PROSPECTS OF USAGE OF TRANSFORMING SYSTEMS FOR EXTINGUISHING FIRE IN TUNNELS

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Description Summary. There are two issues in relation to fires in the tunnels used for movement of transport – evacuation of people and extinguishing the fire. In relation to evacuation during the fire of medium or minor strength, it is more realistic to evacuate by means of transport rather to waiting to recirculation of the air, since the maximum speed of the flow of air in tunnel is 6 meters second (21.6 km/h), which is much lower compared to the average speed of the transport. In case of strong fire, the pressure created by such fire dominates. The dynamic pressure generated by the fire of 1000 equals to 400-450 kPa, while the capacity of the strongest ventilator equals to 15 kPa. Therefore, it is impossible to regulate the air currents by using the ventilation systems. So, 173 cars were burnt during the fire of Tokio-Nagoia highway tunnel and where temperature equaled 1000 degree of Celsius. More than 100 cars have been burnt during the fire in the tunnel of Holland (USA). Fires in the tunnels of Mont Blanc, (France-Italy), Tavern (Great Britain) 1999, St. Gotthard (Switzerland) 2001, Freja's (France-Italy) 2006 took human life. In all abovementioned cases the entrances in to the tunnels were blocked for the fire brigades and extinguishing was done by using non-standard methods. On this background the best way for extinguishing fire is use so called transforming methods of extinguishing the fire, which are used in cosmos or in those places where access for humans is difficult or not possible. The substance of this method is to throw special system towards the source of the fire, which covers the fire and isolates it from the both sides of the tunnel. The system itself is a metal construction which can be unfolded and which is covered by fire proof basalt tissue.

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PROSPECTS OF USAGE OF TRANSFORMING SYSTEMS FOR EXTINGUISHING FIRE IN TUNNELS

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ABSTRACT

There are two issues in relation to fires in the tunnels used for movement of transport – evacuation of people and extinguishing the fire. As a rule extinguishing the fire should start after evacuation of people is completed, which could be achieve by isolating the part of the tunnel where fire had started from the rest of the tunnel.

In relation to evacuation during the fire of medium or minor strength, it is more realistic to evacuate by means of transport rather to waiting to recirculation of the air, since the maximum speed of the flow of air in tunnel is 6 meters second (21.6km/h), which is much lower compared to the average speed of the transport. Inertness of the air currents makes less efficient to change the flow of currents in an operative way. Moreover, the ventilators do not have a reserve to maximize the speed of flow of air.

In case of strong fire the pressure created by such fire dominates and ventilators collapse. The dynamic pressure generated by the fire of 1000^0C equals to 400-450kPa, while the capacity of the strongest ventilator equals to 15kPa.

Therefore, it is impossible to regulate the air currents by using the ventilation systems and considering this method for solving the problem would be too simplistic. This argument could be strengthened by existing statistics. Fires in the tunnels of Mont Blanc (France-Italy), Tauern (Austria), 1999, St. Gotthard (Switzerland), 2001, Fréjus (France-Italy), 2006, took human lives. In all above mentioned cases the entrances to the tunnels were blocked for fire brigades and extinguishing was done by using non-standard methods.

On this background the best way for extinguishing fire is use so called transforming methods of extinguishing the fire, which are used in cosmos or in those places where access for humans is difficult or not possible. The substance of this method is to throw special system towards the source of the fire, which covers the fire and isolates it from the both sides of the tunnel. The system itself is a metal construction which can be unfolded and which is covered by fire proof basalt tissue.

The purpose of the transforming system is to isolate the tunnel in small parts in a short period of time in case of need. It is not an alternative to the metal doors installed in portals or local districts. Quite the opposite two systems are complementary to each other. The major pressure produced by the fire is consumed by the metal doors. This is why the suggested construction is light in weight. Usage of transforming systems includes unhindered functioning of alarm systems, when the operator is well informed about the sources and scale of the fire.

