SOME ASPECTS OF DESIGN VENTILATION SYSTEM IN ROAD TUNNELS

by

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In the base, working of ventilation system can be analyzed in regular and incidental modes of operation. This paper concerns the specification of the longitudinal ventilation necessary to prevent upstream movement of combustion products in a tunnel fire. In this work the objective of the study is to analyze the road way tunnel ventilation system using CFD software to create comfort ventilation system in the tunnel. The comfort ventilation concept refers to the situation when air quality within the tunnel is reduced due to presence of polluted air in the tunnel. This paper is focused on ventilation system in a road traffic tunnel in moment of accident situation as fire. In this investigation numerical simulation of fire was carried out and determination of a critical air velocity depending on the power of the fire was conducted. The output results of the software developed for this purpose, which is also used in the realization of practical projects, are shown.

Key words: *road tunnel, ventilation, CFD modelling, fire, smoke control*

Introduction

The aim of a tunnel ventilation system is to reach the major safety levels as possible both in fire and service situations. In service situations the system has to guarantee that the atmosphere of the tunnel assembles a suitable condition of comfort and safety for the users. Assuming the dilution of the pollutants from the vehicles to the admissible limits, and allowing a suitable reaction capacity in case of a quick demand of flow [1-3].

The role of ventilation system in the traffic road tunnels is to:

- In regular traffic mode to provide the required air quality that is contaminated by exhaust gases of a vehicle.
- In an emergency mode, or in the situation of a fire, the ventilation system shall provide the required air-flow rate to prevent the smoke penetration in the evacuation zone of the passenger.

The ventilation system is responsible for the removal of exhaust gases produced by vehicles and for providing a clear view throughout the tunnels in routine operations and in the event of fire. These tunnels are also equipped with sensors for measuring the concentration of

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NO_2, NO_x, and CO. Both NO_2 and CO are highly toxic, and it is crucial that the ventilation system effectively removes these gases and ensures a safe passage through the tunnels [4, 5].

The ventilation stages can be equipped with one or more fans which can be activated together or separately [6-8].

On the other hand, in case of fire the aims would be control the smoke layer as far from the users as possible, to avoid the spreading of the incident to zones not implied in the fire and to support in rescue tasks.

In a tunnel fire incident, creating a smoke free path for motorist evacuation and facilitating fire fighters to access the fire is critical for fire and rescue operations. A means of achieving this is to use ventilation fans to blow sufficient air down the tunnel ensuring no back-layering of smoke occurs upstream of the fire. The air-flow necessary for such operation is known as the critical velocity [7]. The critical velocity is a function of a number of factors which includes the heat release rate, tunnel gradient and tunnel geometry. In a longitudinal tunnel ventilation system, the design is considered acceptable if the system design velocity is higher than the calculated critical velocity.

Designing of road traffic tunnel is very complex and interdisciplinary approach. Fire in road tunnels is a unique design problem which can lead to serious consequences if not addressed appropriately. One of mayor requirements is carefully designing and calculation of ventilation system in tunnels and is subject of this paper. The control of smoke flow during a tunnel fire is often an important part of emergency planning. The basic scientific problem is the specification of the longitudinal ventilation rate necessary to prevent upstream movement of combustion products in a fire.

Here are considered tunnels with longitudinal ventilation. The main parameter of this type of ventilation is dominantly air velocity. With a proper choice of type of ventilation with its air velocity and working equipment, and installing with the longitudinal axis of the tunnel is crucial for the safety and health of passengers. In the base, working of ventilation system can be analyzed in regular and incidental modes of operation. In the regular mode, the role of ventilation system is to obtain quality air in tunnel tube, or to provide the allowed value of harmful gases emitted by vehicles. This is primarily related to CO and NO_2.

