საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 16, №4, 2022
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 16, no. 4, 2022

Mechanics

FDS Modeling Results for 50-100 MW Fire in Terms of Semi-Transverse Ventilation in Road Tunnels

Omar Lanchava[*], Giorgi Nozadze[**], Davit Tsanava[*]

[*]*Occupational Safety and Emergency Management Department, Georgian Technical University, Tbilisi, Georgia*
[**]*Rope Systems Laboratory, G. Tsulukidze Mining Institute, Tbilisi, Georgia*

(Presented by Academy Member Elguja Medzmariashvili)

The present paper considers a single-tunnel double-roadway tunnel with two ventilation ducts installed parallel to and isolated from each other in the tunnel ceiling partition. A combined semi-transverse ventilation system was used under standard conditions: fresh air is supplied to the tunnel in a transverse direction, while dirty air is removed in a longitudinal direction - from the portals of the road tunnel. During fire a transverse air supply and exhaust system with specified ventilation ducts is activated. Scenarios of 50-100 MW underground fire development in a 400 m long tunnel section with FDS modeling were studied. The paper presents the scenario of development analogical fires and the dynamics of propagation of harmful factors in the main road tunnel. Both, normal and fire ventilation are used for numerical simulations. Both types of ventilation, as already mentioned, function with the semi-transverse principle. By using powerful mechanical exhaust through the exhaust valves and flexible fire-proof ventilation barriers, it is possible to prevent the propagation of smoke gases, thereby increasing the evacuation efficiency to save lives. The concept of critical velocity through exhaust valves $u_{c.exh} \geq 20$ m/s was introduced to allow uniform consideration of cases under similar conditions. Its critical numerical value satisfies inequation $u_{c.exh} \geq 20$ m/s with first approximation. The paper shows that flexible transformable barriers can prevent uncontrolled propagation of combustion products along the tunnel path what must be considered when making decisions about evacuating people from the disaster area. *© 2022 Bull. Georg. Natl. Acad. Sci.*

underground fire development, critical velocity, combined ventilation, backlayering, FDS simulation

The present paper considers a single-tunnel double-roadway tunnel with two ventilation ducts installed parallel to and isolated from each other in the tunnel ceiling partition. A combined semi-transverse ventilation system was used under standard conditions. With this system, fresh air is supplied along the tunnel by means of one of the ventilation ducts in a transverse direction. For this purpose, exhaust valves are provided on the bottom of the said ducts, which is the ceiling of the road tunnel at the same time. The polluted air under the same standard conditions is discharged longitudinally through the road tunnel using the tunnel driving portals. In this case it is more or less possible to achieve greater safety of the cross-ventilation system at a relatively lower cost. This advantage is evident as the fire ventilation starts.

© 2022 Bull. Georg. Natl. Acad. Sci.

During fire ventilation, the supply of fresh air is provided by the method described above. The air saturated with combustion products is exhausted through the second isolated duct located parallel to the air supply duct. Meanwhile, the contaminated air attempts to continue moving through the main road tunnel by inertia. The task is to prevent the movement of the contaminated air by artificially increasing tunnel aerodynamic resistance in order to enable people to evacuate without being caught up by flue gases on their way in the main road tunnel. Aerodynamic resistance of the tunnel is artificially increased by a flexible fire barrier protected by Georgian Patent [1].

Spread of combustion products in underground space

Analyzing various scenarios of small fire development on the horizontal tunnel model, Thomas [2] noticed that combustion products spread on both sides of the seat of fire. The distance of propagation of combustion products in an opposite direction, i.e. backlayering length gradually decreased as the ventilation velocity increased, and at certain velocity, called critical completely disappeared. In view of little fire strength and air flow in Thomas' experiments, the assumption of equal mixing of fresh air and combustion products was valid [3]. Based on this assumption, Thomas also noted that critical velocity of 3 m/s for most tunnels was sufficient to prevent backlayering. Critical velocities of the same value are given in other works [4, 5] as well, what in [6] was not applied to ventilation flows of positive direction, but the very concept of critical velocity is important for designing fire ventilation systems, extinguishing fire and saving lives. We use critical velocity and have determined its numerical values for natural ventilation [7].

Critical velocity for horizontal tunnels is calculated with formula

$$u_c = k\left(\frac{gQ_cH}{p_oc_pTA}\right)^{1/3}, \quad (1)$$

where u_c is critical velocity, m/s; k is proportionality constant; g is gravitational acceleration, m/s^2; Q_c is convective heat, kW; H is tunnel height, m; P_o is density of ambient air, kg/m^3; C_p is specific air heat capacity, kJ/(kg.K); T is average smoke temperature, K; and A is tunnel cross sectional area, m^2.

