Critical velocity analysis for safety management in case of tunnel fire

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Abstract. Heat, smoke and other toxic products may spread along the tunnel, in both directions from the seat of fire, causing different kinds of damage to people. Anyway, underground fire causes complicated results, which is preventing factor for life rescue and evacuation, creating difficulties for firemen and life rescue crew. Analysis of the critical speed, which is necessary for the effective management of combustion products, has been made for tunnel fires with high heat release rate. The characteristic changes in the critical Froude number in the work are presented in accordance with the critical speed. Particularly, it was noted that the formula determining the critical speed requires knowledge of the average smoke temperature, while the formula for calculating the last value includes the value of the required critical speed. In order to overcome this, Froude's critical number Fr_c=4.5 has been introduced, which is not the way of solution, as it directly means constant critical velocity for the fire of any power and accordingly, does not correspond to experimental data.

1 Introduction

Heat, smoke, and toxic products that can cause damage to people of varying severity can be spread from both sides of the fire along the tunnel. In any case, underground fires have severe consequences, hampering both evacuation and saving lives, significantly obstructing the work of rescue teams and firefighters.

The great attention of the society has been attracted with tunnel fires happened at the end of the 20th and at the beginning of the 21st centuries. The powerful fire in the underground of Baku in 1995 is a case for that during which more than 200 people died. In 2003, arson in Daegu, South Korea, as a result of which about 200 people died. The incident of the Austrian city Capron happened in 2000, when 151 people died from fire, in the funicular train. The same fire sacrificed the driver of the opposite train and 3 passengers standing on the upper portal and waiting for the transport [1].

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Due to this reason, there have been founded groups of international experts at the European Commission UN managed by ministers of transport of EU member countries according to the set schedule. This group regularly issued documents which have been quoted herein to certain extent [2-4]. Special purposeful financial support has been provided for further implementation of commonly known researches, part of which is also referred [5, 6].

2 Collapse of ventilation systems

Tunnel fire is characterized with minimum two important differences from open fire: 1. the heat allocated from flammable vehicle is more acutely felt underground as the space is shut and dissipation of flammable products takes place less; 2. backlayering of the stream may rise, which changes the scheme of ventilation and sometimes causes its collapse [7-9]. In the paper [10] proposed and investigated transformable flexible systems that can be used at the stages of evacuation and fire suppression in case of strong fires.

Under fire conditions, after a certain period of time, the influence of the operation of the fans on the ventilation flow decreases, despite the direction in which the temperature effect will be develop - to the side of increase the dynamic pressure; to the side of decrease the air density or both sides. Consequently, the collapse is the process of the emergence and distributing of dynamic pressure due by fire that is commensurable with fan's dynamic pressure [11–14]. We are noted that the dynamic pressure originated by the fire is algebraically summed up with the pressure developed by the ventilator.

Enrico Fermi in his work [15] marks the high accuracy of Clapeyron equation with low pressure and high temperatures. It should be noted that according to the Clapeyron equation in case of tunnel fires, it is possible to obtain compelling and pretty accurate results for static pressure near atmospheric. Fig. 1 shows the results of the development of the fire in the underground space, provided that the power released during a fire is used only to increase the dynamic pressure caused by the presence of the fire.

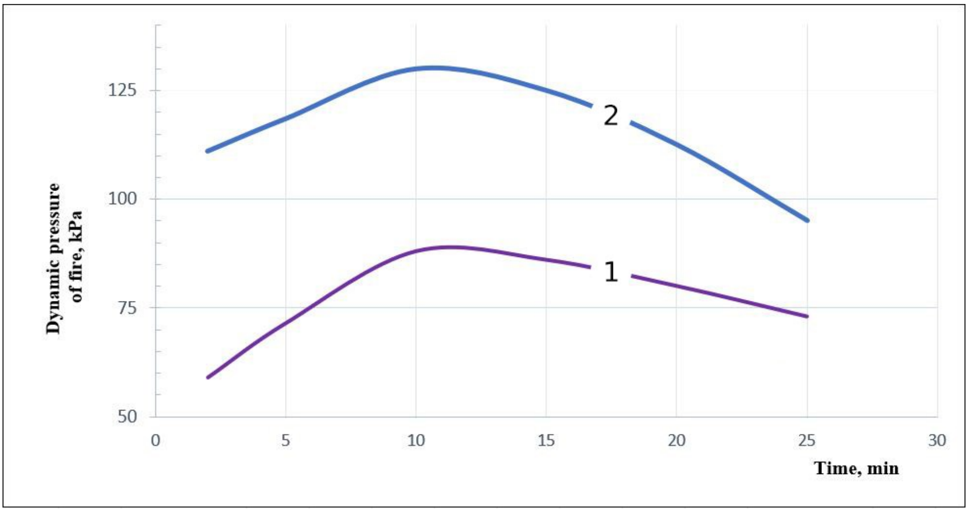

Fig. 1. Changeability of dynamic pressure originated by fire pursuant to heat release rate (HRR) by average temperature of smoke 1000 K: 1 - HRR 30 MW; 2 - HRR 100 MW

From the presented figure, it is obvious that the dynamic fire traction far exceeds the static pressure of the fans produced for ventilating the transport tunnels.

