

The effect of Air Flow Rate on Smoke Stratification in Longitudinal Tunnel Ventilation

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The construction of tunnels is associated with mining. For safety and suitable working conditions, it is necessary to ensure that there is suitable ventilation during construction.

During operation, tunnels form the infrastructure of the area, which has a number of characteristics. Tunnel ventilation is designed with regards to many different factors. Longitudinal ventilation is especially used in one-way, extra-urban tunnels but in some cases also in urban or two-way tunnels.

The article describes the purpose and types of tunnel ventilation, focusing on longitudinal ventilation and ventilation design strategy. Longitudinal tunnel ventilation is the cause of significant turbulence that affects the smoke stratification. The article compares different tunnel ventilation options in terms of selected strategies and the different values of applied airflow rates.

A case study was conducted on the Klimkovice road tunnel in the Czech Republic using the fire model from the Fire Dynamics Simulator. The study compares the effect of airflow rate on smoke stratification. The study was conducted with air flow rate values of 0 to 5 m.s⁻¹.

The results of the study show that even with lower airflow rates, the smoke build-up is so significant that the safety of individuals in the tunnel cannot be ensured. The dynamicity of fire is also an important factor. Opting for a lower airflow rate strategy because of higher expected congestion or other factors is a questionable practice. Greater airflow rates, however, create better conditions for evacuating individuals, although it is also necessary to combine smoke stratification options with the selected ventilation strategy.

Keywords: safety, tunnel, fire, longitudinal ventilation, smoke stratification

Introduction

Tunnel construction must go hand in hand with safety. In the case of tunnelling, there is a necessity to supply fresh air to the exposed face of tunnel tubes. The design requirements for ventilating tunnels aren't as specific as in, for example, gassy or non-gassy mines; however, there is always the necessity to supply fresh air to the workplace.

The most limiting factors in ventilating tunnels are the gases carbon dioxide, monoxide, nitrogen oxides and hydrogen sulphide.

The actual ventilation of the mined tunnels depends on the profile and length of the excavation work. For example, short tunnelling activity can be ventilated by natural ventilation or by diffusion, provided the limit concentrations of the above gases are not exceeded.

In other cases, it is necessary to use artificial ventilation (separate), which is provided by fans usually located in front of the excavation portal and lutes, which bring fresh air to the face, or vice versa used air from the face. In such cases, it is blow or suction ventilation, the most commonly used type of ventilation being the blow type, especially with respect to the purchase costs of lutes, which may not have reinforcements, as in the case of the suction type of ventilation. In exceptional cases, for example, when using tunnelling platforms, or when performing small-profile underground works or extrusions where separate ventilation cannot be established, it can be ventilated by compressed air.

Generally, in tunnelling, there are two basic factors to consider when designing the type of ventilation, namely blasting and the associated exhaust ventilation after blasting operations, and the use of diesel engines, which, apart from electric motors, are the only kind that can work and operate in underground workspaces.

During operation, road tunnels are a complex structure, equipped with a number of construction elements and facilities that enable it to operate, and in many cases contribute to ensuring safety. It stipulates the technical and maintenance requirements for tunnels longer than 500 m (European Parliament Directive 2004/54/ES).

The safety requirements for building road tunnels are given by national regulations of each individual country. Examples are Road Tunnel Ventilation, Design, Dimensioning and Equipment, ASTRA 13001 from Switzerland (ASTRA 13001, 2008), RABT 2006 Tunnel Equipment and Operation Guidelines from Germany (RABT, 2006), Tunnel Ventilation - Basic Principles Austrian Research Association for Roads, Rail and Transport from Austria (RVS 09.02.31 2008) Manual 021 Norwegian Public Roads Administration Standard

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Road Tunnels 03.04 from Norway (Manual 021, 2004)DMRB Volume 2 Section 2 Part 9 (BD 78/99) Design (substructures and special structures). Special structures. Design of road tunnels from Great Britain (DMRB, 1999) or NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways from the United States (NFPA 502, 2017).

In the Czech Republic and Slovakia, these requirements are governed by government decrees (Government decree no. 269/2009; Government decree no. 344/2006), technical standards ČSN 737507, 2013; STN 737507, 2008) and methodical instructions issued by ministries (Marasová et al., 2010).

Under the European Parliament Directive (EU) no. 305/2011 (which stipulates the harmonized conditions for introducing construction products on the market and repeals EU directive 89/106/EHS), one of the conditions road tunnels must also comply with are fire safety requirements (Regulation (EU) No 305, 2011). The requirements include securing the load-bearing property of the structure, limiting the spread of fire inside and outside the structure, ensuring the evacuation and the safety of individuals and securing the safety of rescue units. Safety standards for tunnels are also given by the World Road Association (World Road Association PIARC, 2019).

Operating road tunnels is historically associated with various emergency situations. One of the most dangerous situations is fire, significant examples being the incident in 1982 at the tunnel in Salang, Afghanistan, where 176 people died, the fire in the Montblanc tunnel in France in 1999, which killed 39 people, and the Gotthard tunnel in Switzerland in 2001, where more than 100 people lost their lives. Other notable examples include the fire in the tunnel on the highway between Florence and Bologna in 1993, which killed four people, the fire in the Pfänder tunnel near Bregenz in Austria in 1995, also killing four people, and the fire in the tunnel near Palermo in 1996, which killed five people. The causes of these fires were either road accidents or car fires. (World Road Association PIARC, 2019)

From 2013 to 2018, the Czech Republic experienced five road tunnel fires (Pokorný et al., 2018). Compared to the average total number of fires in the Czech Republic, which is around 20,000, this figure is negligible (Fire Rescue Service, Czech Republic, 2019). Despite this and no significant loss of life or damage to property and the environment, historical events demonstrate that the consequences of fires in tunnels can be devastating. (Kročová, 2015)

In order to mitigate emergency situations, tunnels must be prepared structurally, technically and organisationally (Yang, 2016) by the engineering architect, construction company, tunnel operator and rescue units (especially the fire rescue services and police). One of the most important requirements for securing the safety of underground structures is ventilation. The requirements for tunnel ventilation are similar to the requirements for general aboveground structures (Pokorný and Gondek, 2016).

It is possible to classify road tunnel ventilation into standard operating ventilation, emergency ventilation (fires), and environmentally friendly ventilation. In particular, standard operational requirements can be understood as those ensuring a suitable environment for persons who may be present. Emergency operation means creating conditions that ensure the safe evacuation of persons and effective intervention of rescue units. Environmental ventilation should ensure a minimal impact of the tunnel operation on the environment. (ASTRA 13001, 2008; Ministry of Transport, Department of Roads, 2013; Tomašková and Vargová, 2018).

The aim of this study was to determine the effect of longitudinal tunnel ventilation on the safety of individuals and the effectiveness of fire services under a given strategy and therefore also the different airflow rate values. The article investigates whether some stratification of smoke remained using low airflow rates.

