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Clarification of fire characteristics in a road tunnel based on numerical and laboratory studies

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Abstract: Critical velocity for longitudinal ventilation, as is accepted under the emergency ventilation strategy, is a decisive factor to prevent backlayering. The results of physical and thorough numerical modeling showed that the critical velocity in inclined tunnels in case of descending ventilation and of strong fires would no longer be an important indicator within the projects. Besides, the location of the fire has a significant impact on the thermal physics and aerodynamics of the ventilation flow and the surrounding mining massif. A natural consequence of this is significant variation in critical velocity and backlayering length, which greatly affects the planning and implementation of life-saving measures. The article presents scenarios of underground fire development and analysis of accompanying processes, performed using numerical modeling in the FDS environment. The variation of the critical velocity of longitudinal ventilation, the length of the reverse flow of combustion products and the gradient-factor depending on the fire power, tunnel geometry and other variabilities is shown. It is noted that the critical value of the Froude number, like the critical ventilation rate, are not constant values in complex processes occurring underground. Specific numerical examples show that thermally and mechanically conditioned ventilation flows are algebraically summed, and without considering these circumstances, the processes of rescuing people from underground fires will certainly become more complicated. The paper found, both theoretically and through numerical modeling, that severe fires in tunnels can cause dynamic pressures greater than the static pressure of the fans. The observed dynamic pressures can reverse downward ventilation flows in tunnels with slopes of 3% or more. This work puts on the agenda not only a thorough detailed description and analysis of fire cases, but also the need to develop a clear algorithm of actions taking into consideration the geometry, location, natural conditions and ventilation systems of a specific tunnel, taking into consideration also the scenario of the expected fire. The results obtained should be communicated to rescuers and tunnel service workers through theoretical studies and training. The proposed paper is socially oriented, aimed at improving emergency ventilation technology and thus increasing safety in case of fires in road tunnels, which is an important socio-political and public task.

Keywords: *Backlayering, Critical velocity, FDS modeling, Gradient-factor, Longitudinal ventilation.*

1. Introduction

International recommendations to design emergency ventilation systems [1-3], as well as fire safety guidelines of the USA, one of the world leading countries [4-6], share the view that the critical velocity of a ventilation flow is an important technological parameter, which can be used to control smoke in traffic tunnels in case of any type of fire. The same opinion is given in scientific papers [7-19] following the publication of work by Thomas "The movement of buoyant fluid against a stream and the venting of underground fires" in 1958 [20]. Today, accepting this view without criticism is a big mistake as it is clearly evidenced by the presented graphic material, which indirectly proves that often, fires induce more dynamic pressure than the fans static pressure is. It is necessary to clarify this issue and to distinguish between the cases scientifically as required by the need to realize life-saving emergency ventilation projects. The cases should be differentiated based on fire strength, tunnel geometry, and type

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of the ventilation flow. Solving this issue is an undoubtedly topical problem for further development of the given branch.

Rescuing lives during tunnel fires is a well-known international issue and many people worldwide work to solve it. The emphasis on saving lives has become particularly strong after large-scale fires took many human lives. Examples include the fire in the Mont Blanc Tunnel (France/Italy), which took lives of 39 people; fire in the Funicular tunnel (Austria) taking 155 lives; assault by setting fire to Jungango metro station, South Korea, killing 189 people; fire in a metro station in Azerbaijan killing more than 260 people [1]; fire in Yangzhou Tunnel, China with 40 dead [17]. Special literature describes more than 40 fires with fatal consequences. The proof of the universal recognition of the problem is the work of the UN European Commission in this direction [1, 2].

As it was mentioned, critical velocity in terms of longitudinal ventilation, as is accepted under the emergency ventilation strategy, is a decisive factor to prevent backlayering. Backlayering is an opposite propagation of combustion products on an ascending ventilation flow, in the part of the air-supply tunnel, were, in principle, there must be fresh air. This is caused by high temperature and resulting lower density of the combustion products and floating taking place at the expense of buoyancy. This is a very dangerous event for a human life in case of evacuation. This is particularly evident when an air current moves from a hypsometrically high level to a lower level, and the seat of fire is at a low level.

