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Mechanics

Impact of Strong Fires on a Road Tunnel Ventilation System

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In case of fire in traffic tunnels or other underground structures, almost all methods of evacuation of people, and sometimes, even the fire-fighting plans consider the control of the ventilation current with fans. The presented studies show that the capabilities of the fans in this case are overestimated, and they fail during strong fires. At this time, the direction of flow and intensity of the polluted ventilation air will depend on the fire impact and the parameters of the ventilation currents of the air-supply tunnels will be incompatible with life as great amount of harmful combustion products will mix with clean air current. The paper, by using the Clapeyron Equation, theoretically determines the numerical values of the dynamic pressure induced by fire under different conditions. Using the finite volume method in FDS software environment, various scenarios of underground fire development have been studied by numerical modeling. By using the finite volume method in FDS software environment, numerical modeling wax used to study various scenarios of underground fire development. The fire strength varied between 5, 10, 30 and 50 MW; the inclination of the traffic tunnel varied between 0, 1, 3, 4 and 6%; the type of the ventilation system used: longitudinal; combustion reagent: gasoline. New results were obtained, in particular, it was established that in terms of longitudinal ventilation, the positive ventilation flows will be overturned when the tunnel slope is 3% or more and the fire strength is more than 30 MW. It should be considered that strong fires induce the dynamic pressures much higher than the static pressure of the tunnel fans, and without considering this fact, it will be impossible to evacuate people from the scene of accident. *© 2021 Bull. Georg. Natl. Acad. Sci.*

Dynamic pressure, fire development under the ground, backlayering, reduced air density

The emergency ventilation plans developed for tunnels are designed to save lives during the fires. The calculation of the critical velocity to control the released toxic substances and other harmful factors is a key issue, while the velocity is an important technological parameter on its own. Another such parameter under the same plans is the backlayering length implying the propagation of harmful combustion products in the direction opposite to the movement of the ventilation current. As a result, toxic compounds are released into the fresh air current what is extremely dangerous and difficult to predict. Depending on the tunnel inclination, these figures vary. The rate of variability index is a dimensionless coefficient – the grade correction factor depending on the slope. Consequently, the grade correction factor is used to predict the critical velocity and backlayering length in the well-studied horizontal tunnels for different fire propagation scenarios. The asymmetry of the propagation of the combustion products in respect of the fire hearth is particularly clear when the tunnel is inclined and the fresh air inlet is hypsometrically higher the fire hearth.

Thus, the critical velocity, backlayering length and grade correction factor are important parameters to design the tunnel ventilation studied by a number of scientists. Consequently, in terms of an optimally designed ventilation project, the tunnel service personnel and rescuers equipped with the knowledge and skills based on the provisions given above, seem to be able to assist the people in distress to self-evacuate, but unfortunately, this is not always the case.

As the statistics of traffic tunnel fires evidence, 173 vehicles were burnt in the fire in Tokyo-Nagoya Nihon-zika tunnel, where the temperature in an 1122-meter-long area reached 1000^0C. A 100-ton railway tank in Summit Tunnel (Great Britain) caught fire, the temperature reached $1{,}500^0$C and the brick reinforcement was covered with a 10 to 15-mm-thick molten mass. The temperature during the fire in the Montreal (Canada) subway reached 1000^0C; the liquidation works lasted for 30 hours, and the ventilation failed [1]. Without any exception, these fires could not be localized or eliminated until the combustible materials in the tunnels were completely destroyed what resulted in victims.

The problem is that the capabilities of the fans in combating the fire is overestimated, and during strong fires, they fail to discharge their function, as the fire can “overturn” the ventilation current [2]. This specific term is used when a fan supplies air in one specific direction, while the air moves in the opposite direction. The reason for this is that the air currents induced by the fan and the fire are algebraically summed up. In this case, the inertia forces induced by the fan operation characterize the fresh air current, while the buoyancy acting in the opposite direction is the result of the lower smoke density.