1. INTRODUCTION

European Community (EC) creates Trans-European Network (TEN) as the key element of common market development and solution of strategic social-economical problems. Tunnels perform an important role in infrastructure of above-ground transport and their general length in EC countries is over 1000 km. European Commission emphasized the necessity of adoption of the All-European directive documents to guarantee the appropriate level of safety at tunnel exploitation, particularly of those located in transport corridor network of TEN [1, 2, 3]. Committee on road tunnels of World association of auto roads issued a number of recommendations including the report on the control on inflammability and smoke content.

European Commission included the problem on safety in tunnels within the frames of 5th scientific-research program. In particular, research projects on updating of operating tunnels in fire-fighting respect and also topical training programs for action in tunnels in case of fire were financed.
The measures stipulated in Directive 2004/54 of European Parliament and European Council on safety in road tunnels will, most likely, promote the decrease of incident occurrence risks. The general cost of works for implementation of directives requirements is within 2.6-6.3 billion euro. The less quantity corresponds to the situation when safety level in the existing tunnels may be increased with less expense for replacement of the systems of ventilation with more updated ones. Without delving in the sense of "contemporary ventilation system" we shall note that safety and ventilation systems are closely interconnected. And fire safety is one of the classifying signs by which the tunnel ventilation systems are divided.
The given work presents the results of research which testify the necessity of new conception of ventilation systems and in particular, of their fire safety.
Theoretical part of the given work corresponds to the report of European Commission on ventilation [1, 52p] where it is noted that "the defining factor for construction of ventilation systems are their functional possibilities in case of fire" and to the conclusion of the report which is stated on p. 72 "Permanent researches are necessary to be performed with objective to refine ventilation systems and improve their operation". Technical decision presented in the given work corresponds to Measure 3.06 set forth on p. 61 of the same report.
Besides, it can be mentioned that nullification of blower efficiency which is noted in the given report, was the cause of peoples, death in the accident in St. Gotthard tunnel in October24, 2001. In any event the contradictory facts given in the report of Mr. Michel Egger, the chairmen of a special multi profile group of experts on safety in tunnels cannot be explained otherwise, in particular in point 9 of report [2] he notes that "Within 1-2 km from fire centre 11 dead persons were found. Neither of them has any signs of physical trauma. All of them died of poisoning with poisonous smoke", while point 8 of the same report says that ventilation system in tunnel functioned well and effectively.

2. THEORETICAL STUDY

Considering the problem of reliability of fire safety even of transverse, i.e., the best of ventilation systems we can preliminarily note that for evacuation of people not all combined systems of airing are good but just longitudinal-transverse one and that only in the case if there is the possibility of people's transfer to the channel with fresh airflow. For longitudinal-transverse system in the common operation regime in ventilation channel there is contaminated air. Therefore, even at technical possibility of people's transfer in this channel, this measure is all the same void of sense, as it is necessary to wait "filling" of channel with fresh air. Considering relative speeds of transport facilities and air flow, also time lag of reverse due to moving air resistance, it is better to leave fire environment on transport than wait the results of reversal.
The fact is that in case of conflagration air recirculation is impossible.
It is quite evident that single tunnel combines systems have no advantage before longitudinal ones neither in the task of people's evacuation nor in the task of fire extinguishing. Therefore, they are used in the common regime of airing and have great expenses (minimum by one degree More) just because they expect positive operation of the system during fire.
Consider specific longitudinal-transverse ventilation system: fresh air is supplied through the entrances of left and right wings (Fig.1) and contaminated air is sucked away with entrance ventilators through openings in false ceiling over transport zone. There are 40 openings on the left and 40 openings on the right wings with regulated section area and consequently, with regulated aerodynamic resistance.