The FIRE in-house software is primarily intended to determine the critical air-flow rate, V_C, in the tunnel tube in which the fire occurred. Analytical-empirical methods are used to determine the critical air-flow rate, which should be provided by the ventilation system, in order to prevent the penetration of smoke into the passenger evacuation zones. These methods take into account: all the geometrical characteristics of the tunnel tube in which the fire occurred, the power of the fire, the location of the fire in relation the position of the fans in the tunnel tube, the characteristics of the fluid in the tunnel tube. Analytical and empirical methods were primarily used for this purpose.

Instead of experimental testing for each situation, this software allows obtaining parameters for automatic control of ventilation system [9-11].

In some European countries, regulations stipulate minimum velocity of fresh air velocity that the ventilation system must be able to provide primarily for situations in incidental mode [12-14]. The RABT is German regulation for single-mode traffic [15] and defines that the minimum velocity of fresh air should not exceed the critical smoke control velocity. The Austrian standard RVS 09.02.319 [16] prescribes that the ventilation system for longitudinal ventilation should be able to reduce the air velocity rate in one-way traffic air between 1.5 m/s to 2 m/s, and for bi-directional traffic to a value between 1 m/s and 1.5 m/s. In the meantime, it has been accepted by professional organizations and bodies, PIARC (World Road Association) [12], as the world's leading organization in the field of road transport.

Longitudinal ventilation systems generally represent technology to protect humans from fire and smoke exposure following an accident into road tunnels of small and medium length, fig. 1. In order to avoid backlayering *i.e.* the smoke spread in the upstream direction, a minimum velocity of longitudinal ventilation system is required the so called critical ventilation velocity. It must be noticed that fire risk in road tunnel is recognized in the European Community Directive 2004/54/CE [9] dealing with the safety on the trans-European road network.

Figure 1. Road Tunnel Čemerno

Our previous research, which was considered in [17], referred to the use of analytical and empirical expressions to determine the critical ventilation velocities that should provide a ventilation system to prevent the penetration of smoke into passenger evacuation zones in the event of a fire in a tunnel pipe. Air-flow velocities along the tunnel tube produced by the ventilation system have not been considered. The velocity of air-flow along the tunnel tube is important to prevent the penetration of smoke on the one hand and not to disturb the normal flow of traffic on the other. The CFD numerical simulations using FLUENT software code [18] were used in this paper for precise definition of air-flow, which is also the subject of this paper.

The CFD numerical simulations of air-flow in tunnel tube

Modern concept of ventilation systems in traffic traveling tunnels projecting, use CFD numerical simulation for air-flow velocity in tunnel tubes [19-21]. In first phase of project it is necessary to make more combinations for ventilation system and placing in tunnel and for type of fans, to provide efficient and economic system.

Here, preliminary election of ventilation system can be done on the base of numerical-empirical methods. That includes percent of toxic material throwed out from passenger and freight vehicles, and calculation of air-flow velocity in tunnel. All valuation is on empirical bases and it is very difficult to take into a consideration complex geometric configurations. Basic demand for tunnel ventilation system is to provide required air-flow velocity which can throw out toxic materials from tunnel. In this case, it is previous CO and smoke particles (project demands).

Near providing minimal air-flow velocity, ventilation system must be chosen not to develop velocities which would cause (damaged) on normal traffic. Air-flow velocities are between 7.5 to 9.5 m/s.

Simulation realized using very sophisticated software based on finite volume method. This software is based on solutions of Navier Stokes 3-D equations for air-flow, which are included fluid viscosity. In this analysis different influences are included on air-flowing in tunnel, including rough walls of tunnel tubes.

In next sections the air-flow of ventilation system will be showed in tunnel ČEMERNO (length is 2109 m). Because of space it will be presented only more important cases of tunnel ventilation systems. Numerical simulations of air-flow are done for different dispositions of fans in tunnel and different capacity of fans.

In this analyze reversible fans are used, made by WOODS firm, with all performances given by producer. In basic, two types of fans denoted as 63 KTS and 56 JTS here are used. Their basic characteristics, given in tab. 1, are essential for producing of air-flow picture in tunnel.