Determination of Dynamic Pressure during the Fires

Dynamic pressure induced by fire can be theoretically determined by the Clapeyron Equation, which connects the pressure of gases, specific volume and temperature with the following formula

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

where: p is the pressure; v is the specific air volume; $\left(vp = 1, v = {}^{1}\!/_{\rho}\right)$, m^3/kg; ρ is the density, kg/m^3; R is the specific air constant, R=287 J/(Kg.K); T is the absolute temperature, K.

It should be noted that Enrico Fermi in paragraph 16 of the cited paper [3] notes that the Clapeyron Equation well reflects the state of real gases at high temperatures and low pressures what exactly corresponds to tunnel fires, as static pressure does not increase. Thus, Clapeyron Equation can be used to obtain reliable results for tunnel fires. This statement is even more convincing considering that the calculation, production, testing and operation of the fans use standard air density of ρ = 1.2 kg/m^3 as calculated by Clapeyron Equation in terms of 101.3 kPa at sea level and 20^0C, i.e. even in practice, with the approved technology, the ventilation current is considered an ideal gas.

Following the above-mentioned, as per formula (1), the dynamic pressure induced by the fire with a temperature of 1000^0C in tunnels is 121.6 kPa that is more than the atmospheric pressure, and is 8 times more the maximum static pressure of the most powerful fans. At this time, the air density is reduced to 0.277 kg/m^3. Consequently, in case of a strong fire, it will be virtually impossible to control the ventilation current with fans, and the direction of the air current and air flow will be caused by the depression induced by the fire.

Clearly, the strength of fire depends on the mass of fuel that is related to the burnt gas mass (*m*). By multiplying both sides of equation (1) by the given value, the following equation is gained

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

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

$$dV = Sdl = Sdu \,, \tag{3}$$

where, dV is the volume increment (m^3); S is the tunnel cross section area (m^2), $S = Const$; dl is the distance traveled by the current at a given moment of time (m); du is the current velocity increment by the given moment of time that also depends on the traction induced by the fire (m/s).

For the tunnels with the length of 1.5-2 km, following the vehicle driving speed in them, the evacuation should end in 2 minutes. The pressure variability is interesting in this period. Thus, time variability interval τ of the independent variable is: $0 \le \tau \le 120$, where, τ is given in seconds, and formula (3) will be written down as follows

$$V = S\int_0^{120}\left[u_0 + u(\tau)\right] d\tau \;, \tag{4}$$

where, u_0 is the initial velocity of the air current (m/s); and $u(\tau)$ is the velocity of the air current given as a time function (m/s).

By considering formula (4), formula (1) gives the value of pressure induced by the fire on the hearth

$$p_2 = \frac{mRT}{S\int_0^{120}\left[u_0 + u(\tau)\right] d\tau} \,. \tag{5}$$

In this formula, the primary value of the integrand function is not known. As per the experimental data, an approximate solution can be obtained [4].

In the experiment made in Switzerland, the air velocity induced by the artificial fire hearth varied within 50-100 m/s. A real fire will usually travel longer distances and will have greater traction. However, for the initial assessment, the results of the said experiment will be helpful.

Let us find the approximate value of the integral with a trapezium rule. For this purpose, let us divide the range of variability $0 \le \tau \le 120$ of τ into ten equal time sections, i.e. $\tau_0 = 0$, $\tau_1 = 12$,..., $\tau_9 = 108$, $\tau_{10} = 120$. Let us distribute the maximum velocity specified for the given sections linearly. Consequently, if denoting the function under the integral by $f(\tau)$, i.e. $f(\tau) = \left[u_0 + u(\tau)\right] d\tau$, then, by inserting the relevant values of the initial ve-locity $u_0 = 1.5$ and $u(\tau)$, we will gain $f(\tau_0) = 1.5$, $f(\tau_1) = 11.5$, $f(\tau_2) = 21.5$, $f(\tau_3) = 31.5$, $f(\tau_4) = 41.5$, $f(\tau_5) = 51.5$, $f(\tau_6) = 61.5$, $f(\tau_7) = 71.5$, $f(\tau_8) = 81.5$, $f(\tau_9) = 91.5$, $f(\tau_{10}) = 101.5$. As per the trapezium rule, we will have: $V \approx 60S\left[f(0) + 2f(\tau_1) + \cdots + 2f(\tau_9) + f(\tau_{10})\right] = 61800S$, if inserting the datum close to the real value of one-way tunnel (25 m^2), then formula (4) will give the air volume participating in the burning process (1545000 m^3). The given volume is used to calculate the pressure induced by the fire with formula (5).