As for the critical velocity of the ventilation flow, it is a minimum velocity preventing backlayering. The critical velocity depends on the fire heat release rate, the cross-sectional size and the slope of tunnel. Since the dynamic pressure induced by fire and the similar pressure created by jet fans are summed algebraically, in order to prevent the section of the tunnel with a clean flow from the pollution with smoke, the fresh air current must have the velocity higher than the critical velocity. As a result, with a longitudinal ventilation system, the flow with the critical velocity will expel smoke and other harmful combustion products from the seat of fire only to one side of the tunnel, while, as an idea suggests, there must be fresh air on the other side of the tunnel.

As the Clapeyron Equation shows, the dynamic pressure induced by fire with a temperature of 1000 °C is 121.6 kPa in tunnels, i.e., greater than the atmospheric pressure, and 8 times more the maximum static pressure of the most powerful fans. In this case, 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 flow by means of fans, and the air direction and discharge will be determined by the depression caused by fire [21-25]. A comparison of the dynamic pressure caused by fire and the static pressure developed by different types of fans is shown in Fig. 1. It is evident from the figure that the pressure developed by a strong fire always dominates compared to the mechanical excitation of air movement. This should be given great importance from the point of view of planning fire prevention measures, organizing emergency ventilation and saving lives in tunnel fires. It should be noted that the issues presented in this article have been considered more or less deeply in our published works [26-31].

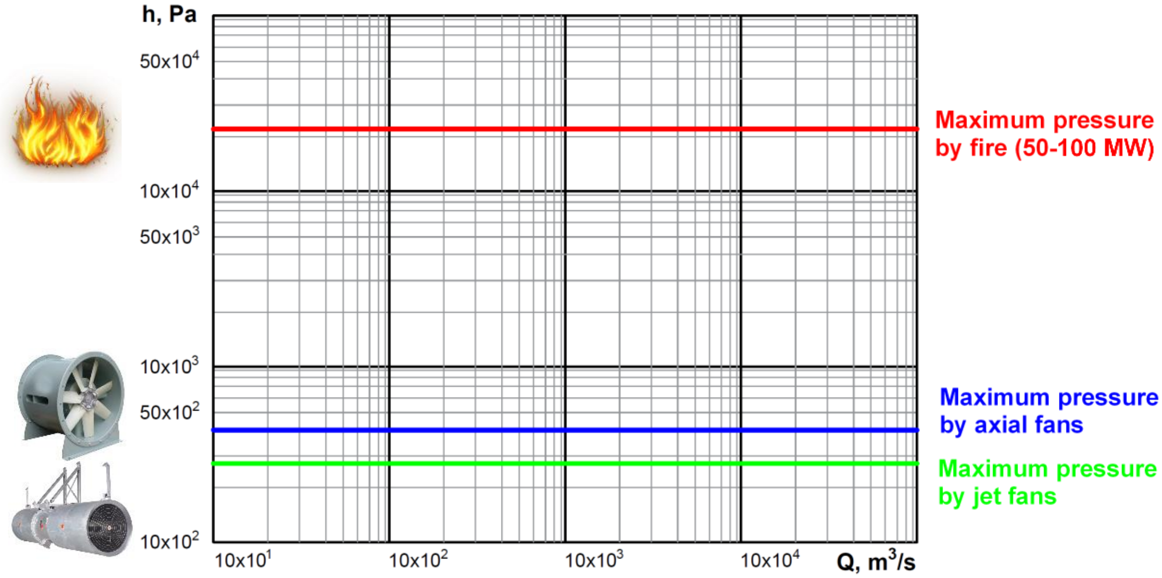

Figure 1.
For the comparison of mechanical and thermal flows in a tunnel equipped with a longitudinal ventilation system.