Table 1. Basic properties of fans

Fan type	63 KTS	56 JTS
Outlet velocity	V_s = 34.6 m/s	V_s = 28.64 m/s
Thrust	T = 445 N	T = 247 N
Volume flow	q = 10.8 m^3/s	q = 7.0 m^3/s
Outlet of jet cross-section	F_s = 0.280 m^2	Fs = 0.246 m^2

Simulation of air-flow in tunnel for maximal regime

The 63 KTS type maximal regime includes all fans placed in the tunnel. For maximal regime is predicted build of 20 fans marked as 63 KTS. They are arranged in 10 groups of two fans along the tunnel on mutual length of 190 m. In supplement, in project documentation, on drawings, it is showed the disposition of fans along the tunnel and in light profile.

The results of air-flow, for maximal regime, are presented in this paper. On fig. 2 the cross-section finite volume mesh and the longitudinal finite volume mesh is presented. The complete results of air-flow, compared for two groups of fans, are shown in figs. 3-7. On basic of graphic illustration of flowing distribution along the tunnel, it is evident that fan in all zones provide required air-flow velocity which is enough to throw toxic materials out. It is necessary to emphasize that air-flow velocities near road, fig. 6, varies from ground to tunnel veiling in diapason 7.5-9.5 m/s, what cannot endanger traffic safety (10 m/s.). Within the numerical simulation of air-flow in a tunnel tube, several finite volume meshes were used. The finite volume meshes were refined (shredded) in several steps with a comparison of the results (flow rate). The final mesh in the tunnel tube was adopted when the obtained flow velocities for the two adjacent meshes were in the range of less than 3%. Figure 2(a), shows the final fineness of the cross-section mesh, through the cross-section of the tunnel tube, as used for CFD numerical simulations of air-flow in the tunnel tube within this paper. It is evident from the presented mesh that in the zones of *concentration* of load or precisely in the zones of the fans themselves located in the dome of the tunnel, a refined mesh was necessary to ensure faster convergence of results.

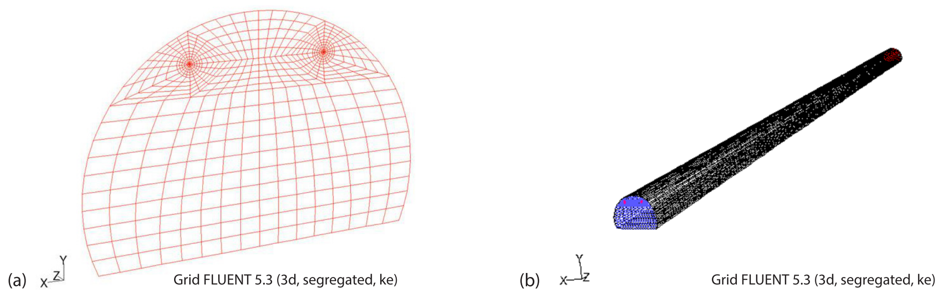

Figure 2. Numerical model of finite volumes of tunnel; (a) cross-section finite volume mesh and (b) longitudinal finite volume mesh

In figs. 3-7 air velocity is shown in different cross-sections of tunnel tube (compering Group 1 and Group 2 of fans) with reversible fans type AVT-650 where the velocity of the air jet from the fan is 39.2 m /s.

The results of numerical simulation show that the air-flow velocity is in the range from 7.5 to 9.5 m/s (near the carriageway), fig. 8.