Material and Methods

Tunnel fire ventilation

Tunnel fire ventilation is a supporting measure for the evacuation and rescue of individuals and also supports rescue units.

For the design of fire ventilation in tunnels, the essentials are the following (ASTRA 13001, 2008; NFPA 502, 2017):

- traffic intensity and mode,
- tunnel length,
- operating mode (one-way or two-way).

Based on the above criteria, tunnels can be divided into the following categories for ventilation purposes (ASTRA 13001, 2008; Ministry of Transport, Department of Roads, 2013):

- tunnels with unidirectional traffic and low probability of congestion (cat. T1, usually highway tunnels),
- tunnels with unidirectional traffic and a high probability of congestion (cat. T2, usually highway tunnels),
- tunnels with two-way traffic (cat. T3).

The following concepts (strategies) are applied in designing fire ventilation (Ministry of Transport, Road Department, 2013):

- natural (longitudinal) ventilation (suitable for short tunnels or T1 tunnels),
- longitudinal ventilation, fixed installation (suitable for tunnels or T1 tunnels),
- longitudinal ventilation with airflow regulation at defined values (suitable for T2 and T3 tunnels),
- transverse ventilation (suitable for T2 and T3 tunnels).

The given classification was put in place in the Czech Republic. In principle, however, it is also used for many foreign countries where the classification may be modified.

For longitudinal ventilation in tunnels, the required airflow rate is essential. Airflow velocity requirements vary somewhat in the design guidelines and are listed in Table 1 for clarity.

Table 1. Airflow velocity setpoints for longitudinal ventilation

Country	Character (category) tunnel	Required flow rate for longitudinal ventilation (m.s ⁻¹)	Note
France (Annexe n° 2, 2000)	one-way extra-urban tunnels	3	
	one-way urban tunnels	3	recommended for tunnels up to 500 m long
		1 - 2 (Phase 1) 3 (Phase 2)	Phase 1 - the evacuation of persons 2nd phase - support of rescue units
	bidirectional	3	
Czech Republic (Ministry of Transport, Department of Roads, 2013)	unidirectional tunnels with a lower incidence of congestion (T1)	critical air velocity up to 10	the critical speed is generally about 3 m.s ⁻¹
	unidirectional tunnels with a higher incidence of congestion (T2)	1.2	
	bidirectional tunnels (T3)	1.2	
Germany (RABT, 2006)	unidirectional tunnels with a lower incidence of congestion	2.3 – 3.6	depends on tunnel slope, tunnel tube shape (rectangular, hipped) and fire intensity
	unidirectional tunnels with a higher incidence of congestion	1.5	
	bidirectional tunnels (T3)	1.5	
Netherlands (Huijben et al. 2006)	Not dependent on tunnel characteristics	2.5	
Norway (Manual 021, 2004)	tunnels longer than 500 m and inclined $\geq 2^\circ$	min. 2	fire ventilation is specified by calculation
	other tunnels with inclination $< 2^\circ$	2	fire intensity 5 MW
		3.5	fire intensity 20 MW
Austria (RVS 09.02.31 2008)	Not dependent on tunnel characteristics	2	or air volume flow in the tunnel 120 m ³ .s ⁻¹
Switzerland (ASTRA 13001, 2008)	unidirectional tunnels with a lower incidence of congestion (RV 1)	3	
	unidirectional tunnels with a higher incidence of congestion (RV 2)	1.5 - 3	depending on the tunnel gradient and direction of ventilation
	bidirectional (GV)	1.5	
Slovakia (TP 049, 2018)	one-way traffic with a low probability of congestion (common highway tunnels) (A)	1.5 - 2 (1 – 1.5 for exceptional bidirectional traffic)	phase 1 - the evacuation of persons
	one-way traffic with a high probability of congestion (common highway tunnels) (B)	1 – 1.5	in the case of smoke extraction with longitudinal ventilation 1.5 - 2 m.s ⁻¹ from both sides to the extraction point
	two-way traffic tunnels (C)	1 – 1.5	
	all variants	critical air velocity up	2nd phase - support of

		to 10	rescue units initiation upon the demand of rescue units
United States of America (NFPA 502, 2017)	Not dependent on tunnel characteristics	critical air velocity up to 10	
		2.54 – 2.95	large-scale tests
Great Britain (DMRB 1999)	Not dependent on tunnel characteristics	1.3	fire output 3 MW
		3	fire output 25 MW
		7	fire output 25 MW

Table 1 shows that in unidirectional tunnels with a lower incidence of congestion, critical speeds are generally required. In unidirectional tunnels with a higher incidence of congestion, it is usually required to reduce the airflow rate below the critical speed (the flow rate reduction is in the range of 1.2 – 1.5 m.s⁻¹).

Conversely, higher airflow rates will cause a more intense influx of smoke to the tunnel (smoke stratification will be quickly interrupted, and the smoke will be channelled in one direction).

The fire ventilation design is strongly linked to risk analysis. Risk analysis determines the choice of type and strategy of the ventilation system. The general techniques for risk analysis are applied to evaluate risk in road tunnels (for example, ČSN EN 31010, 2011; ČSN ISO 31000, 2018).

Fire design

An important factor in designing tunnel ventilation is the fire scenario most likely to develop fire (Haukur Ingason et al., 2015; ISO 16733-1, 2015; KUČERA et al., 2009). The heat output of the fire scenario in relation to the number of heavy truck vehicles per unit of time (typically a day) and the length of the tunnel is 5, 30 and 50 MW. Different heat outputs can be determined in the risk analysis. (Ministry of Transport, Roads Department, 2013). A heat output value of 30 MW is typically considered in a fire ventilation design.

Fire ventilation design and strategy in tunnels

Just as in other buildings and structures, the movement of smoke created during a tunnel fire is affected by several factors that range from low to high importance. The main factors affecting the movement of smoke in tunnel structures are as follows (Pokorný and Gondek, 2016):

- the tunnel's geometry,
- chimney effect,
- effect of stationary vehicles,
- wind,
- buoyancy effect created by the fire,
- increased gas volume,
- ventilation equipment.

When fire ventilation is designed for tunnel structures, these are important factors that must be considered.

Suitable strategies are applied to ventilate road tunnels. The strategy for longitudinal tunnel ventilation depends on the characteristics of the tunnel in terms of traffic direction (one-way or two-way) and the probability of congestion occurring (low or high). Fire ventilation should fulfil its given function in the selected strategy.