This is especially noteworthy considering that like other countries, the sustainability of the economy of Georgia much depends on trouble-free operation of the transport system in the country. A tunnel is a key element of this system, as, generally, it provides the means to overcome the most difficult sections on the road and significantly accelerate shipment turnover. A tunnel in general, and in terms of high conductivity, is a problematic element at the same time because of possible fires. A tunnel fire has a strong destructive force and the resultant long-term negative impact on the trouble-free operation of the tunnel.

Long disruptions in the operation of tunnels will cause direct damage, hinder economic development and put the country to hardship. This is why novel solutions to safe tunnel ventilation issues are very important. These solutions must analyze the causes and consequences of resonant fires occurring in world tunnels. The capabilities of the ventilation system must be assessed more realistically. Expected collapse of the ventilation system and measures to reduce negative impacts must be considered and addressed adequately. As a result, it will be possible to save lives more reliably in road tunnels of Georgia, as well as to prevent long-term dysfunction of tunnels because of fires.

In addition to reducing the direct material damage caused by the collapse of a tunnel and its infrastructure, this will help avoid losses caused by tunnel inactivity and diversion of international shipments. Thus, the proposed project is socially oriented, aims at improving ventilation technology and thus, enhancing fire safety during road tunnel fires providing a potential prospect for significant socio-political and public development.

2. Numerical Modeling of Tunnel Fires

We did an experimental numerical modelling for a 100-meter-long tunnel. The goal of the experiments was to demonstrate a steady increase in critical velocity as the fire strength increases, as well as pointlessness to rely on this concept in preventing backlayering based on the results of numerical modeling results. The velocity profiles obtained through numerical modeling are given in Figure 2.