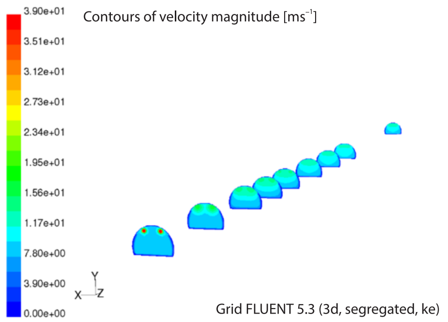

Figure 3. Distribution of air velocity in the characteristic cross-sections of tunnel tube

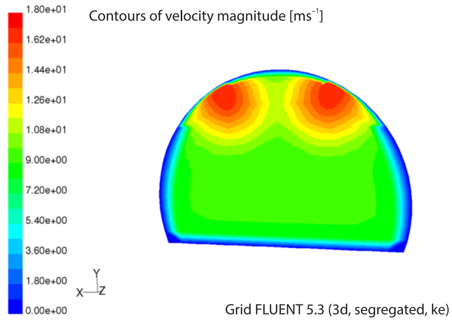

Figure 4. Distribution of air velocity at distance 30 m after first group of fans

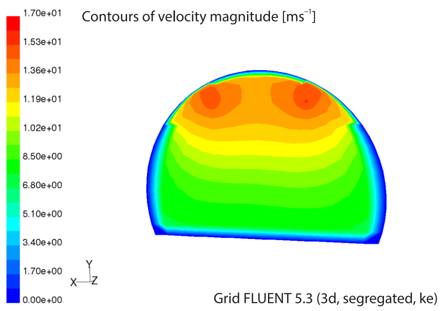

Figure 5. Distribution of air velocity at distance 60 m after first group of fans

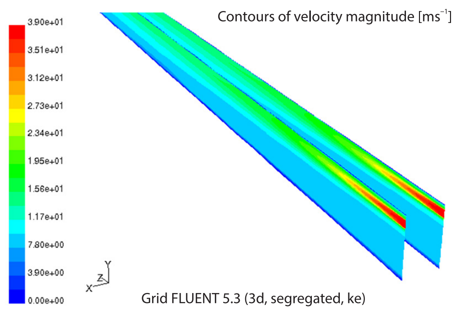

Figure 6. Distribution of air velocity in two vertical plane along axes of fans

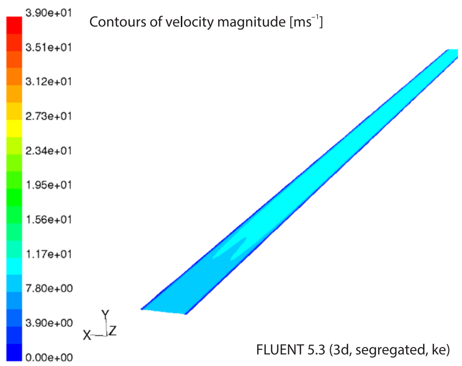

Figure 7. Distribution of air-flow velocity in horizontal plane along axes of fans, *H* = 1.8 m

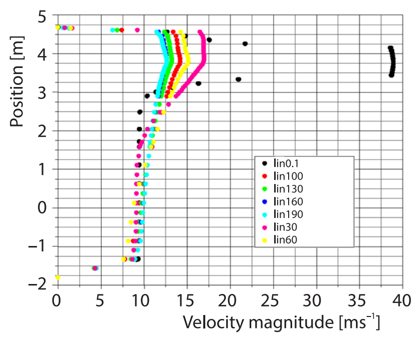

Figure 8. Distribution of air-flow velocity along heights of tunnel tube in different location along tunnel tube (here the *y*-axis is located at 2 m above the carriageway)

So, in order to meet the requirements in terms of air in tunnel in the aspect of allowed concentration of harmful substances and smoke, it is necessary to install 20 reversible jet fans type AVT-650 in the ČEMERNO tunnel, arranged in ten groups of two fans along the tunnel tube in which two-way traffic takes place.

Severity of tunnel fire is more critical in longitudinal ventilation system that its efficiency in smoke management depends on air-flow velocity by mechanical means, such as jet fans or booster fans in the absence of mechanical smoke extraction system. Emergency ventilation design guidelines typically require the air-flow velocity to be kept as low as possible in order to maintain the smoke stratification.