The aim of longitudinal ventilation in tunnels operating with one-way traffic and a low probability of congestion (T1) is to channel (expel) the smoke in the direction of vehicle traffic and prevent it spreading towards stationary vehicles. The critical air flow rate is typically between 2.5 to 3 m.s⁻¹. (ČSN 737507, 2013)

The aim of longitudinal ventilation in tunnels with one-way traffic and a high probability of congestion (T2) or in two-way traffic tunnels (T3) is to channel the smoke and limit its spread, or else decrease its flow rate and create the conditions for smoke stratification for a certain period of time. Generally, the airflow rate used is 1.2 m.s⁻¹. (ČSN 737507, 2013)

The critical gas flow rate is defined as the rate that ensures the smoke is channelled in the direction of vehicle traffic and limits its spread towards stationary vehicles. The critical gas flow rate and average smoke temperature can be determined by Kennedy's model and calculated with the following equations (NFPA 502, 2017):

$$V_c = K_1 \cdot K_g \cdot \left(\frac{g \cdot H \cdot Q}{\rho \cdot c_p \cdot A \cdot T_f} \right)^{\frac{1}{3}} \quad (1)$$

$$T_f = T + \left(\frac{Q}{\rho \cdot c_p \cdot A \cdot V_c} \right) \quad (2)$$

where

V_c critical flow rate [m.s⁻¹]

K_I	Froude number, $Fr^{-1/3}$ (0.606) [-]
K_g	slope/gradient factor [-]
g	acceleration due to gravity [$m.s^{-2}$]
H	height of the tunnel at the location of the fire [m]
Q	convective ratio of released heat flux [kW]
ρ	average density of introduced air [$kg.m^{-3}$]
c_p	specific heat capacity of smoke [$kJ.(kg.K)^{-1}$]
A_n	area perpendicular to the airflow [m^2]
T_f	average smoke temperature [K]
T	average introduced air temperature [K]

Case study

Aim of the study

The frequently selected strategies, and therefore also different airflow rates for longitudinal fire ventilation in road tunnels, were evaluated in the case study.

The Klimkovice tunnel located in the Moravia-Silesian region near the city of Ostrava in the Czech Republic was selected for the case study. The Klimkovice tunnel is part of the D47 highway along the Bílovec – Ostrava, Rudná section. The tunnel is designed for one-way traffic with two tunnel tubes. The length of the tunnel is approximately 1000 m. The width of the road is 9.5 m, and the width of the two-way sidewalks is 1 and 1.2 m, the height of the tunnel is 4.8 m. The tunnel tubes have a longitudinal gradient of 0.6 %. The tunnel tubes are connected with five jumpers. Longitudinal ventilation is installed in the tunnel and consists of eight pairs of ventilators. The ventilators comply with the standard requirements of the Czech Republic to remain operational in temperatures of 400 °C for 90 minutes. The ventilators always become operational after five seconds. The tunnel commenced operation in 2008.

Fire model

The mathematical fire model used for the case study is the Fire Dynamics Simulator (FDS). The FDS model is a CFD model developed by NIST (National Institute of Standards and Technology, Maryland, USA) and allows numerous parameters associated with fire development to be set, including the ‘enclosure volume’ factor. The model applies Navier–Stokes equations, which are useful for evaluating the flux of smoke movement and also take heat into account. This fire model uses the Smokeview software to visualise the numerical calculations. (Fire Dynamics Simulator, 2019)

A computing grid with cell dimensions of 0.5 x 0.5 x 0.5 m was used for calculation. The initial temperature was set to 15 °C, relative air humidity at 70 %. The environmental conditions were determined primarily by the technical properties of the concrete linings and the airflow rate into the computing zone.

The input assumptions of the study

For the purposes of the study, the tunnel was evaluated as an isolated system without considering external effects on the portal (such as wind). The point of origin of the fire was set at a distance of 256 m from the more elevated portal in the direction of traffic (approximately one-third of the tunnel length). The main channel of longitudinal ventilation was therefore expected to be against the gradient of the tunnel. The heat output of the fire was simulated at two design levels: 5 MW (personal vehicle fire) and 30 MW (small truck or freight vehicle fire). The airflow rate of the tunnel was set for when ventilation was not in operation, these being 0.5 $m.s^{-1}$, 1 $m.s^{-1}$, 1.5 $m.s^{-1}$, 2 $m.s^{-1}$, 2.5 $m.s^{-1}$, 3 $m.s^{-1}$, 3.5 $m.s^{-1}$ and 5 $m.s^{-1}$.

The geometry of the tunnel and the location of the fire origin are shown in Fig. 1.

Evaluation method of the study

The study evaluated the effect of airflow rate on retaining smoke stratification in the tunnel. Environment visibility was selected as a limiting criterion. Visibility was evaluated at 20 evenly spaced measurement points along the axis of the tunnel (one point every 50 m of the tunnel’s length) at a height of 2.5 m above the road’s surface (the conventional limit value for evaluating the safety of individuals in respect of smoke from a fire) (ČSN P CEN/TR 12101-5, 2008). The moment of interruption of smoke stratification was defined as the moment when visibility decreased to 15 m. This is the conventional limit value when panic and a significant increase in the difficulty of evacuation is anticipated (Folwarczny and Pokorný, 2006; Hurley, 2015). Generally, the time for the safe evacuation of individuals via an unprotected emergency exit is expected at 2.5 min (HOSSER, 2013). The rate of movement of individuals towards an unprotected emergency exit is typically given as 30 $m.min^{-1}$ (ČSN 73 0804, 2010). On the basis of these assumptions, the distance of moving individuals to a safe distance was approximately 75 m.

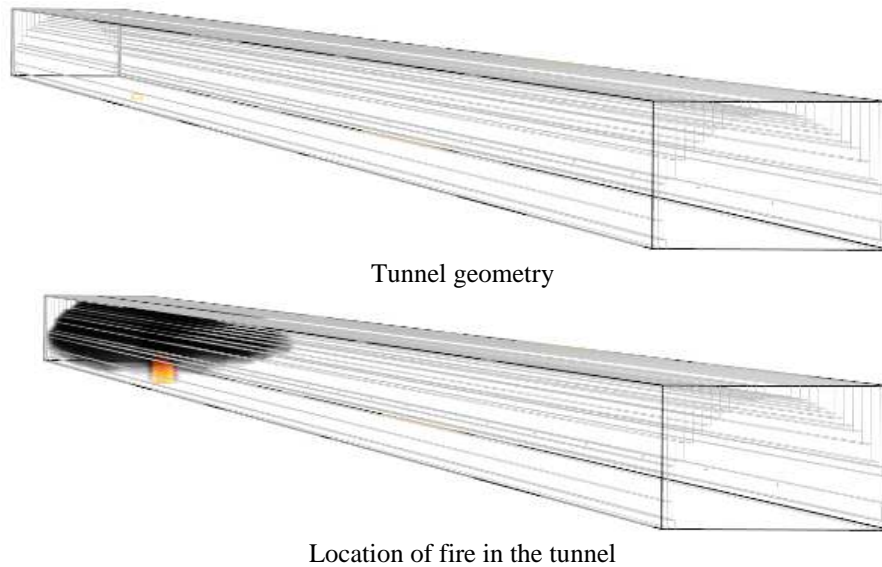


Fig. 1. The geometry of the tunnel and the location of the fire origin

Simulation results

The following figures show the results of the fire simulation model. Fig. 2 shows the temperature profile at 180 s during fire thermal power 30 MW and the movement of smoke near the fire origin point without ventilation at 600 s and during the fire thermal power at 5 MW.