Proportionality constant is calculated with critical Froude Number

$$k = Fr_c^{-1/3}. \quad (2)$$

Critical Froude Number is caluclated with formula

$$Fr_c = \frac{\Delta pgH}{\rho_o u_c^2}, \quad (3)$$

where Δp is the difference in densities of ambient air and smoke, kg/m^3. Other values are explained above.

Convective heat emitted by fire is caluclated with formula

$$\dot{Q}_c = \rho_0 c_p u_o A\Delta. \quad (4)$$

where u_0 is initial velocity of longitudinal ventilation, m/s; ΔT is temperature difference between smoke and ambient air, K.

Average smoke temperature is caluclated with formula

$$T = T_o + \frac{Q_c}{\rho_0 c_p A u_c}, \quad (5)$$

where T_0 is temperature of ambient air, K. Other values are explained above.

Total fire strength is determined according to convective heat with formula

$$Q = 1.43Q_c. \quad (6)$$

Length of backlayering is caluclated with formula

$$\frac{L_b}{H} = 18.5\ln\left(u_{cs}/u_c\right), \quad (7)$$

where in addition to the values explained above, L_b is backlayering length, m; and u_{cs} is critical velocity in an inclined tunnel, m/s.

Although the described fire ventilation plan uses transverse rather than longitudinal exhaust of polluted air, longitudinal movement of dirty air through the road tunnel still takes place regardless of the numerical value of classical critical velocity u_c (introduced by Thomas), because air continues to move by inertia at the same or close to it velocity.

As for pressure change, it spreads at the speed of sound what is important to obtain the results of vigorous mechanical exhaust in fire exhaust valves. This vigorous exhaust will reduce the numerical value of critical velocity (u_c) what will also reduce the spread of harmful combustion products along the tunnel roadway. This statement was confirmed by the results of numerical modellings. The concept of critical velocity through exhaust valves $u_{c.exh\geq 20}$ m/s was introduced to allow uniform consideration of cases under similar conditions. Its critical numerical value satisfies inequation $u_{c.exh\geq 20}$ m/s with first approximation.

This inequation is valid both, for horizontal and inclined tunnels.

FDS Modeling, Modeling Results and Discussion

The research given in the present paper is based on FDS modeling for a 400 m long tunnel section. The cross-sectional area of the main road tunnel is 57.5 m^2. The tunnel is equipped with semi-transverse ventilation system. The cross section of the standard ventilation duct is 8 m^2. Exhaust valves with a fixed cross section of 0.175 m^2 distanced by 15 m from one another are installed in the mentioned duct. The valves supply fresh air to the tunnel both, in normal mode of ventilation operation and in case of fire. The total number of exhaust valves with fixed area of 0.175 m^2 for each model is 26. Cross section of the fire ventilation duct is 10 m^2. There are fire exhaust valves with fixed area of 8 m^2 distanced by 90 m from each other at the bottom of the duct (i.e. in the road tunnel ceiling). The total number of similar valves on each model is 5. In normal conditions the fire exhaust valves are closed and tunnel is ventilated with a classic semi-transverse plan: air is supplied through the ventilation duct with fixed area of 8 m^2 and with exhaust valves with fixed area of 0.175 m^2, while dirty air is exhausted longitudinally through the road tunnel. During fire, as noted above, air supply plan does not change, but the longitudinal exhaust pattern of polluted air is changed by the transverse one. Transition to the transverse plan is provided by opening fire exhaust valves with fixed area of 8 m^2 and exhausting dirty air through the fire duct. The schematic drawings of the tunnel are given in Fig.1.

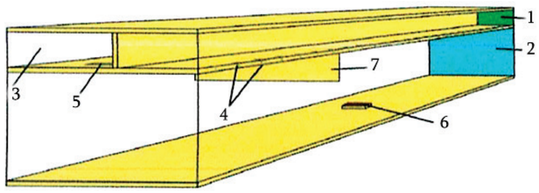

Fig. 1. Numerical modeling plan: 1 – air-supply ventilation duct (cross section: 8 m^2); 2 – main road tunnel; 3 – polluted air exhaust duct (cross section: 10 m^2); 4 – standard exhaust valves (cross section: 0.175 m^2, distanced by 15 m from one another); 5 – fire exhaust valves (cross section: 8 m^2, distanced by 90 m from one another); 6 – seat of fire; 7 – flexible fire-proof barrier lowered from the ceiling to 2 m.

The paper presents the scenario of development of 50-100 MW fires and the dynamics of propagation of harmful factors in the main road tunnel. Both, normal and fire ventilation are used for numerical simulations. Both types of ventilation, as already mentioned, function with the semi-transverse principle.