To the collapse is very close the result, received from FDS modeling, presented in the work [16], which mentions that the fire tends to resist distribution of ventilation stream and the more powerful the fire is, the higher the resistance. This has been evidently shown that more and more jet ventilators are required for the waste disposal of flammable products from tunnel depending on the increase of fire. The paper [17] mentions that aerodynamic resistance in tunnels, on the seats of fire, increases at least 6 times. The concept of collapse is also very close to the newly published work [18], which mentions that smoke movement is asymmetric due to buoyancy along the longitudinal tunnel axis. Calculation coefficient of the critical velocity has also been marked, which is much higher compared to prove values, which indicates to stimulation of dynamic pressure as a result of fire. In unpublished handwriting [19], the author also refers to thrust caused by fire, while the work [20] presents results about the liquid fuel fires that cause the strong natural draught under the conditions of vertical mines.

3 Positive and negative directions of ventilation stream

Due to algebraic sum of depression caused by the fire and of ventilation system, it is possible to determine positive and negative directions of ventilation stream in inclined tunnels.

The direction of fire traction thrust can be considered as negative. Consequently, the positive direction of ventilation shall be opposite, i. e. if fresh air entrance is hypsometrically high rather than the seat of the fire. Therefore, the positive direction of fresh air movement is downward, while negative direction is upward. The natural direction of combustion products movement is always upward (see fig. 2).

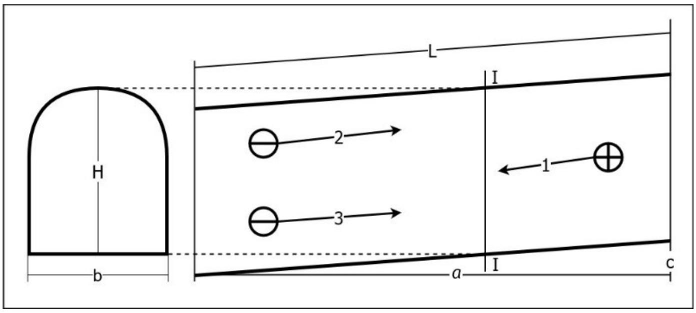

Fig. 2. Directions of fresh air and combustion products movement in inclined tunnels: 1 - positive direction fresh air's movement; 2 - negative direction fresh air's movement; 3 - natural direction of the combustion products movement (negative, upward); L is tunnel length, m; b - tunnel width, m; H - height of the tunnel, m; a - horizontal projection of the tunnel length, m; c - vertical projection of the tunnel slope, m

In addition, we proposed the flexible ventilation system, as well as flexible deploying-folding systems of refractory basalt fabric that support the formation of bifurcation flows and can be used during evacuation and fire extinguishing stages even in conditions of a cheap longitudinal ventilation system. The application of the proposed systems is expedient on the basis of the experimentally established fact that the boundary between bifurcated streams in longitudinal ventilated tunnels easily disappears, especially in the case of backlayering. Buoyancy capacity of one gas towards the other is shown with dimensionless parameter, numeral of Richardson (Ri), which shows the exchange of masses in between the streams and differs from the aforementioned Froude's number (Fr), that indicates to the general form of the layer in ventilation stream. The results obtained through the numerical analysis for tunnel fires controlled by ventilation have been presented in the works [21–23]. The results of simultaneous heat and moisture transfer in the tunnels were investigated previously [24, 25].

4 Critical velocity analyses

In case of downward movement of fresh air opposite movement of smoke and other combustion products – backlayering is especially evident. The critical velocity of backlayering and the backlayering length are important technological parameters, which determine and condition methods of evacuation and fire fight.

Critical velocity can be explained as the minimum velocity of longitudinal ventilation, which excludes formation of smoke backlayering. The correlation of critical velocity with temperature in horizontal tunnels has been profoundly studied, while in inclined tunnels less attention has been paid to it due to complicity. The smoke within the backlayering length is spread opposite the ventilation stream. This is especially intense for ventilation stream with positive mark. Backlayering length is significant indexes of fire extinguish stage. While, using the critical velocity is more characteristic for evacuation. Considering the volume of the article, critical velocity is the only aspect to pay attention to.