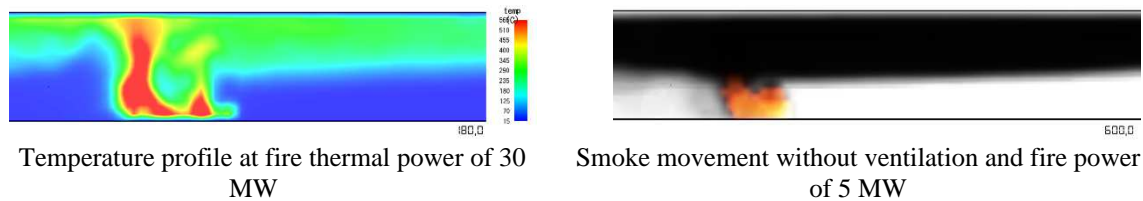


Fig. 2. Representation of temperature profile and smoke movement in the enclosed space

The movement of smoke near the fire origin at 5 MW and 30 MW at 600 s and various smoke velocities are shown in Fig. 3.

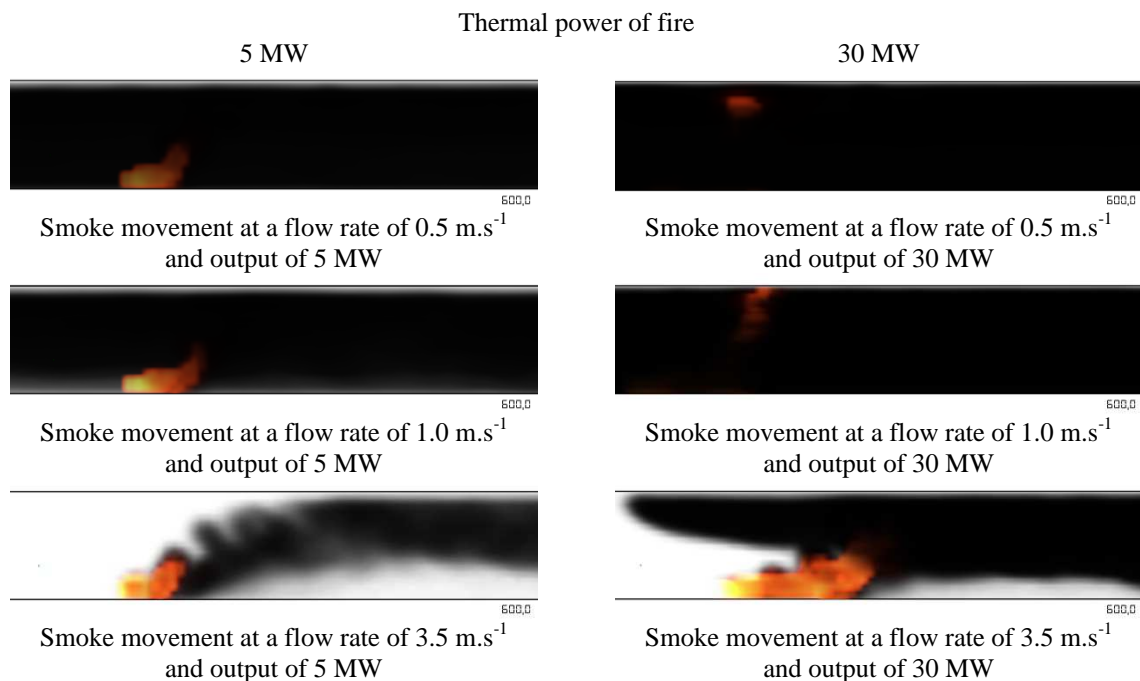


Fig. 3. Demonstration of smoke movement near the fire origin at a thermal output of 5 MW and 30 MW

Visibility was evaluated after 100 seconds, 200 seconds, 300 seconds, 400 seconds, 500 seconds, and 600 seconds after the fire's development. The decrease in visibility for a fire heat output of 5 MW in relation to the simulated time and tunnel position is shown in Figures 4 to 12 (the source of fire is indicated by the red dashed line).

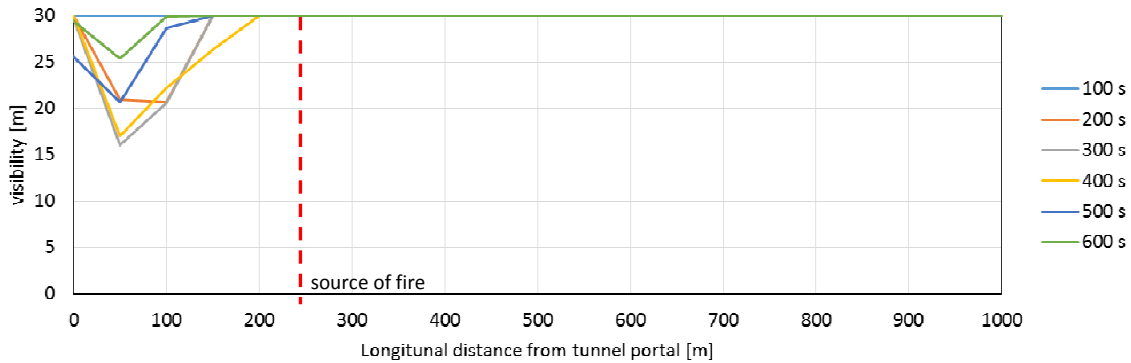


Fig. 4. Visibility without ventilation in relation to simulated time and position in the tunnel

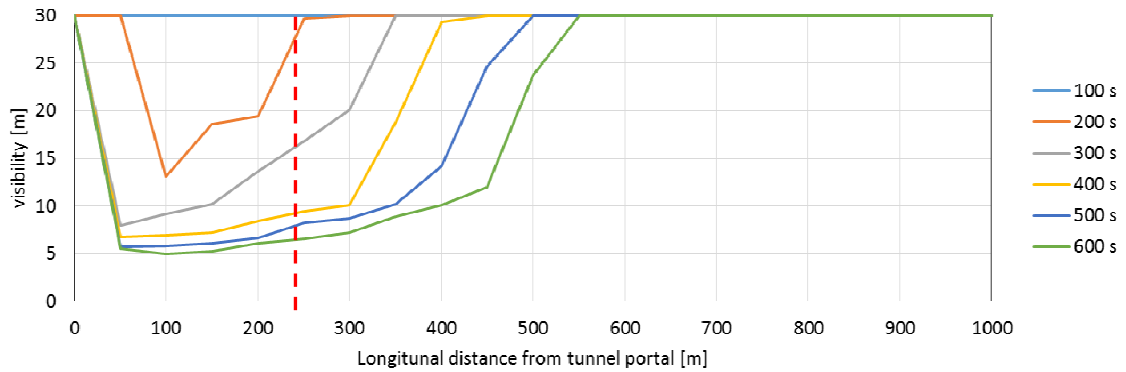


Fig. 5. Visibility for the flow rate of 0.5 m.s⁻¹ in relation to simulated time and position in the tunnel