In order to apply the results of numerical study in practice, several basic scenarios of fire development were designed and realized: scenario N1: fire occurs in terms of simultaneous operation of standard and fire ventilation. The valve with a cross-section of 8 m^2 necessary for fire ventilation located left of portal at the distance of 90 m from the seat of fire is open. In scenario N1, flexible fire barrier is not activated.

Scenario N2 repeats scenario N1 completely. However, with scenario N2, in addition to an open fire valve, a flexible fire barrier at distance of 94 m from the seat of fire, left of portal is activated.

Scenario N3: during the fire the standard and fire ventilation operate together; two valves needed for fire ventilation are open. One of them is activated at distance of 90 m from the seat of fire, left of portal, and another – at distance of 109 m from the seat of fire right of portal. One flexible fire barrier is activated on each side of portals at both ventilation valves, distanced from the seat of fire.

Each scenario had the following initial and boundary conditions: standard ventilation and fire ventilation modeling assumed 33% increase in air volume due to increased volume of combustion products so that the same velocities: 5, 10, 15 and 20 m/s are maintained in the fresh air supply and polluted air exhaust duct in case of same ventilation flow. Modeling time was 60 seconds. Such configuration of initial and boundary conditions allows assessing each scenario. As a result, the features typical to the more realistic fire scenario as compared to Thomas scenario, which, as mentioned above, assumed a 100% increase in ventilation air flow due to flue gases, were identified.

Fig. 2 and Fig. 3 show the results of realization of scenario N1 in the main road tunnel on the

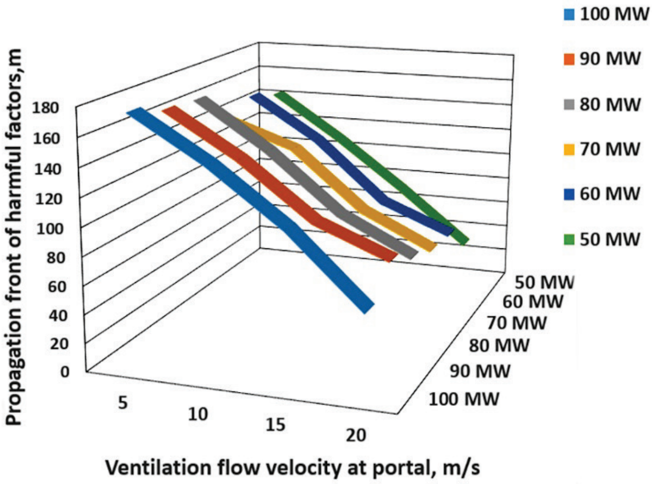

Fig. 2. Variation of concentration of carbon monoxide on the right wing of the tunnel during the simultaneous action of fire and standard ventilation when the seat of fire is not enclosed by a fire-proof barrier.

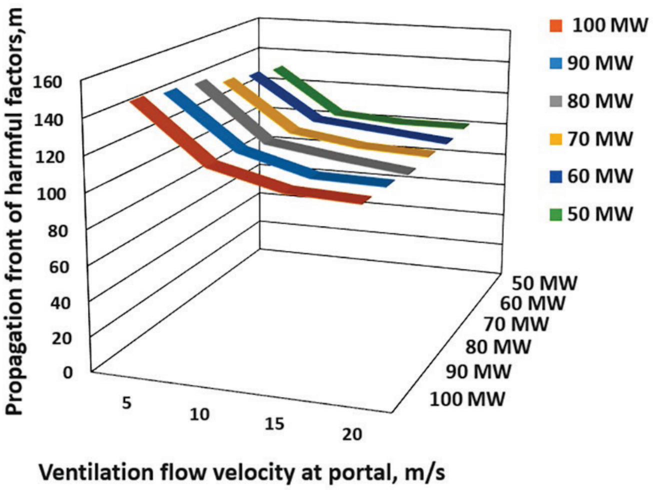

Fig. 3. Variation of concentration of carbon monoxide on the left wing of the tunnel during the simultaneous action of fire and standard ventilation when the seat of fire is not enclosed by a fire-proof barrier.

example of propagation of principal harmful factor – carbon monoxide (CO) for 50-100 MW fires.

Fig. 2 shows that for the initial conditions when the critical exhaust velocity from the fire exhaust valves satisfies condition $u_{c.exh} \geq 20$ m/s, virtually no propagation of flue gases occurs in the main road tunnels beyond the activated fire exhaust valve. This is particularly clearly seen on the right portal side.