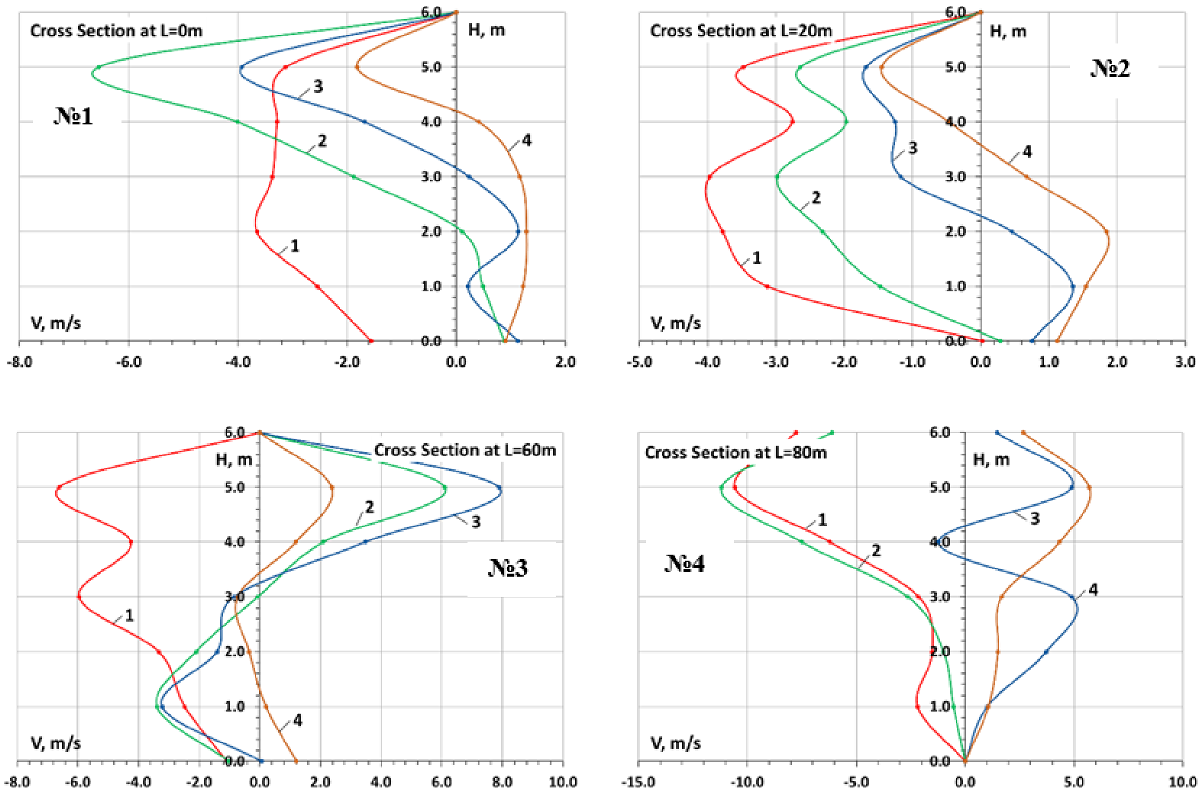

Figure 2.
Profiles of velocities of a descending ventilation flow during the operation of two jet fans. The curves are given for the following time intervals: 1 -τ= 60 s; 2 -τ= 80 s; 3 -τ= 100 s; 4 -τ= 120 s.

The cross sections are given depending on the distance from the lower portal with the following principle: Drawing N1 - Lower portal (the portal No1); Drawing N2 – Distance from the lower portal: 20 m; Drawing N3 - Distance from the lower portal: 60 m, and Drawing N4 - Distance from the lower portal: 80 m. The curve numbers show the following time intervals from the start of the experiment; 1 - = 60 s; 2 - = 80 s; 3 - = 100 s; 4 - = 120 s. The negative and positive velocity values in all drawings of velocity profiles mean the movement of flow to Portal 1 and Portal 2 (hypsometrically the upper portal), respectively.

Curve 1 in Drawing 1 of Fig. 2 shows that the air current moves towards Portal 1 before the fire starts, and the velocity diagram is classical. At this time, two jet fans work simultaneously at the upper portal. As soon as the fire starts, the situation changes immediately (see curves 2, 3 and 4). The direction and intensity of air movement are more determined by the dynamic pressure induced by fire, while the impact of the fans tends to decrease. It should be noted that all the presented drawings of velocity profiles show that the pressure variability propagates at a speed of sound, resulting in the variability of the corresponding results at a similar rate.

Based on the above, cases should be distinguished from each other: 1. when it will be possible to develop emergency ventilation projects in order to save life within the existing classical knowledge; 2. When existing knowledge is no longer sufficient to carry out similar projects and new research results are needed to provide a new approach to the issue.

3. Results Obtained by Laboratory Experiments

Modeling strategy by Froude number is widely used in small-scale fire experiments. Its essence is that the Froude number, which characterizes the forces of inertia and buoyancy forces, will be directly maintained in the experiment. When simulating a fire based on the Froude number, the temperature fields are the same, and the scaling of the heat release rate and ventilation rate between model and nature is expressed as follows:

$$\frac{Q_m}{Q_n} = \left(\frac{\ell_m}{\ell_n}\right)^{2.5} \quad (1)$$

$$\frac{u_m}{u_n} = \left(\frac{\ell_m}{\ell_n}\right)^{0.5} \quad (2)$$

Figure 3 shows the scheme of the tunnel model made of stainless metal sheets and the accessories connected to it, and the picture of the tunnel model fixed in a horizontal position is given in fig. at 4. In the physical model, the tunnel length was 12 m, supplied with air by a separate air duct. The cross section of the model is 0.467 m^2, length 12 m, width 0.85 m, height 0.55 m.

