critical velocity and the results of numerical experiments, as given in Table 2. The calculation of critical velocity according to the corresponding value of fire heat emission was done by formula (10) when $Fr_c^{-1/3} = 0.606$.

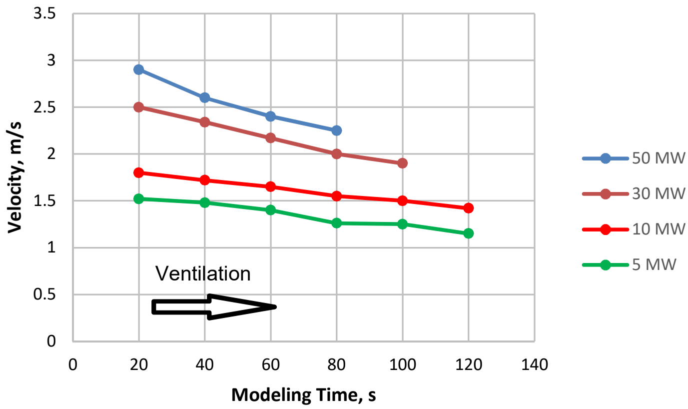

Fig. 1. Variability of the propagation of combustion products in a horizontal tunnel according to numerical modeling for fires of different strengths in terms of natural ventilation.

Table 2. Comparison of the theoretical and numerical experiment results for critical velocity.

No	Fire heat emission rate, $\dot{Q}$, MW	5 MW	10 MW	30 MW	50 MW
1	Critical velocity u_c, m/s (experimental)	1.55	1.85	2.5	2.85
2	Critical velocity u_c, m/s (theoretical)	1.75	2.30	2.87	2.89
3	Relative error	11.4 %	19.6 %	13 %	1.4 %

As Table 2 shows that matching of numerical values of the critical velocity obtained by modeling and calculated theoretically should be considered sufficiently accurate in engineering practice.

2.3 Results of numerical modeling

The scenarios of development of fires of different strengths (5, 10, 30, 50 MW) in tunnels with different slopes (0, 1, 3, 4, 6%) have been studied with FDS software using the finite volume method. The tunnel geometry was as follows: length: 100 m; width: 8 m; height: 6 m; area of the seat of fire: 16 m^2. The seat of fire was located in the central part of the tunnel. Combustion reagent for fire modeling: gasoline; modeling time: 120 sec. Two jet fans with 28 m^3/s capacity and 2000 Pa pressure to switch parallel to one another at portal B, at τ = 0 sec. The fans will eject air flow, whose discharge can be calculated depending on air velocity and tunnel cross section. At τ = 20 sec, the fire will start on the model, and the experiment will continue to the end in terms of fire. By this moment, the ventilation flow has covered the distance from Portal B to the seat of fire what is shown in Fig. 2 for fires of different strengths.

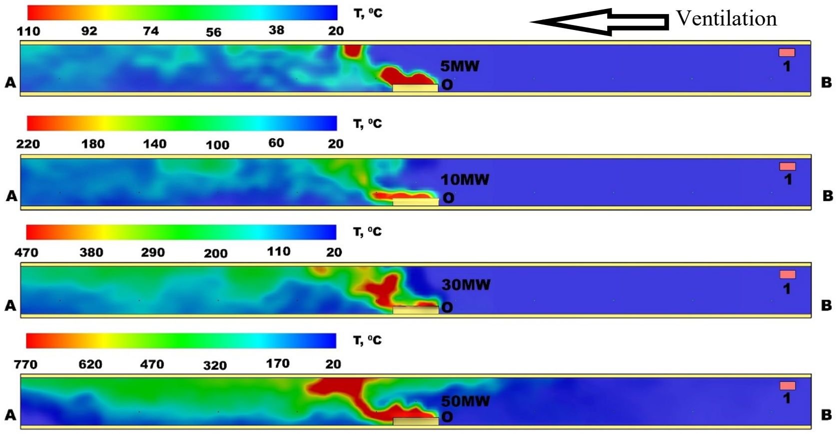

Fig. 2. Ventilation of a horizontal tunnel by τ = 120 sec of 5, 10, 30, 50 MW fires: 1 – jet fan; O – center of the seat of fire.

The volumes of harmful gases and smoke emitted during fires of different strengths are given in Table 3. The assessment is accomplished for zero tunnel inclination. In this case, decreasing air density due to increasing temperature virtually does not cause back-layering, while the combustion products interfere with the ventilation flow and increase its velocity. The air velocity in the tunnel was calculated with numerical models according to the frontal movement of the air flow from Portal B to Portal A. Velocity u_1 was calculated by the distance from Portal B to point O and the time needed to cover it. The corresponding air flow is G_1. Velocity u_2 corresponds to the distance from point O to Portal A. The corresponding air flow is G_2. The discharge of smoke and other toxic combustion products was calculated by formula $G = G_2 - G_1$.

Table 3. Air discharge and velocity in the tunnel according to the numerical experiment.

Strength of fire, MW	u_1, m/s	u_2, m/s	G_2, m^3/s	G_1, m^3/s	G, m^3/s
5	2.9	3.6	139.2	172.8	33.6
10	2.9	4.1	139.2	196.6	57.6
30	2.9	5.0	139.2	240.0	100.8
50	2.9	5.6	139.2	268.8	129.6

In sloping tunnels, despite the mixing of fire products, the ventilation flow velocity does not always increase after the fire start period (τ = 20 s). Figure 3 shows that for fires with the strengths of 30 and 50 MW, the average velocity of the ventilation flow decreases, even though more combustion products are mixed into the air than in case of a 5 MW fire. In this case, in view of the impact on the process, the rate of increase of the ventilation flow volume is much less than the rate of increase of the impact of the buoyancy forces.