It should be noted that condition $u_{c.exh} \geq 20$ m/s is crucial for safe ventilation. The situation on either side of fire is aggravated when fire ventilation rate is low and does not exceed 15 m/s in fire exhaust valves and polluted air exhaust duct.

For quick and efficient localization of flue gases emitted by fire, the method provided by Georgian Patent P 2022 7371 is proposed. The method implies installation of fire-proof barriers near fire valves in a certain way and actuating them at the right time. In particular, a flexible transformable fire barrier in scenario N2 is installed near the fire valve left of portal in 4 m (94 m from the seat of fire). As a result, it prevents the propagation of flow induced by fire beyond the barrier by inertia.

Fig. 3 shows a situational picture of fire development when a 2-meter-high fire-proof barrier is suspended from the tunnel ceiling near the fire heart left of portal, in 4 m from the valve.

Fig. 3 shows that near the active fire valve installed 94m left from the seat of fire, ventilation conditions between the barrier and the left portal improved following the activation of the fire-proof barrier. In particular, the propagation of harmful factors in the barrier action zone was hampered. On other side of fire without such a barrier the situation virtually did not change compared to scenario N1.

Thus, the effectiveness of the fire-proof barrier is obvious compared to condition $u_{c.exh} \geq 20$ m/s even for lower exhaust rates. In particular, for velocities 10 and 15 m/s, the propagation of fire flows was limited by the location of the installed fire barrier (94 m).

The results of scenario N2 were taken as baseline and used to develop scenario N3 when a 2-meter-high fireproof barrier was suspended from the road tunnel ceiling, at active (open) fire valves on both sides of fire. The obtained results are shown in Fig. 4.

As Fig. 4 shows, the barriers are located at corresponding fire valves at distance of 94 m left and 109 m right of the seat of fire. Depending on modeling results, at exhaust rates of 15 and 20 m/s

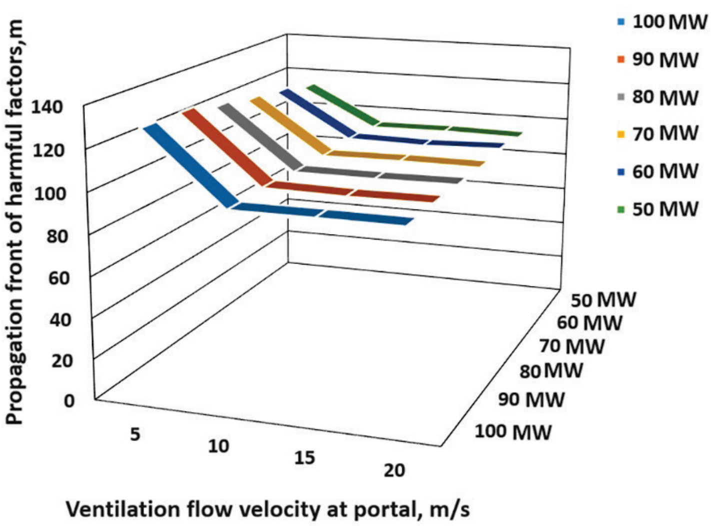

Fig. 4. Left tunnel wing with an open fire valve at 94 m from the seat of fire bordered by flexible barriers from both sides.

in fire valves, propagation of flows induced by fire was completely limited to distances specified by the fireproof barrier of 94 m and 109 m, while at critical numerical value $u_{c.exh} \geq 20$ m/s and at much lower velocities of 5 and 10 m/s, the propagation of combustion products was inhibited only partially. In particular, at velocity of 10 m/s, fire was propagated beyond the barriers in both directions of fire at distances of 113 and 120 m, in each direction respectively. At velocity of 5 m/s, the harmful factor was propagated to distances of 147 m and 151 m, respectively.

The action of fire flows considered in the presented problems is largely determined by the exhaust rate of ventilation flow in fire valves (or about by same order of air velocity at portals of both ducts), fire strength and backlayering length of combustion products. The obtained results in Figures 3 and 4 are generalized for 50-100 MW fires. The Figures above show the variance of propagation front of harmful factors depending on flow velocity at the portals of the ventilation ducts.

The Figures show that the use of flexible barriers reduces the distance of propagation of combustion products from the seat of fire by at least 10% for any fires considered. Barrier efficiency is obvious when the barrier is installed on both sides of fire in the open fire valves impact zone, near them.

Conclusions

1. Flexible transformable barriers, artificial increase of tunnel aerodynamic resistance by partial overlapping the cross section of roadway and additional intense air exhaust in ventilation valves make it possible to prevent uncontrolled propagation of combustion products (harmful factors) along the tunnel carriageway.