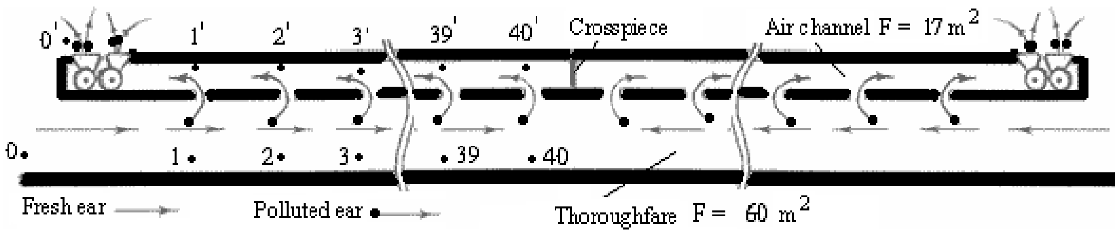

Fig.1. Longitudinal-transverse ventilation in normal operation regime

The first opening, in any case, has the greatest resistance so that total depressions of all sections, in accordance with the basic law of parallel branches are equal. i.e.

$$H_{0-1-01'-0'} = H_{0-2-2'-0'} = H_{0-3-3'-0'} = \cdots = H_{0-40-40'-0'}. \qquad (1)$$

In the central part of ventilation channel there is an arch due to which the whole system is divided into two symmetrical wings. Through each opening the ventilators suck away 1.25% of general air consumption.

Now consider the principle of system operation in conditions of fire; this result was convincing even for us until receiving the results of the given work.

Assume fire centre is in the left wing between openings 2 and 3. In such case, the first and all successive openings (4, 5, etc.) in the left wing are automatically closed, the second and third openings are opened for maximum section and the right wing continues operation in the common regime. As a result, on the section 3-40 of the left wing air motion is discontinued and respectively, the combustion products will not propagate. In the left wing air will pass only by routes 0-2-2'-0' and 0–3–3'–0' ejecting combustion products into air. In the second and third openings there will be active suction of air promoted by other closed openings and high temperature of air. Here it is supposed, that notification system has already been actuated, transport do not enter tunnels and all transport vehicles from tunnel move to entrances in one way. During 2-3 min transport evacuation is finished and the system automatically transfers to the regime of fire extinguishing (Fig.2).

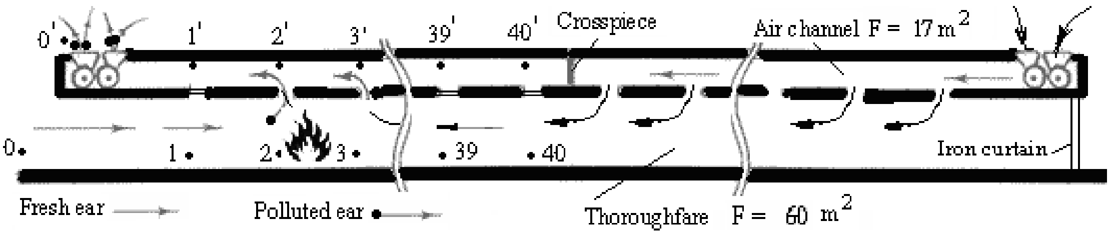

Fig.2. Longitudinal-transverse system of ventilation in the regime of fire extinguishing

Therewith the right entrance is automatically shut with iron door and ventilators of the right wing immediately are reversed. Air suction in this case will be done only in openings 2 and 3 and fire fighting service will start to act approaching the fire centre from both sides.

Note that the above mentioned will take place only if ventilator head suppresses fire draft.

Suppose fire draft intensity exceeds by much the ventilator head. In such case fire will suck in air not only from the left opening but through ventilator plants, as well consequently ventilators will be working on suck-in and air flow will have opposite direction and this will continue until ventilators fail. Thus, if we want save ventilators they should be safely isolated from ventilation system. In any case, ventilators of the left wing will not any more initiate the directed air transfer.