In inclined tunnels, calculation of critical velocity numerical value can be done according to that for horizontal tunnels according to the following equation [26]

$$u_c = K_g u_{c(0)} \tag{1}$$

Where K_g is gradient factor, which is used for fires in inclined tunnel.

The critical velocity in horizontal tunnels can be figured with the following formula

$$u_c = k\left(\frac{g\dot{Q}_c H}{\rho_0 c_p T A}\right)^{1/3} \tag{2}$$

Among which, k is the constant of proportionality; g - free falling acceleration, m/s^2; $\dot{Q}_c$ - convectional heat excreted from fire, kW; H - height of tunnel, m; ρ_0 - density of external air, kg/m^3; c_p - specific thermal capacity of air, kJ/(kg.K); T - average temperature of smoke, K; A - cross-sectional area of the tunnel, m^2.

Proportionality ratio is determined with the following formula

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

Whereas Fr_c is the Froude critical number, which shall be fixing with this formula

$$Fr_c = \frac{\Delta p g H}{\rho_0 u_c^2} \tag{4}$$

Where Δp is the difference between densities of external air and smoke, kg/m^3.

Average temperature of smoke shall be figured with the following formula

$$T = T_0 + \frac{\dot{Q}_c}{\rho_0 c_p A u_c} \tag{5}$$

Where apart from the explained symbols T_0 is the external air temperature, K.

In order to determine critical velocity according to formula (2), the average temperature of smoke T and ratio of proportionality k should be known, while their calculation formulas (3)-(5) include search value which is - u_c. In order to overcome this, there has been critical number by Froude, introduced which equals to 4.5, which is not a solution to the problem that shall be found out below.

Critical velocity of backlayering has been first connects with Froude's criterion by Thomas [27], while the paperwork [28] studies the fire caused with wooden pallets of 0.3X0.3X10 m size in an aerodynamic tube; it also mentioned that the aerodynamic resistance to the seat of the fire increased 6 times for ventilation stream, while on both sides beyond the fire it increased only 1.5 times.

In literature [29, 30], without any analysis, like Reynolds's number they expected Froude's number to have critical numerical volume as well, therefore critical numerical value 4.5 has been introduced as if according to the quoted work [28].

This assumption simplifies the problem, since in this case the coefficient is k= 0.606 according to formula (3), but it is not the correct result. According to a similar assumption, we can also get the same value of the critical speed for fires of any type and power, and therefore the problem will not exist. And in fact, the critical speed will change in nature.

The fig. 3 proves that the numeral value of critical velocity varies in terms of 2.5-3.2 m/s, provided that $Fr_c = 4.5$. Actually, changeability diapason of critical velocity is wider and therefore, the Froude's number does not equal to 4.5.

Regarding the assessment of the critical value of the Froude number and the corresponding concept associated with it, in the literature [20] it is noted that the critical Froude number 4.5 well characterizes large fires, but does not correspond to relatively small fires. However, as follows from the above, even in cases with strong fires, there are notes concerning the formulas presented, and there are errors shown in Fig. 3.