The PIARC report [22] provides extensive details on smoke management and PIARC report [5, 23-27] discusses different ventilation methodologies and operation strategies [28-30].

Longitudinal ventilation system induce a longitudinal flow along the axes of the tunnel and this provides an efficient smoke-management system as long as the tunnel is occupied only on one side of the fire, thus assuming that traffic downstream can proceed out of the tunnel. Smoke is blown toward the unoccupied side, so that egress can be carried out in the upwind direction. This is achieved when longitudinal ventilation is conducted at least at the critical velocity. The low velocity would result in smoke propagation upstream of the fire (*i.e.* back-layering).

In the case of fire in tunnel tube, the control of the air velocity in a tunnel is of the most importance, since it is a key factor in facilitating self-rescue condition for tunnel users. In this investigation CFD modelling has been presented as a powerful tool to predict the flow behaviour in a road tunnel under fire conditions. Hence, the longitudinal ventilation system has been defined and properly modelled, especially when buoyant driven air-flows are well-established.

The procedures, which define the operation of the ventilation system, are incorporated into our software (in-house software), according to the power and location of the fire along the tunnel tube. European norms and directives [9] must be respected in the case of fire and risk analysis.

In these norms and directives requirements are defined, including the safety requirements for fire in the traffic road tunnels. Analyzing of fire in the tunnels, first of all is important precise defining of working conditions of ventilation system, to prevent smoke penetration in the passenger evacuation zone. Table 2 shows the modes of fire (fire power) in the situation of different types of vehicles in fire.

Table 2. Models of fire in tunnels

Type of fire	Calorific energy [MW]	Maximum temperature [°C]	Amount of smoke [m^3s^{-1}]
Passenger vehicle	5	400	20
Bus/truck	20 to 30	700	60
Fuel tank	100	1000	100-120

The critical velocity, V_c, that is the minimum value capable of avoiding backlayering and thus force smoke to move only downstream, is, obviously, a key parameter in design process of ventilation system.

Computation of the critical air velocity in the tunnel tube

Ventilation must also be considered for road tunnels to provide the necessary control of smoke and heated gases resulting from a fire within the tunnel and to keep the environment suitable for emergency evacuation and rescue in the evacuation path.

An important aspect of a ventilation design is definition of the power of fire and the corresponding heat release rate. Applying the specifications from the responsible fire department [1], a worst-case fire scenario that concluded a maximum heat release rate of 50 MW was derived. For the current study, fires with maximum heat release rates of 50 MW, 40 MW, 10 MW, and 5 MW were simulated.

The value of the critical velocity ensures upstream route to be clear of smoke in the event of a tunnel fire and it is one of the most important criteria for the design process of the emergency ventilation system for road tunnels. A commonly known empirical model proposed by Danzinger and Kennedy [13] is given in eq. (1) that has been adopted in some international design guidelines, such as American Society of Heating Refrigerating and Air Conditioning Engineers Inc. [29] and National Fire Protection Association [30]:

$$V_c = K_1 K_2 \left(\frac{gQH}{\rho_0 T_f c_p A} \right)^{1/3} \tag{1}$$

with

$$K_1 = FR_c^{-1/3} \tag{2}$$

$$K_2 = 1 + 0.037(\text{grade})^{0.8} \tag{3}$$

A fire in a tunnel significantly increases the air temperature in the tunnel roadway. Average temperature of fire site gases is defined:

$$T_f = \frac{Q}{\rho_0 c_p A V_c} + T_0 \tag{4}$$

where Q is the heat that fire adds directly to air at the fire site, H – the height of duct or tunnel at the fire site, T_0 – the temperature of fresh air, c_p – the specific heat of the air, A – the surface of the cross-section of the tunnel tube, grade – gradient of the tunnel in percent, and $\mathrm{Fr_c}$ [%] – the critical Frude number and inclination which is the gradient of the path in tunnel. Equations (1) and (4) represent a coupled system because both of them represent V_c and some of the iterative methods should be used. For calculation of critical flow velocity the software package *FIRE* was used. This software package is intended for fire simulations for different types of tunnels (with two tunnel tubes, one tube, one-way (one direction) and two-way (two directions) traffic as well as for different ventilation systems).