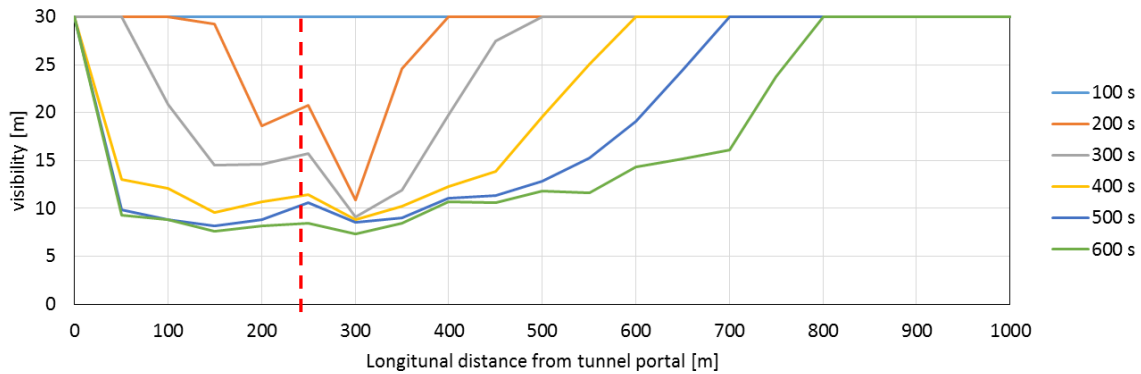


Fig. 6. Visibility for the flow rate of 1.0 m.s⁻¹ in relation to simulated time and position in the tunnel

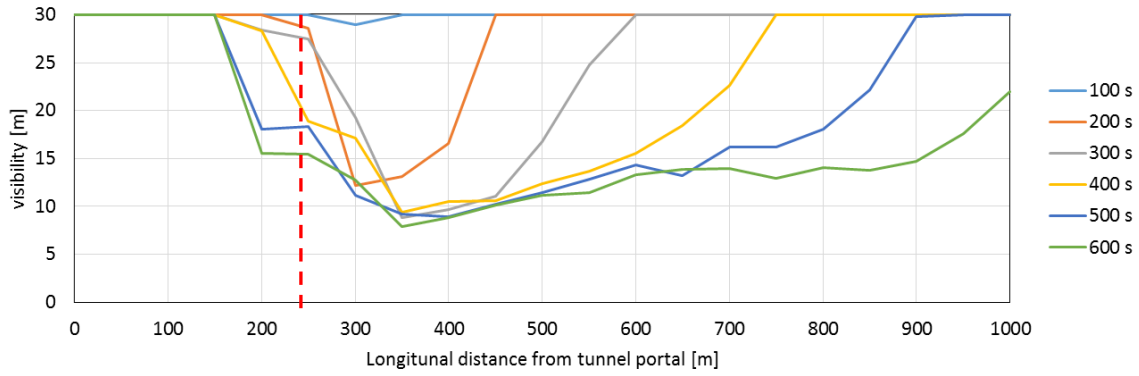


Fig. 7. Visibility for the flow rate of 1.5 m.s⁻¹ in relation to simulated time and position in the tunnel

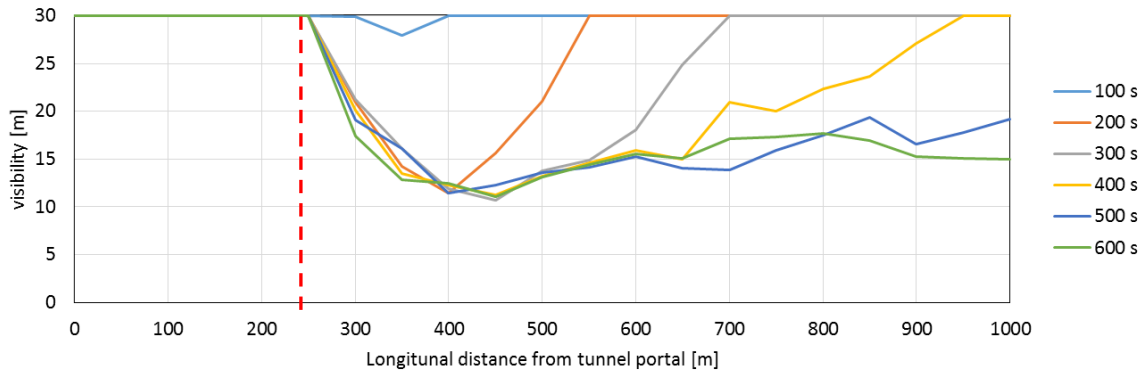


Fig. 8. Visibility for the flow rate of 2.0 m.s⁻¹ in relation to simulated time and position in the tunnel

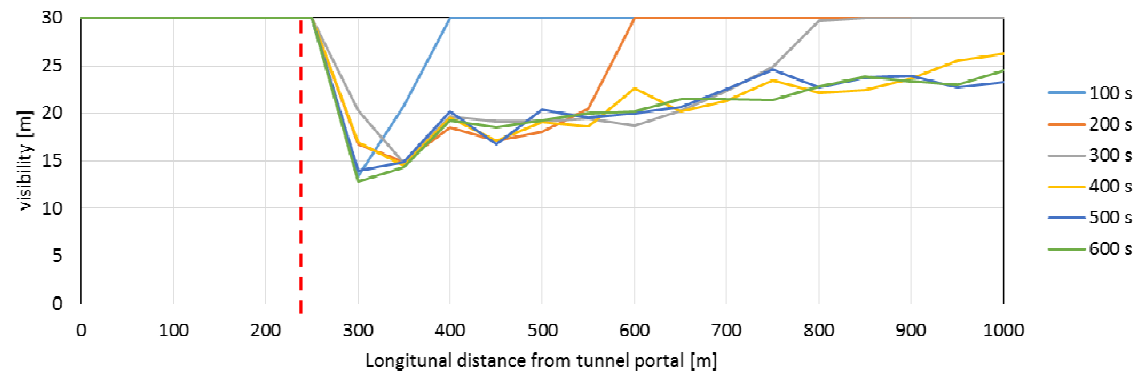


Fig. 9. Visibility for the flow rate of 2.5 m.s⁻¹ in relation to simulated time and position in the tunnel