It is known that 1 m^3 gasoline vapor needs 58.80 m^3 air to burn, and the density of the gasoline vapor is 0.73 kg/m^3. The gained air volume of 1545000 m^3 is needed to burn approximately 18 tons of gasoline vapor, during which approximately 42.6 kPa excess pressure is induced. It is clear that during the fire in Nihon-zika tunnel [1] where 173 vehicles were burnt, the combustible materials, together with the fuel, would be of a greater equivalent mass. In any case, in the first approximation, the traction force induced by the fire much exceeds the maximum static pressure of the fans (2.0-4.0kPa) used in the traffic tunnels. Consequently, induction of 2.0-4.0kPa pressure in the tunnel typical to jet fans is possible even when the fuel mass is much less, approximately 0.9-1.8 tons.

Numerical Experiments and Discussion

A finite volume method was used in FDS software environment to study the scenarios of development of fires of different strengths of 5, 10, 30 and 50 MW in the tunnels with different slopes of 0, 1, 3, 4 and 6%. The angle of the tunnel inclination for the same percentage values was 0, 0.6, 1.7, 2.3 and 3.4 degrees, respectively. Tunnel geometry: length: 100 m; width: 8 m; and height: 6 m; the area of the fire hearth: 16 m^2; the fire hearth was in the central part of the tunnel. The combustion reagent for fire modeling was gasoline; modeling time: 120 s; at Portal B, for time τ = 0 s, two jet fans with the power of 28 m^3/s and pressure of 2000Pa will turn on. The fans will capture the air current through injection, whose discharge can be calculated depending on air velocity and cross section of the tunnel. At time moment τ = 20 s, the fire starts on the model and the experiment continues for the rest of the time under fire. By this time, the ventilation current has covered the distance from Portal B to the fire hearth what is shown in Fig. 1 for the fires of different strengths.

The amounts of harmful gases and smoke emitted during the fires of different strengths are shown in Table. The assessment is provided for zero-sloping tunnels. In this case, the decrease in air density following the temperature rise does not virtually cause backlayering, while the combustion products will mix with the ventilation current and increase its velocity.

The air velocity in the tunnel was determined with numerical models, in accordance with the air current front movement from Portal B towards 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 discharge 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 products was calculated by formula

$$G = G_2 - G_1 . \tag{6}$$

In the sloping tunnels, despite the mixing of fire products after the fire start period $(\tau = 20s)$, the ventilation current velocity does not always increase. Fig. 2 shows that for fires of 30 and 50 MW strength, the average velocity of the ventilation current decreases despite the fact that more combustion products are mixed with it than in case of a 5 MW fire. In this case, in the final run, the inertia forces of the current are greatly exceeded by the forces of buoyancy caused by the decrease in air density. More exactly, in view of the impact on the process, the rate of increase of the ventilation current volume is much less the rate of impact of the buoyancy forces.

This is well seen in Fig. 3 showing 50 MW fire development scenarios for horizontal and sloping tunnels (3%). The buoyancy forces for a zero-

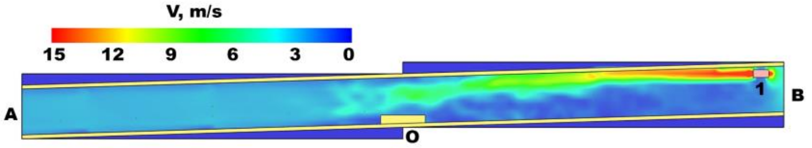

Fig. 1. Horizontal tunnel ventilation by the outbreak of 5, 10, 30 and 50 MW fire by time moment τ = 20 s: 1 – Jet fan; O – Fire hearth center.

Table. Air discharge and velocity in the tunnel obtained from the numerical experiments

Fire strength, 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

sloping tunnel contribute to the better ventilation. For a 3% inclination, fire acts as an aerodynamic barrier to ventilation, while the combustion products from both portals mix with the atmosphere.