The reduction of the ventilation flow velocity is the result of the algebraically summing the flow of the flue gases moving in the negative direction induced by the reduced density and the ventilation flow moving in the positive direction. Apparently, the higher the fire heat release rate (hrr) is, the stronger the back-layering is and the lower the average total velocity is.

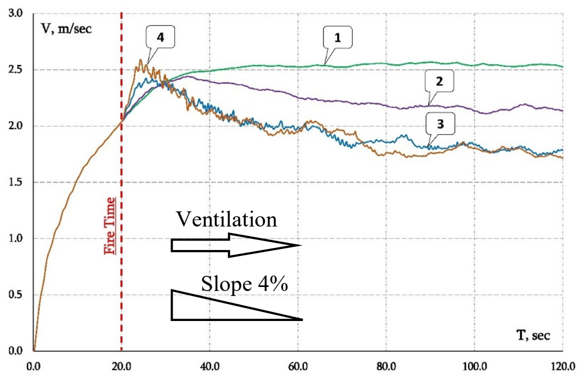

Fig. 3. Variability of average air velocity in the sloping tunnel (4%) for positive (descending) ventilation flows depending on the fire strength: 1 - 5 MW; 2 - 10 MW; 3 - 30 MW; 4 - 50 MW.

Figure 4 shows the time variation of the mean velocity of ventilation flow of a negative direction in the cross sections of both portals. After starting the fire, at τ = 60 sec, there is a two-way air movement at both portals (curves 3 and 4 at Portal A and curves 2, 3, and 4 at Portal B) what is the result of back-layering. It is noteworthy that we provided similar numerical models to prove that in spite of the same direction of the distribution of the ventilation flow and combustion products, as the total flow obtained following the algebraic summation intensifies, it is necessary to have a critical or higher flow velocity to avoid back-layering. Otherwise, as Fig. 4 shows, there occurs back-layering. Therefore, based on the results of numerical modeling, the critical velocity of the ventilation flow of a negative direction does not decrease.

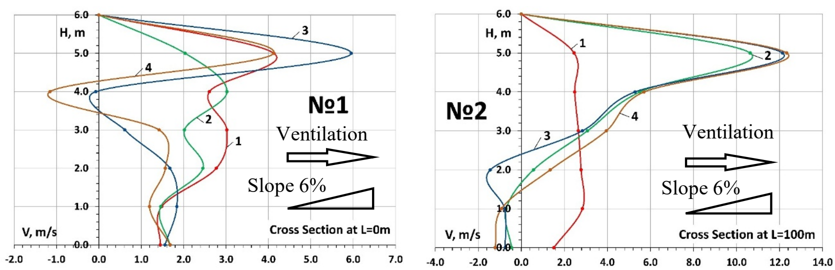

Fig. 4. Time variation of the profiles of average velocity of an ascending ventilation flow (of a negative direction) in the cross sections of the portals; air supply from Portal A; tunnel length: 100 m, gradient: 6%, fire strength: 50 MW, 1 fan (28 m^3, 2000 Pa): 1 - 60 seconds; 2 - 80 seconds; 3 - 100 seconds; 4 - 120 seconds.

As for the ventilation flows of a positive direction, as the results obtained by the Clapeyron equation show, their algebraic summation with the combustion products moving in a negative direction will almost always direct the total flow opposite to the fan-induced flow in terms of sufficient fire strength. This is also confirmed by the results given in Fig. 3.

Figure 5 shows the results of numerical modeling for positive ventilation flows. As it can be seen from the figure, average velocity of the ventilation flow at τ = 60 s of the fire start period exceeds critical velocity. Despite this, after 120 s (curve 4 at Portal B), there occurs back-layering. A similar numerical modeling was also provided in terms of simultaneous operation of 4 fans at Portal B when the average velocity of the ventilation flow was almost 6 m/s, but back-layering was still the case.

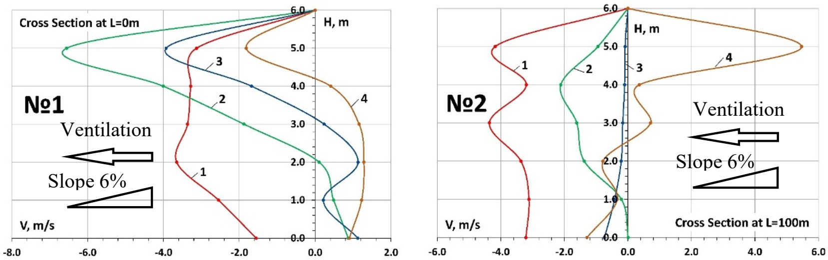

Fig. 5. Time variation of the profiles of average velocity of a descending ventilation flow (of a positive direction) in the cross sections of the portals; air supply from Portal B; tunnel length: 100 m, gradient: 6%, fire strength: 50 MW, 2 fans (56 m^3, 2000 Pa): 1 - 60 seconds; 2 - 80 seconds; 3 - 100 seconds; 4 - 120 seconds.

3 Conclusion

Based on the results of numerical modeling, we can conclude that the negative (ascending) ventilation flows in inclined tunnels must necessarily be have the critical velocity typical to the ventilation of horizontal tunnels to avoid back-layering. As for positive (descending) ventilation flows, it is not possible to avoid back-layering even at 6 m/s critical velocity, as strong fires cause much greater dynamic pressure than the tunnel jet fans do.

Acknowledgements

This work was supported by Shota Rustaveli National Science Foundation (SRNSF) [Grant number AR-19-1936, Project title "*Development and testing of transformable system to save life in road tunnel in case of fire*"].

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