Apparently, fire power, height and cross-sectional area of tunnel are the typical factors contributing to the V_c. The critical air velocity had aimed to prevent smoke penetration into the passenger evacuation zone and is one of the most important parameters that should be provided by the ventilation system in the situation of fire. Ventilation must also be considered for road tunnels to provide the necessary control of smoke and heated gases resulting from a fire within the tunnel and to keep the environment suitable for emergency evacuation and rescue in the evacuation path.

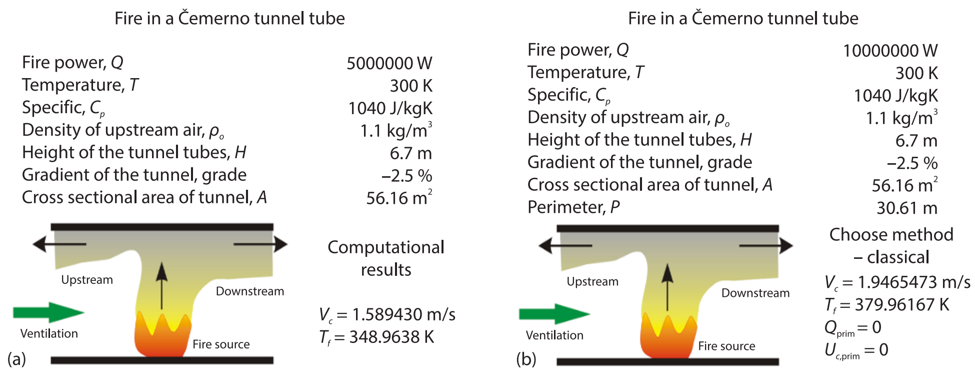

Figure 9. Results of fire simulation obtained by software package for; (a) fire power of 5 MW and (b) fire power 10 MW

Figure 9 shows the results of the calculation for the critical velocity of fresh air-flow which should be provided by the ventilation system in case of a fire from a burned passenger vehicle, fig. 9(a), as well as in the case of fire from a burned two passenger vehicles, fig. 9(b). Figure 10 shows results of critical velocity for fire of a burned truck/bus, fig. 10(a), and fire of a conflagration with power of 50 MW, fig. 10(b). The impact (dependence) of fire power, Q, on the required critical velocity value V_c is evident.

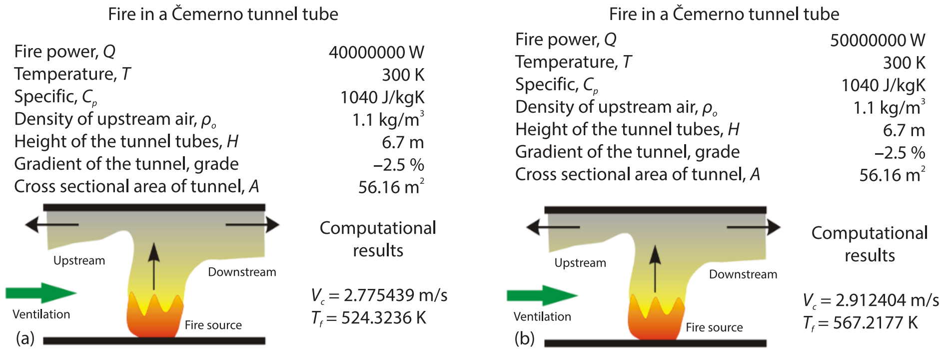

Figure 10. Results of fire simulation obtained by software package for; (a) fire power of 40 MW and (b) fire power 50 MW