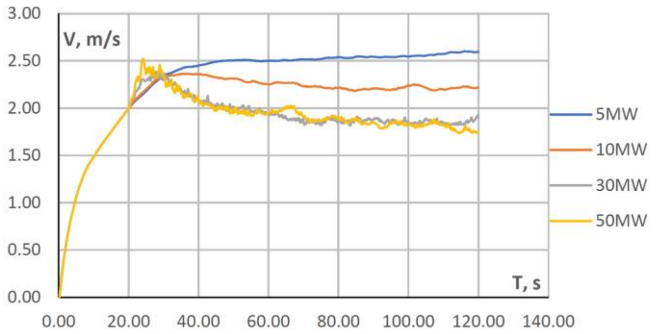

Fig. 2. Variation of mean air velocity in the sloping tunnel (3%) depending on the fire strength.

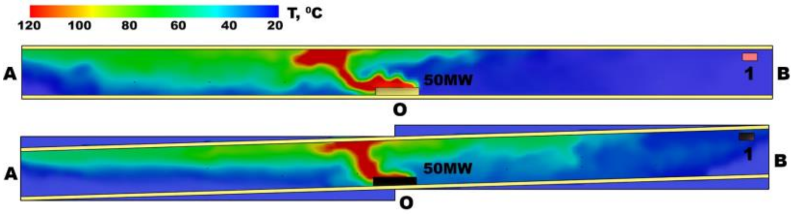

Fig. 3. Scenario of development of 50 MW fire for the horizontal tunnel and the tunnel with a 3% inclination: the air from Portal B is supplied with fan-1.

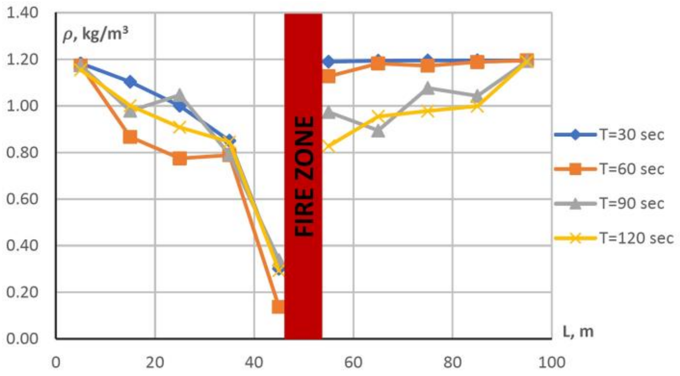

Fig. 4. Variation of the ventilation air density along the tunnel with 3% inclination, in terms of 30 MW fire.

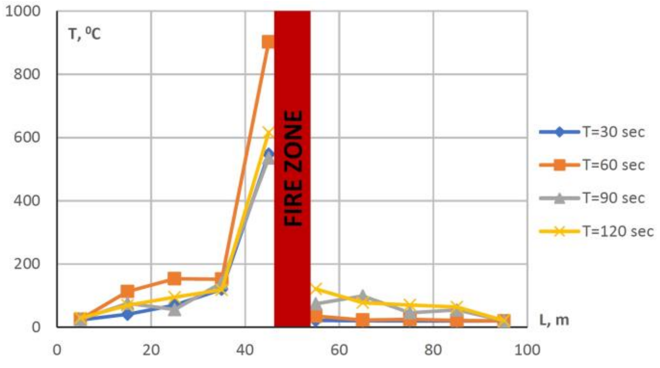

Fig. 5. Variation of the ventilation air temperature in case of 30 MW fire on the central longitudinal tunnel plane 1.7 m above the floor, along the tunnel with 3% inclination.

The dynamics of the ventilation air density, depending on the fire hearth and the tunnel length, are given in Fig. 4. The Figure shows that the air density of the downward current is reduced and its minimum value immediately near the hearth of fire varies within 0.18-0.28 kg/m^3. Let us take 0.28 kg/m^3. Maximum temperature at the hearth of fire reducing the air density to the mentioned level, is 610^{0}C, i.e. 883 K (see Fig. 5). Let us use Formula (1) to calculate the pressure induced by fire in the given situation that is 71.0 kPa. Let us note that the dynamic pressure of the given value in the tunnel will cause the overturn of the ventilation current.