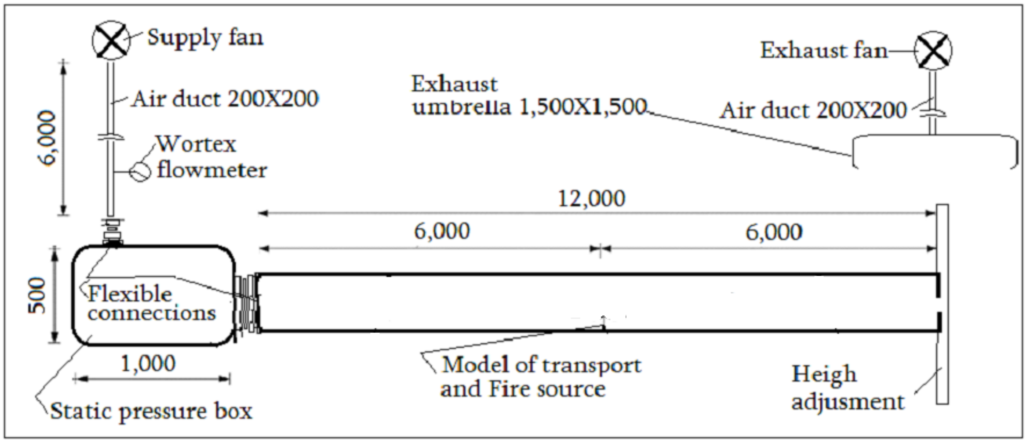

Figure 3.
An experimental device scheme with a 12 m length tunnel model, linear scale 1:10.

3.1. Physical Model

For the physical modeling we choose linear scale $M_l = l_m/l_n = W_M/W_N = H_M/H_N = 0.1$; The other scales of the modeling according to the above formulas will be: for HRR $M_Q = 0.00316$; for ventilation velocity $M_u = 0.316$.

We have the tunnel model that made of 2 mm thick stainless-steel sheets. There are two types of transport for all tunnel models: Nissan Patrol 2014, which has the dimensions: 5160X1995X1938 mm and "Euro-trans" - 13600X2450X2450 mm. The distance between the bottom of transport and the tunnel floor will be 0.08 m (80 mm), which in nature corresponds to 0.8 m (800 mm).

To ensure of stable turbulence in all the models was used the static pressure box with 1 m length, 0.5 m width and 0.5 m height. In the box air was delivered through a duct fan, whose consumption was 20-150 m3/h with maximum static pressure - up to 150 Pa. Fire source were porous burners with a surface area of 130X50 mm and 340X60 mm. The surface of the fire source was at the tunnel floor level. A natural gas was used, whose consumption was measured by a rotameter at 1% accuracy. In the tunnel cross-section were installed one or two burners. The HRR of the model was calculated according to the gas flow. The air flow in the tunnel was measured by a vortex flow meter with accuracy of 1%. The speed of the air was not measured; it was calculated according to air flow and tunnel model size.

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Definition of the symbols in the formulas (in order of appearance in the text)
Q_m - convection HRR on the model, kW; Q_n - convection HRR in the nature, kW; ℓ_m- tunnel length on the model, m; ℓ_n- tunnel length in the nature, m; u_m- air velocity on the model, m/s; u_n- air velocity in the nature, m/s; $\boldsymbol{\zeta}$ **- t**he ratio of tunnel width to height; α - the tunnel filling coefficient by transport; F - the area of transverse section of transport, m^2; f - the area of a tunnel cross-section, m^2; K_g - a grade correction factor, to be applied for fires in slopping tunnels; $u_{c,0}$ - critical velocity (CV) of horizontal tunnel, m/s; $u_{c,\theta}$ - CV in the inclined by angle θ tunnel, m/s; s - tunnel sloping, %; k - proportionality constant; g - gravitational acceleration, m/s^2; $\dot{Q}_c$ - convective heat release rate, kW; H - tunnel height, m; ρ_0 - outdoor air density, kg/m^3; c_p- heat capacity of air, kJ/(kg. K); T - the average temperature of smoke, K ; Fr_C - Frouds critical number; $\Delta\rho$ - density difference, kg/m^3; T_0 - outdoor air temperature, K .