It is easy to guess that air stream with burning products is directed to the right opening. In this case the roadway and crown part of the tunnel are parallel workings and air consumption will correspond the law expressed by formula

$$\frac{R_1}{R_2} = \frac{Q_2^2}{Q_1^2}, \qquad (2)$$

Where R_1 is total aerodynamic resistance of ventilation channel, ventilation openings and ventilators, N.m^8/s^2; R_2 - aerodynamic resistance of the main tunnel N.m^8/s^2; Q_1, Q_2 - air volume consumption in ventilation channel and tunnel, m^3/s.

From this formula follows that depressions of tunnel and system "ventilation channel-openings-ventilators" are the same and equal to depression of fire draft (depressions of ventilator and fire are algebraically summed up), i.e.

$$R_1 Q_1^2 = R_2 Q_2^2. \qquad (3)$$

Consequently, air stream direction will be opposite to that shown in Fig.2 for right wing as well and through ventilation channel less air will be passing than in the main tunnel. But even this consumption will be sufficient that ventilators of the right wing be put out of action. Thus, these ventilators may be saved only if they are isolated and excluded from ventilation system.

Proceeding from the above said, a preliminary conclusion can be made that if fire centre excites more dynamic pressure than static head of ventilators one-tunnel combined system of ventilation automatically transfers into more natural longitudinal system and the advisability of using combined system may be doubtful.

Now show tentative amount of fire draft. In case of reliable determination of air pressure in fire centre, depression may be calculated with the help of Bernoulli equation between two sections (1 and 2) of the tunnel for which air stream speed (U_1, U_2), height over sea level (z_1, z_2) and air density (ρ_1, ρ_2) are constants, i.e.

$$h = P_1 - P_2 = \int_1^2 dh, \tag{4}$$

Where h is depression caused by fire, kPa; P_1, P_2 are air pressure in sections 1 and 2, respectively. Section 1 coincides with entrance and section 2 with fire centre. In such case P_1 is atmospheric pressure and P_2 is pressure caused with fire.

3. IN-SITU MEASUREMENTS

Use statistic data about fires in transport tunnels. In 1979 fire happened in roadway tunnel Nihodzaka (between cities Tokyo and Nagoya, length of tunnel about 2 km) in 400 m from the entrance when temperature was 1000 ^0C on tunnel section of 1122m length. Also, temperature achieved 1000 ^0C in fire in Montreal metro (Canada). In 1984 during fire in Summit tunnel (Great Britain) oil tank of 100t volume has been caught in fire and temperature in the centre achieved 1500 ^0C [4]. Fires in the tunnels of Mont Blanc (France-Italy), Tauern (Austria), 1999, St. Gotthard (Switzerland), 2001, Fréjus (France-Italy), 2006, took human lives. In all above mentioned cases the entrances to the tunnels were blocked for fire brigades and extinguishing was done by using non-standard methods.

4. THEORETICAL DEMONSTRACION

The burning products obey the general principles of thermodynamics and according to Clapeiron equation for ideal gases pressure may be determined in fire centre at definite temperature.

$$Pv = RT, \tag{5}$$

Where P is air pressure, kPa; v - specific volume of air ($v\rho = 1$, v =1/ ρ), m^3/kg; ρ - density, kg/m^3; R - specific constant of air, R =287 J/(kg.K); T - absolute temperature, K.

Calculation, design and test of ventilators is done for standard air density ρ = 1.2 kg/m^3 which is received by Clapeiron equation for atmospheric air pressure on sea level $P = 1{,}02 \times 10^5$ Pa at temperature 20 ^0C. Thus, the approved technology of ventilators construction receives air as an ideal gas. Basing on this we can make approximate calculation of air pressure in fire centre. But there are data which prove that using equation (5) we can get sufficiently enough true results. First of all, we must note the work of Enrico Fermi [5], creator of quantum statistics (Fermi-Dirac statistics), who does not touch upon the problem of statistical physics, moreover, quantum statistics at consideration of Klapeiron equation concluding in paragraph 16 of the mentioned work that "equation of ideal gas state expresses well enough the behavior of real gases at high temperatures and low pressures".