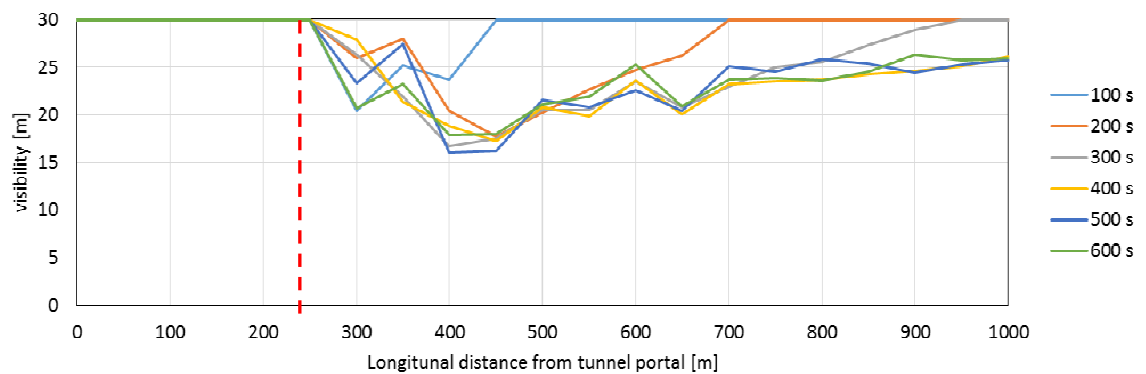


Fig. 10. Visibility for the flow rate of 3.0 m.s⁻¹ in relation to simulated time and position in the tunnel

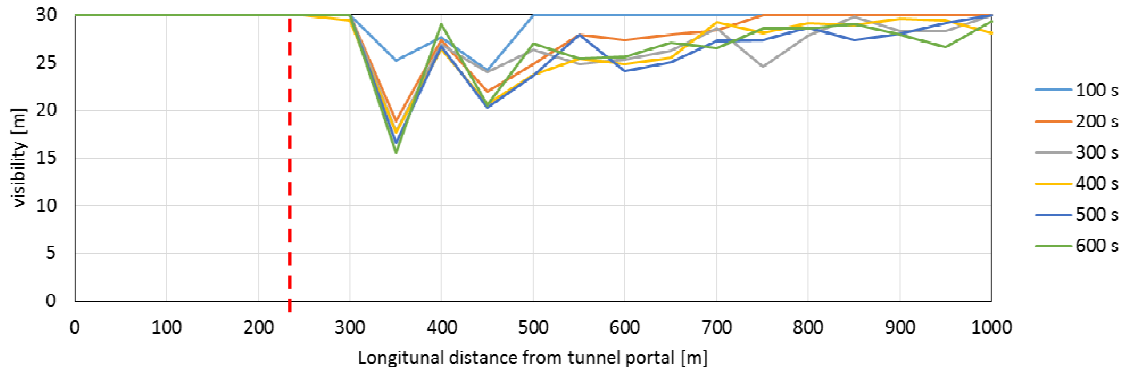


Fig. 11. Visibility for the flow rate of $3.5 \text{ m}\cdot\text{s}^{-1}$ in relation to simulated time and position in the tunnel

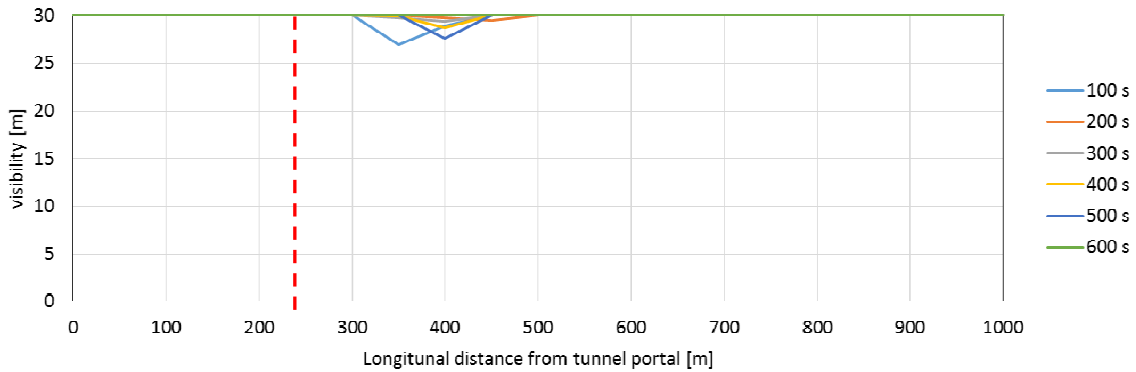


Fig. 12. Visibility for the flow rate of $5.0 \text{ m}\cdot\text{s}^{-1}$ in relation to simulated time and position in the tunnel

The decrease in visibility present during a fire heat output of 30 MW in relation to simulated time and position inside the tunnel is shown on Figure 13 to 21 (the source of fire is indicated by the red dashed line).

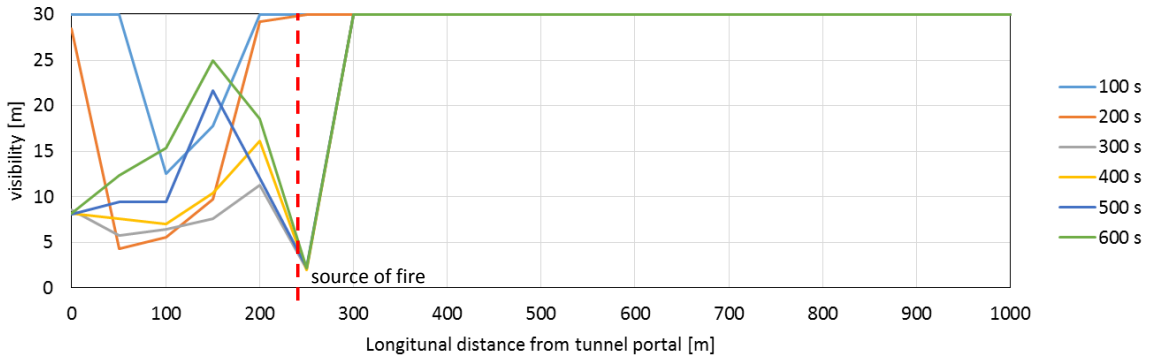


Fig. 13. Visibility without ventilation in relation to simulated time and position in the tunnel