3.2. The Ratio of Tunnel Width to Height - ζ.

The ratio of tunnel width to height$\zeta = \frac{W_m}{H_m}$. $\boldsymbol{\zeta} =$ 1.54.

3.3. The Coefficient of Tunnel Filling by a Transport - α.

The calculation of the coefficient α of tunnel filling by a transport is possible by means of the following formula:$\alpha = \frac{F}{f}$ The numerical values of the coefficient α, according to the planned experiments, are given in table 1.

Table 1.
Tunnel filling coefficients with transport.

Numeric values of $\boldsymbol{\alpha}$ according to the number of vehicles in the tunnel crossing, %		
One Nissan Patrol 2014	One "Euro-trans"	Two "Euro-trans"
8.3	12.5	25.0

3.4. Air Speeds on the Model and in the Nature

The air consumption was 20-150 m^3/h. The calculated speed data is included in Table 2.

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Table 2.
Air velocities on the model and in nature.

Air consumption, m^3/h	Air velocity on the model, m/s	Air velocity in the nature, m/s
20-150	0.185-1.389	0.59-4.4

3.5. Heat Release rate (HRR) on the Model and in the Nature

Particularly clear is the flexibility of the modeling by number of Froude in the case of comparison the values of HRR (Heat Release Rate) between model and reality in nature. Based on a simulation scale of $M_Q = 0.00316$, to simulate a fire which in nature has an HRR of 5 MW, on the model requires only about 15.8 kW HRR.

Figure 4.
Tunnel model fixed in a horizontal position.

3.6. Providing of Tunnel Incline on the Model

The variability of the planned tunnel incline angles is -8 <s <8 degrees, each degree gives a 1.75% inclination. The models were provided with special lifting devices. The deviation quantities of the model from the horizontal plane are given in Table 3.

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Table 3.
The angle of inclination of the tunnel and the corresponding distances.

Tilt angle, degrees	Vertical distance, m	Tilt angle, degrees	Vertical distance, m	Tilt angle, degrees	Vertical distance, m	Tilt angle, degrees	Vertical distance, m
-1	-0.21	-6	-1.25	1	0.21	6	1.25
-2	-0.42	-7	-1.46	2	0.42	7	1.46
-3	-0.63	-8	-1.67	3	0.63	8	1.67
-4	-0.84	-	-	4	0.84	-	-
-5	-1.05	-	-	5	1.05	-	-

3.7. Determination of the Back-Layering Length

The back-layering length was determined by measurement of the air temperature changing on the length of the tunnel. Temperature was measured by using K-type stainless steel-sheathed thermocouples with a diameter of 1.0 mm. The thermocouples deployment scheme is given in Figure 5. In all modeled tunnels the thermocouples were installed bellow of the ceiling at a distance of 20 mm as the entire length of the upward and downward flow. On the both sides of the tunnel center on distance 2-2 m were installed 40 pieces of thermocouples with intervals 0.1 m. The rest of the modeled tunnel were also installed similar devices with intervals 0.2 m between thermocouples. Temperature measurement from thermocouples were done through an online system of observations when the temperature on the model is at least 5 degrees above the ambient temperature.

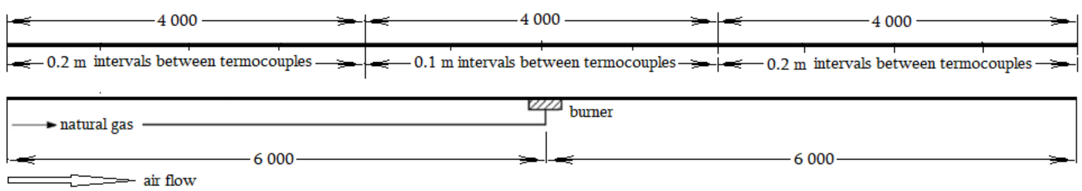

Figure 5.
Positions of thermocouples on the models.