The effects of fire power, Q, on critical velocity, V_{ci} are given in tab. 3

Table 3. The effects of Q to V_c

Q [MW]	5	10	20	25	30	40	50
V_c [m/s]	1.59	1.95	2.35	2.48	2.59	2.78	2.91

Figure 11 shows the relationship between the V_c and Q in the tunnel tube. This dependence can also be expressed in analytical form:

$$V_c = 1.53 \cdot 10^{-05}Q^3 - 1.83 \cdot 10^{-03}Q^2 + 8.75 \cdot 10^{-02}Q + 1.21$$

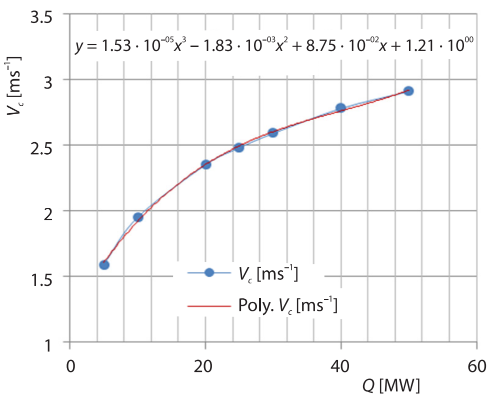

Figure 11. Definition of analytic formulae for the critical velocity

Computation procedure for the previously defined analytical expression (5) for the critical velocity as a function of the fire power in the tunnel tube is suitable in the preliminary design of the ventilation system.

As shown in fig. 11 the critical velocity increases rapidly with the fire size up to about 50 MW and then only increases slightly with increased heat release rate [21].

Conclusions

In this work ventilation system in road tunnel is analyzed in regular (service) and incidental modes of operation. To determine precise air velocity of fans in tunnel tube in regular mode operation CFD numerical simulations are used. The CFD numerical simulations were conducted to research the characteristics of the air-flow in a road tunnel. In this work, computation models were carried out to investigate the air velocity distribution inside tunnel tube with different arrangement modes jet fans. Longitudinal ventilation by means of jet fans is a solution that is commonly adopted in tunnels, namely for its simplicity of installation combined with reduced capital and maintenance costs. In incident mode determination critical value of the fresh air-flow velocities which should provide ventilation system in fire situation in traffic road tunnel tube for different power of fire are considered.

The velocity of air-flow velocity along the tunnel tube is important to prevent the penetration of smoke on the one hand and not to disturb the normal flow of traffic on the other. The CFD numerical simulations were used in this paper for precise definition of air-flow, which is also the subject of this paper.

In this work *in-house* software package *FIRE* was used. Main goal of this software package is to determine critical velocity depending on the power of fire, including all geometric properties of tunnel tube and the characteristics of the fluid in the fire zone in the tunnel tube.

In summary, in addition CFD numerical simulations for precize air-flow velocity distributions in tunnel tube, it is necessary to use other internal semi-empirical software to provide reliable and accurate predictions for such analyzes, thus making the conducted studies more credible.

Acknowledgment

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Nomenclature

A – surface of the cross-section of the tunnel tube, [m^2]
c_p – specific heat of the air
i^{th} – gradient of the path inside the tunnel
$\mathrm{Fr_c}$ – critical Frude number and inclination which is the gradient of the path in tunnel, [%]
F_s – outlet of jet cross-section, [m^2]
H – height of the tunnel tube, [m]
q – volume flow, [m^{3}s^{-1}]
Q – thermal fire power, [MW]
T – thrust [N]
T_0 – temperature of incoming air in the tunnel tube, [K]
V_c – critical flow velocity, [ms^{-1}]
V_s – outlet velocity, [ms^{-1}]

Acronyms

grade – gradient of the tunnel in percent
PIARC – Permanent International Association of Road Congress (now World Road Association), Paris, France
RABT – RABT-Richtlinien fur die Ausstattung und den Betrieb fon Strassentunneln. German regulation for single-mode traffic

Greek symbols

ρ_0 – density of the air inside the tunnel, outside the fire zone, [kgm^{-3}]

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