2. For the specified tunnel geometry, fire and standard ventilation technology, it is possible to control the process of toxic gas propagation and localize them to the impact zone of fire valves near the seat of fire by activating fire valves at 90-110 m from the seat of fire and barriers installed near them for 50-100 MW fires.

3. Threshold values of all harmful factors increase in the localization area surrounded by barriers what should be considered by tunnel operators when making decisions on the evacuation of people from the disaster zone.

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

მექანიკა

50-100 მგვტ სიმძლავრის ხანძრების FDS მოდელირების შედეგები საგზაო გვირაბების ნახევრად განივი ვენტილაციის პირობებში

ო. ლანჩავა*, გ. ნოზაძე**, დ. ცანავა*

**საქართველოს ტექნიკური უნივერსიტეტი, შრომის უსაფრთხოებისა და საგანგებო სიტუაციების მართვის დეპარტამენტი, თბილისი, საქართველო*
***გ. წულუკიძის სამთო ინსტიტუტი, საზაგირო გზების ლაბორატორია, თბილისი, საქართველო*

(წარმოდგენილია აკადემიის წევრის ე. მეძმარიაშვილის მიერ)

განხილულია ერთგვირაბიანი ორმხრივი მოძრაობის საავტომობილო გვირაბი, რომლის ცრუ ჭერში მოწყობილია ერთმანეთის პარალელური და ერთმანეთისაგან იზოლირებული ორი სავენტილაციო არხი. სტანდარტულ პირობებში გამოიყენება კომბინირებული – ნახევრად განივი ვენტილაციის სისტემა. სუფთა ჰაერის მიწოდება ხდება გვირაბის გასწვრივ განივი სქემით, ხოლო გაჭუჭყიანებულის არინება გრძივი სქემით – სატრანსპორტო გვირაბის პორტალებიდან. ხანძრის შემთხვევაში როგორც ჰაერის მიწოდება, ისე მისი არინება ხდება განივი სქემით, მითითებული სავენტილაციო არხებით. 50-100 მგვტ სიმძლავრის ხანძრის მიწისქვეშ განვითარების სცენარები შესწავლილია 400 მ სიგრძის გვირაბის მონაკვეთისათვის FDS მოდელირების საფუძველზე. სავენტილაციო ფანჯრებში ენერგიული მექანიკური გაწოვისა და მოქნილი სავენტილაციო ცეცხლგამძლე ბარიერების გამოყენების შედეგად შესაძლებელია ნამწვი აირების გავრცელების შეფერხება, რითაც მოსალოდნელია ევაკუაციის ეფექტურობის ამაღლება სიცოცხლის გადასარჩენად. ანალოგიურ პირობებში შემთხვევათა განხილვის ცალსახობისათვის შემოტანილია ფანჯრებში გაწოვის კრიტიკული სიჩქარე, რომლის კრიტიკული რიცხვითი სიდიდე პირველი მიახლოებით აკმაყოფილებს უტოლობას $u_{c.exh} \geq 20$ მ/წმ. ამგვარად, მოქნილი ტრანსფორმირებადი ბარიერების გამოყენებით შესაძლებელია შევაფერხოთ წვის პროდუქტების უკონტროლო გავრცელება გვირაბის სავალი ნაწილის გასწვრივ, რაც მხედველობაში უნდა იქნეს მიღებული უბედურების ზონაში მოქცეული ადამიანების ევაკუაციასთან დაკავშირებული გადაწყვეტილებების მიღების დროს.

REFERENCES

1. Lanchava O., Nozadze G., Jangidze M. (2022) Georgian Patent, P 7371.
2. Thomas P.H. (1958) *Fire Research Notes* 351, http://www.iafss.org/publications/frn/351/-1
3. Thomas P.H. (1968) *Fire Research Notes* 723, Fire Research Station, Watford, UK.
4. Vaitkevicius A., Carvel R., Colella F. (2016) Investigating throttling effect in tunnel fires. *Fire Technology*, **52:**1619–1628 DOI: 10.1007/s10694-015-0512-z.
5. Ingason H., In: Beard A., Carvel R. (2012) Handbook of tunnel fire safety, 273–308. ICE Publishing, London.
6. Lanchava O., Javakhishvili G. (2021) Impact of strong fires on a road tunnel ventilation system. *Bull. Georg. Natl. Acad. Sci.,* **15**(4): 38-45.
7. Lanchava O., Ilias N., Radu S.M., Nozadze G., Jangidze M. (2022) Preventing the spread of combustible products in tunnels by implementing a divisible system. *Environmental Engineering and Management Journal*, **21**/4: 627-635.

Received September, 2022