Besides, in gun chamber the Klapeiron equation at pressures $P = (2100 - 4600) \times 10^5$ Pa gives inaccuracy within 8-12.5% [6]. Thus, for tunnels in open entrances of which we have atmospheric, i.e., low pressure, we can freely use this equation.

Suppose that in fire centre air density changed but negligibly as there get heavy products of combustion and comparatively light water steam which compensate one another. The considerable increase of air density may be the result of considerable growth of static pressure which does not happen in tunnels, as the allowance of this means the formation of strong vacuum in other place and self-extinguishing of fire which is not happening in nature. Consequently, all of pressure increment happens because of dynamic component. Hence it follows that the value of specific air volume v does not go beyond the limits of measurement or determination error.

Proceeding from the above said temperature 1000 ^0C, according to formula (5), may cause dynamic pressure around 447.6kPa which is about 30 times higher than static head of the most powerful mine ventilators. Consequently, air movement direction and its consumption in case of conflagration is not any more determined with ventilators and thus, our preliminary conclusion has been proved.

Evidently, fire power depends on fuel mass which somehow is connected with total mass of burn product and ventilation air m. Multiplying by this value the formula (5) gets the following form

$$PV = mRT\ , \tag{6}$$

Where $V = mv$ is air volume which participates in the process of burning, m^3. The mentioned volume may be expressed by formula

$$dV = SdU\ , \tag{7}$$

Where S is the area of transverse section of tunnel, m^3 $S = const$; dU - increment velocity which depends on fire power, m/s.

We suppose that in tunnels with length up to 2 km for avoiding incidents the evacuation of people and transport should be ended in 2 minutes proceeding from transport speed and test data which prove that tunnel section is filled with burn products in 5-6 minutes [7]. Consequently, we may give time interval in $0 \le \tau \le 120$ seconds and formula (7) will take the form

$$V = S\int_0^{120}[U_0 + U(\tau)]d\tau\ , \tag{8}$$

Where U_0 is initial velocity of air stream m/s, $0.1 \le U_0 \le 6$; $U(\tau)$ - air velocity presented as time function, m/s.

Under the effect of fire draught the velocity of air stream increases with time and assuming that unlimited quantity of fuel was spilled in tunnel for the specific it tunnel achieves a definite maximum. Thus, sub-integral function is complicated and unknown. Therefore, for determination of approximate fuel mass (burning material) which may overturn ventilators we use the value of air stream speed observed in tunnels at fire. This speed makes 15-20 m/s [8].

Undoubtedly, the mentioned speed is not the final speed in tunnels and its achieving by the stream has, by no means, a linear character. But, having no other choice we linearized the mentioned speed in time interval $0 \le \tau \le 120$ and calculated the values of function $U(\tau)$ for time moments τ_0=0, $\tau_1 = 12$,..., $\tau_9 = 108$, $\tau_{10} = 120$ [9]. The corresponding values of function are as follows: $f(0) = 1.5$, $f(\tau_1) = 3.35$, $f(\tau_2) = 5.20$, $f(\tau_3) = 7.05$, $f(\tau_4) = 8.90$, $f(\tau_5) = 10.75$, $f(\tau_6) = 12.60$, $f(\tau_7) = 14.45$, $f(\tau_8) = 16.30$, $f(\tau_9) = 18.15$, $f(\tau_{10}) = 20.0$. Then by formula of trapezium we get $V \approx S\frac{120-0}{20}\left[f(0) + 2f(\tau_1) + ... + 2f(\tau_9) + f(\tau_{10})\right] = 12900S$. For section $S = 24$ m^2 which corresponds to roadway tunnel with one-way motion, by formula (8) we get that $V = 322500$ m^3.