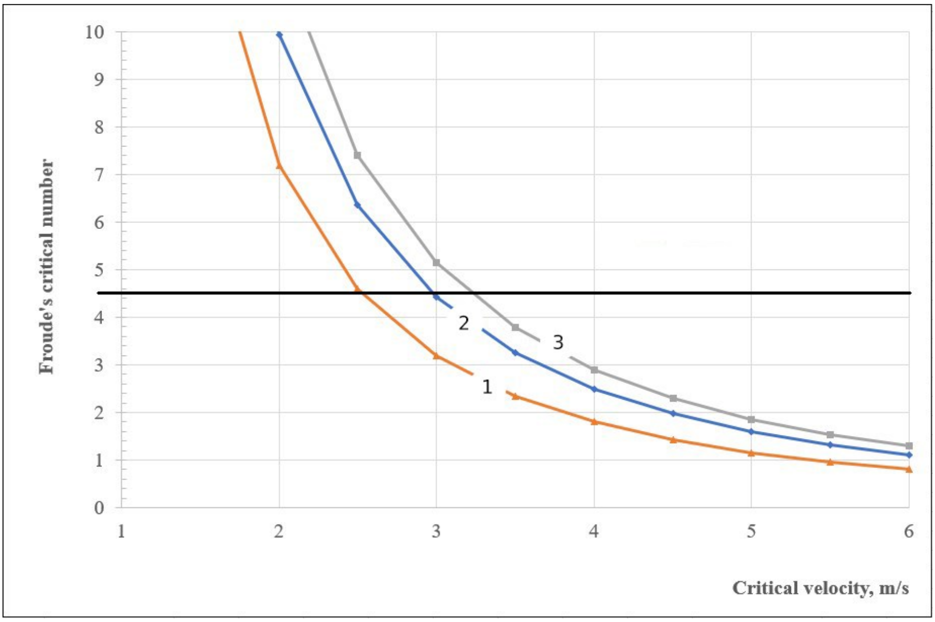

Fig. 3. Changeability of Froude's critical number according to critical velocity, where the height of tunnel is 6 m., external air temperature – 293 *K*, pursuant to average temperature of smoke, *K*: 1–573; 2 –903; 3 –1373

It should be noted that the graphs of Fig. 3 correspond to powerful fires controlled by ventilation, the change in the heat release rate of which, depending on the speed of the ventilation flow, is given in Fig. 4.

Unlike fires in open spaces, oxygen in a tunnel is not always enough, and therefore there are two types of fires in tunnels: a) fuel-controlled fires (FCF) and b) ventilation-controlled fires (VCF). In the case of FCF, the amount of air is large, the heat release rate of the fire and the amount of noxious combustion products released (heat, smoke, toxic compounds) depends on the amount of fuel. With such fires, the concentration of combustion products in the air is low due to the large amount of air. In the case of VCF, the fire power is determined by the amount of air, since the amount of fuel in this case is also large. In this case, the concentration of combustion products is high, and therefore, there may be a risk of explosion of volatile substances at high concentrations. In any case, depending on the heat release rate of the fire, will take place the regularity that shown on the fig. 4.

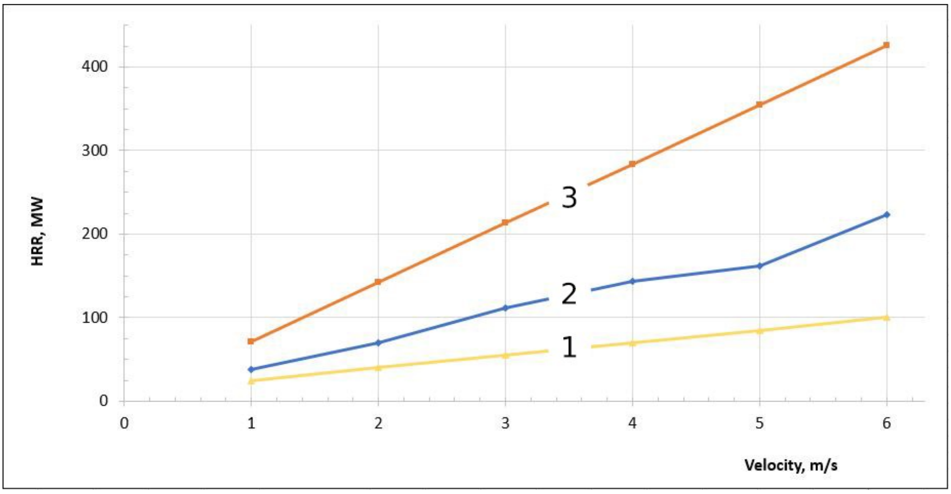

Fig. 4. Changeability of heat release rate according to ventilation stream velocity, where the height of tunnel is 6 m; cross-section area 50 m^2; external air temperature - 293 *K*; pursuant to average temperature of smoke *K*: 1 - 573; 2 - 903; 3 – 1373

Unfortunately, without overcoming the inaccuracy of the concept of the critical Froude number, in order to justify its use, dimensionless concepts of critical velocity, backlayering length, heat release rate, convective heat are introduced into scientific literature and the magnitudes of their change. This circumstance allows the use of piecewise constant functions and obtains more or less approximate results within the specified limits, but, as noted above, this is not a reliable solution to the problem.

5 Conclusions

According to the results presented here we can conclude that critical index of Froude’s number 4.5 does not fit current fires with high heat release rate in reality and express supposition that even the concept of critical index of Froude’s criterion may be deprived of physical contents for large fires, happening in reality.

Fires in the underground space increase the air flow of the negative direction and weaken the positively directed air stream. For the ventilation flows of both directions, the ventilation system collapse is expected, during which the ventilation direction and intensity determines dynamic pressure developed by the fire.

One of the ways to avoid the collapse of the ventilation system is to divide the tunnel into small length sections.

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