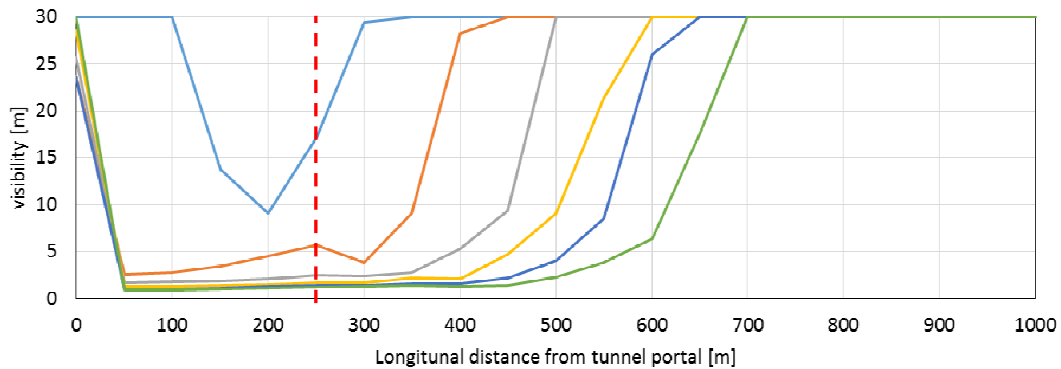


Fig. 14. Visibility for the flow rate of $0.5 \text{ m}\cdot\text{s}^{-1}$ in relation to simulated time and position in the tunnel

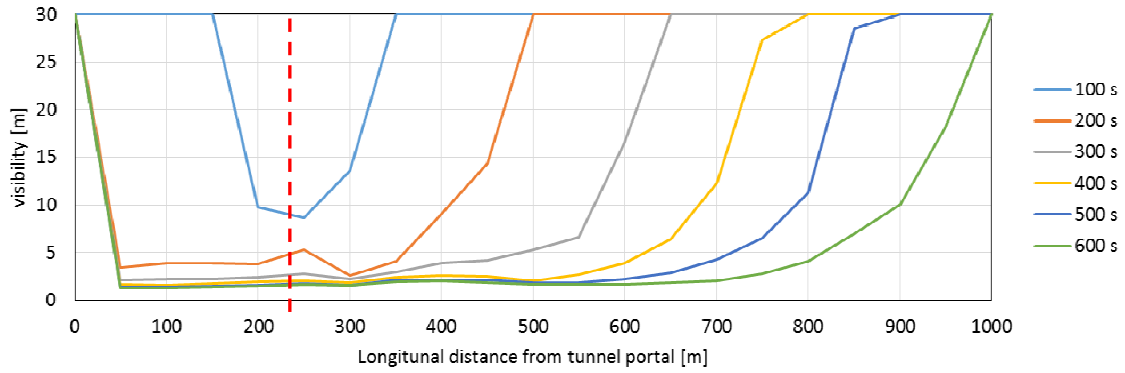


Fig. 15. Visibility for the flow rate of $1.0 \text{ m}\cdot\text{s}^{-1}$ in relation to simulated time and position in the tunnel

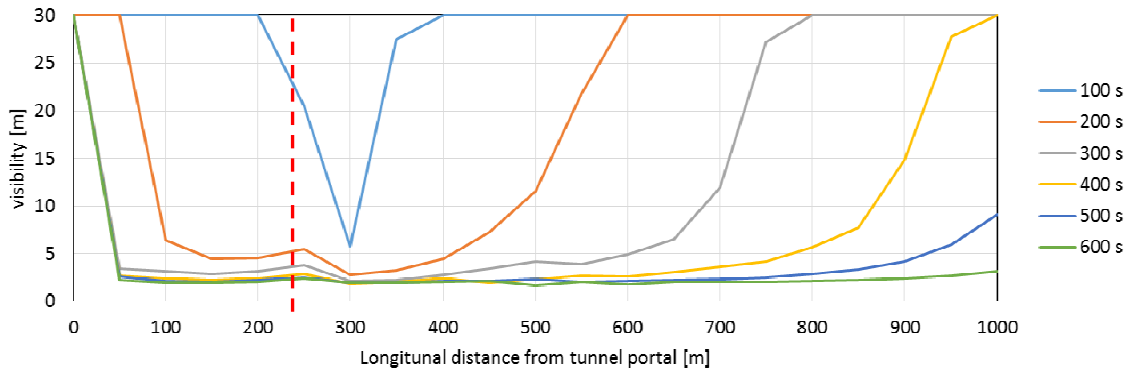


Fig. 16. Visibility for the flow rate of $1.5 \text{ m}\cdot\text{s}^{-1}$ in relation to simulated time and position in the tunnel

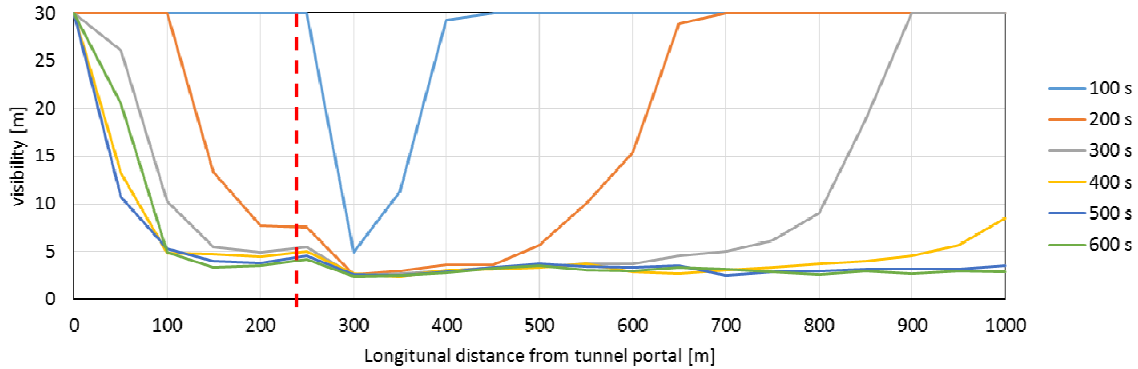


Fig. 17. Visibility for the flow rate of $2.0 \text{ m}\cdot\text{s}^{-1}$ in relation to simulated time and position in the tunnel

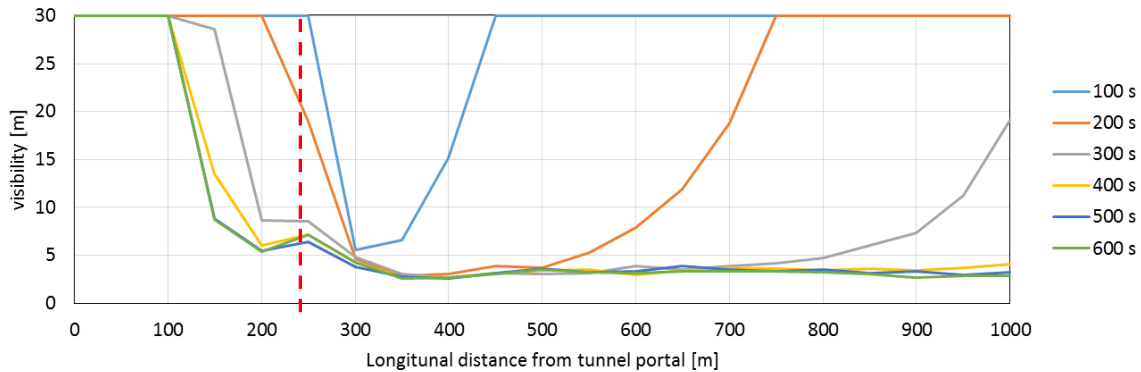


Fig. 18. Visibility for the flow rate of $2.5 \text{ m}\cdot\text{s}^{-1}$ in relation to simulated time and position in the tunnel