With the help of formula (8) we get the formula showing the pressure in fire centre with consideration of burn product mass and consequently, by some relation, of fuel mass

$$P_2 = \frac{mRT}{S\int_0^{120}[U_0 + U(\tau)]d\tau}\ . \tag{9}$$

It is known that for burning 1 m^3 of petrol steam at 0.73 kg/m^3 density 58.80 m^3 air is needed [10]. The diagram of relation of burning components "petroleum mass-air volume" is given in Fig.3.

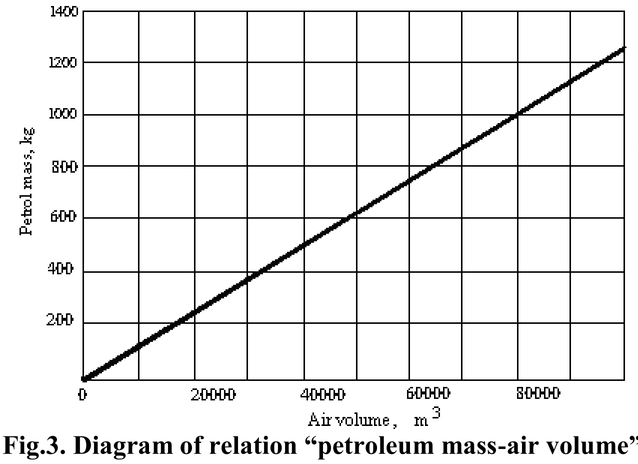

Fig.3. Diagram of relation "petroleum mass-air volume"

According to the given data, in order to receive burn products of volume 322500 m^3 about 4000 kg ($322500 \times 0.73/58.8 = 4003.8$) petroleum or equivalent fuel material is needed. By formula (9) burning of such volume of petroleum will cause dynamic pressure of about 365kPa which can suppress static pressure or any ventilators. As to the collapse of tunnel ventilators, this may be cause by burning of about 150-300 kg petroleum or equivalent combustion material.

5. HISTORY OF APPLICATION OF NATURAL DRAUGHT

Summarizing the theoretical part of the given work, it can be stated that with the necessity of airing of underground structures people have been faced long ago. In Spain in Rio-Tinto the remains of Roman mines operating about 2000 years ago have been exposed. The airing of these mines was done with addition of short ventilation trenches to long mining galleries while natural draught was used as the actuator of air motion. The methods of creation of natural draught in mines are described by Pliny the Elder in his “Natural history” (I century).

6. PRACTICAL APPLICATION OF RESULTS

For the cases of airing with natural draught and ventilators the diagrams may be drawn as are given in Fig.4. The left of them is also some graphical illustration of the law expressed by formula (2).
As are seen in diagrams, in order to determine air consumption at natural draught the knowledge of aerodynamic characteristics of ventilation circuit and draught is sufficient while at using artificial stimuli the unstable area of ventilation operation must be avoided. For example, for ventilation circuit which is characterized with curve 1 (the right graph, Fig.4) the ventilator given in the same figure cannot be used as surge will cause the break of ventilator and nullification of its efficiency.

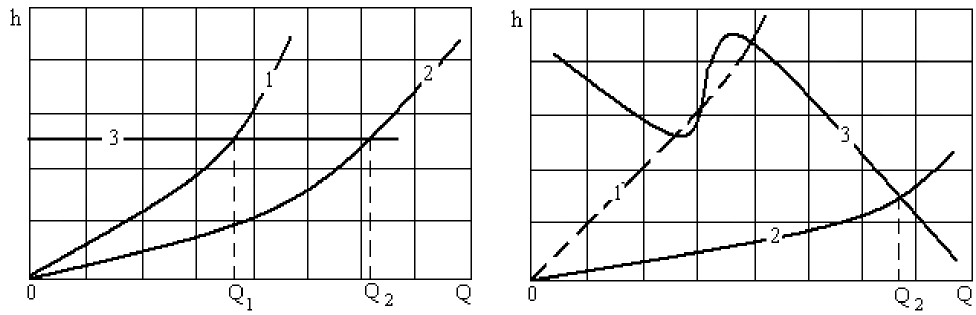

Fig.4. Characteristics of underground structures and air motion actuators:
1 – aerodynamic characteristic of tunnel $h = R_1Q^2$; 2 – aerodynamic characteristics of tunnel $h = R_2Q^2$ (supposedly only aerodynamic resistances R_1, R_2 differ which causes the difference in air amount); 3 – on the left diagram, the characteristics of natural draught, its form is simplified; on the right diagram, characteristic of ventilator, the saddle-shaped part of which is magnified for illustration