The monitoring system consists of a central DAT85 data collection module manufactured by Data Taker and 4 types sensors connected to it. Namely, there are two types of the Thermocouples, duct mounted air velocity transmitter and Mass Flow Controller. System should control gas flow, measure and log the air velocity and temperature change across the modeled tunnel.

3.8. Experimental Determination of Gradient-Factor

Experimental determination of gradient-factor as physical so mathematical models was made by the formula $K_g = \frac{u_{c,\theta}}{u_{c,0}}$. Note also that this formula can be used to analyze and correlate the obtained results. The variation of numerical values of the gradient factor determined by laboratory experiments according to the power of the fire and the slope of the tunnel is shown in Fig. on 6.

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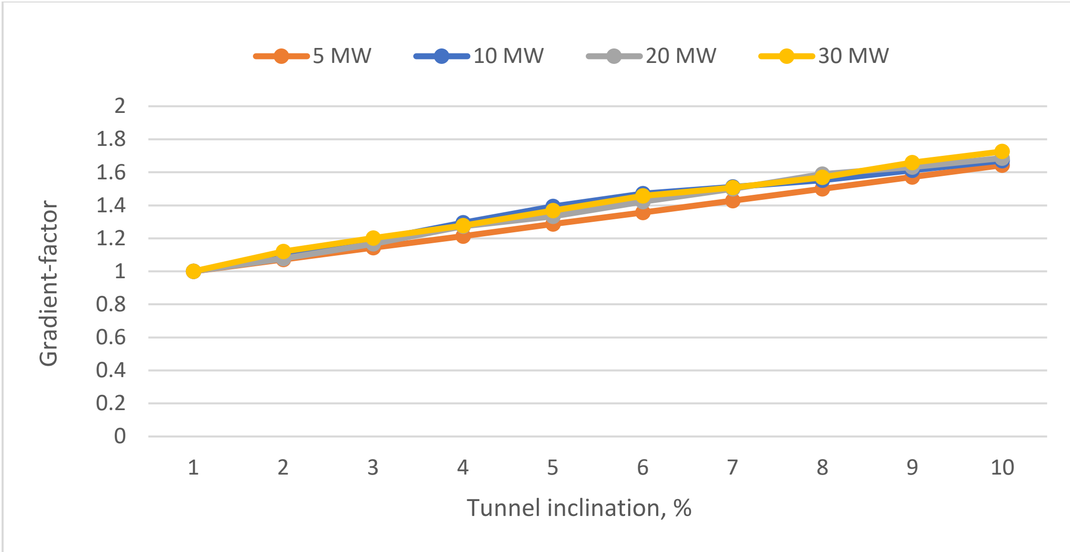

Figure 6.
The nature of the variation of the gradient-factor depending on the power of the fire and the inclination of the tunnel.

3.9. Experimental Inspection of the Expected Collapse of the Ventilation System

In conditions of strong fires, after a certain period, the effect of the fan on the ventilation flow decreases due to high temperatures. The effect of these temperatures will either increase the dynamic pressure of the air flow, or reduce the density of the air, but in any case, the effect of fans on the air exchange will constantly decrease, accompanied by an increase in the proportion mentioned exchange due to elevated temperatures. Influence of heat release rate on ventilation conditions in the scientific literature is evaluated differently. By means of tunnel tilt vary and heat release rate exchanges we plan to bring clarity in the matter. In any case theoretical base will be the Clapeyron equation.

4. Conclusion

The paper found, both theoretically and through numerical modeling and laboratory experiments, that severe fires in tunnels can cause dynamic pressures greater than the static pressure of the fans. The observed dynamic pressures can reverse downward ventilation flows in tunnels with slopes of 3% or more. This work puts on the agenda not only a thorough detailed description and analysis of fire cases, but also the need to develop a clear algorithm of actions taking into consideration the geometry, location, natural conditions and ventilation systems of a specific tunnel, taking into consideration also the scenario of the expected fire. The results obtained should be communicated to rescuers and tunnel service workers through theoretical studies and training.

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