Thus, the fact of a strong fire capable of inducing the dynamic pressure greater than the static pressure of the fans, which can overturn the ventilation current in the tunnels with a 3% or greater inclination, must be considered established both, theoretically and based on the numerical experiments. A current is positive if the fresh air is supplie from a hypsometrically high level and moves downwards.

Fig. 6 shows the fire development scenarios for different strengths of fires at the end of 120 s. The Figure shows that in case of a 30 MW fire and 3% tunnel slope, the combustion products from both portals of the tunnel are emitted into the atmosphere evidencing the overturn of the ventilation current, and consequently, the air all along the tunnel is polluted. It should be noted that as the modeled scenario suggests, the combustion products started to propagate in an opposite direction to 50 m in about 30 seconds after the fire broke out and mixed with the atmospheric from the Portal supplying the air to the tunnel.

Fig. 6 also shows that the fire flame is inclined towards the direction of the ventilation current induced by the fans, i.e. from right to left in case of 5 or 10 MW fires. In such terms, the dynamic pressure induced by the fire is less, and the flame of 30 and 50 MW fires is virtually of a vertical orientation.

Conclusion

The present paper provides the theory and numerical experiments studying the impact of fires of different strengths on the longitudinal ventilation systems of the traffic tunnels. The analysis of the tunnels evidences that a strong fire induces a dynamic pressure higher than the tunnel fan static pressure, and evacuation of people in disaster or extinguishing the fire is impossible without considering its value and direction.

We must consider it as an established fact that the ventilation currents will be overturned if the tunnel inclination is 3% or more and the fire strength is more than 30 MW. In this case, the direction of the polluted ventilation air will be influenced both, by the fan and the fire, while the parameters of the ventilation current will be incompatible with life even at the air supply portal due to the high concentration of harmful combustion products in the fresh air current.

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მექანიკა

ძლიერი ხანძრის გავლენა საავტომობილო გვირაბის სავენტილაციო სისტემაზე

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(წარმოდგენილია აკადემიის წევრის ე. მეძმარიაშვილის მიერ)

სატრანსპორტო გვირაბებისა და სხვა მიწისქვეშა ნაგებობების პირობებისათვის, ხანძრის შემთხვევაში, ადამიანების ევაკუაციის თითქმის ყველა მეთოდი, ხოლო ზოგჯერ ხანძრის ლიკვიდაციის გეგმა ითვალისწინებს სავენტილაციო ნაკადის მართვას ვენტილატორების მეშვეობით. წარმოდგენილი კვლევებიდან ჩანს, რომ ვენტილატორების შესაძლებლობები ამ შემთხვევაში გადაჭარბებითაა შეფასებული და ძლიერი ხანძრისას ისინი თავის ფუნქციას ველარ შეასრულებენ. გაჭუჭყიანებული სავენტილაციო ჰაერის მოძრაობის მიმართულება და ინტენსიურობა ამ დროს განპირობებული იქნება ხანძრის გავლენით და ჰაერმიმწოდებელი გვირაბების სავენტილაციო ნაკადების პარამეტრები შეუთავსებელი იქნება ადამიანის სიცოცხლესთან ჰაერის სუფთა ჭავლში დიდი რაოდენობის წვის მავნე პროდუქტების შერევის გამო. ნაშრომში კლაპეირონის განტოლების გამოყენებით თეორიულად შესწავლილია ხანძრის მიერ აღძრული დინამიკური წნევა. FDS პროგრამულ გარემოში სასრულ მოცულობათა მეთოდის გამოყენებით, რიცხვითი მოდელირებით შესწავლილია მიწისქვეშ ხანძრის განვითარების სხვადასხვა სცენარი და მიღებულია ახალი შედეგები. კერძოდ, დადგენილია, რომ გრძივი ვენტილაციის პირობებში მოხდება დადებითი სავენტილაციო ნაკადების ძლიერი უკუდინება (გადაყირავება) მაშინ, თუ გვირაბის დახრილობა არის 3% და მეტი, ხოლო ხანძრის სიმძლავრე აღემატება 30 მეგავატს.

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