As seen from Fig 5, conflagration creates comparatively higher air consumption than working of ventilator.
Respectively, consumption is about $20Q$ for tunnel ventilator, about $3000Q$ for mine ventilator and about $20000Q$ for fire draught. Thus, conflagration will, in any case, cause ventilator collapse and nullification of their efficiency.
In the described conditions we consider that one of the means of fire localization may be the use of transformable systems which, as a rule, are widely used in space and in such places where it is complicated or impossible for human being to get [11].
The essence is that from mobile facility a special system is launched to fire centre which will cover from both sides the whole perimeter of the tunnel and will isolate the centre. The system itself is a metal unfolding construction with overstretched basalt fireproof fabric.
The purpose of transformable system is prompt division of the tunnel into short isolated sections. It is not the alternative of metal doors mounted at entrances or local sections. On the contrary, the doors and the proposed systems will supplement each other for fire localization. The main loading of the excited dynamic pressures come on metal doors, that’s why the proposed system is a lightweight construction. Use of transformable construction means efficient

operation of automatic notification system in tunnels when operator gets true information about fire centre scale and its geometrical size.

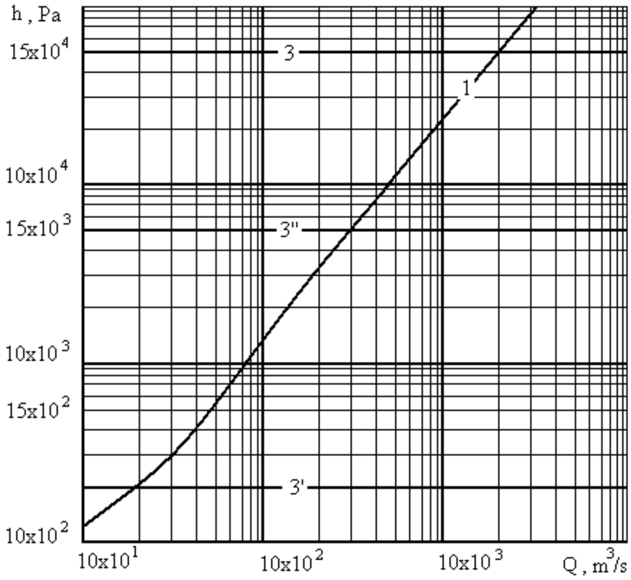

Fig.5. Characteristics of underground constructions and air movement stimuli:
1 – Aerodynamic characteristics of tunnel; 3'' –aerodynamic characteristics of tunnel ventilator (Static pressure 2000 Pa); 3''– aerodynamic characteristics of mine ventilator (Maximum static pressure 15kPa); aerodynamic characteristics of fire draught (Dynamic pressure 150kPa –maximum near 450kPa); for clearness ventilator characteristics are presented as straight lines; in fact mine ventilators make less pressure in case of real circuit as compared to maximum with the aim of avoiding of transition of operation into unstable zone; on the Figure the direction of air streams created by ventilators and fire draught coincide, but they also may not coincide

7. CONCLUSION

On the basis of the presented material it can be concluded that when solving the problems of evacuation of transport facilities and people, also of fire suppression and minimization of its negative effect, on stages of design, building and exploitation of ventilation system of transport tunnels the effect of fire draught and use of nonstandard met hods of fire extinguishing are to be considered.

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