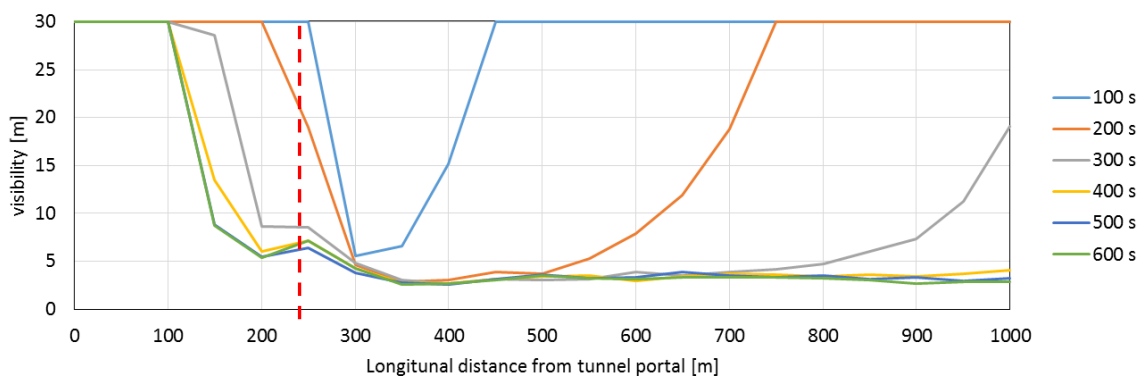


Fig. 19. Visibility for the flow rate of $3.0 \text{ m}\cdot\text{s}^{-1}$ in relation to simulated time and position in the tunnel

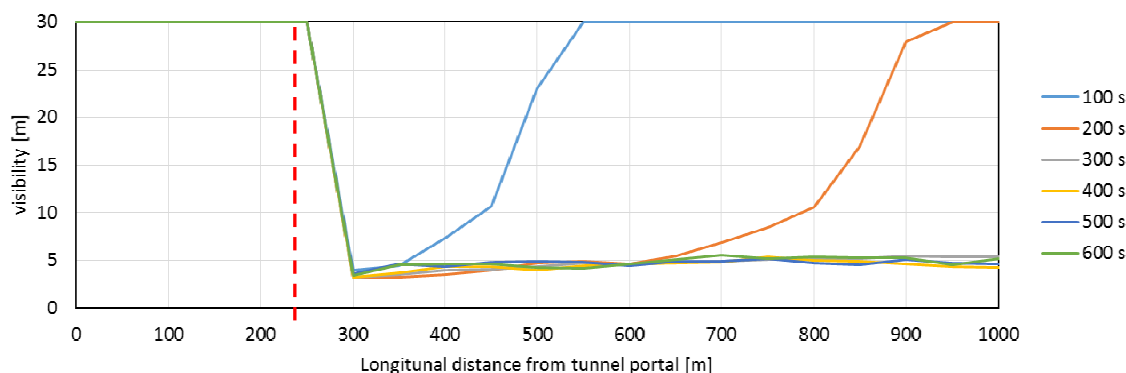


Fig. 20. Visibility for the flow rate of $3.5 \text{ m}\cdot\text{s}^{-1}$ in relation to simulated time and position in the tunnel

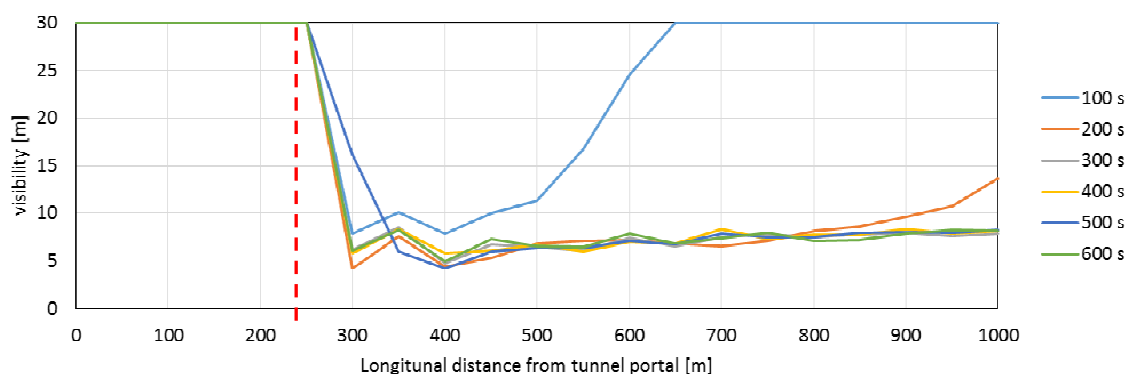


Fig. 21. Visibility for the flow rate of $5.0 \text{ m}\cdot\text{s}^{-1}$ in relation to simulated time and position in the tunnel

Results and Discussion

The Fire Dynamics Simulator model is a perspective model that has had a long development and been tested on real fires. It is used in a wide range of fire situations and considered suitable for tunnels (Mozer, 2013).

In the case study, the point of origin of the fire at a distance of 256 m from the more elevated portal in the direction of the flow of longitudinal ventilation (the first third of the tunnel) correlated strongly with smoke stratification observed along significant sections of the tunnel's tube (the remaining approximate two-thirds of the tunnel).

Heat outputs of 5 MW and 30 MW were considered for the case study. Although the heat output selected for the tunnel's fire ventilation design could be higher, the most common design value is 30 MW. The lower heat output value for evaluating smoke stratification in a tunnel represents an auxiliary situation in the context of the case study. A discussion on the variability and uncertainty of fire designs is given by (Kadic and Mozer, 2017).

From Table 1, which describes the required air velocity values for longitudinal ventilation, it is apparent that in unidirectional tunnels with higher congestion rates and in bidirectionally operating tunnels, it is generally

required to reduce the air velocity (below the critical velocity 1.2 - 1.5 m.s⁻¹). In unidirectional tunnels with a lower incidence of congestion, it is usually required to reach critical rates (usually in the range of 2.5 - 3.5 m.s⁻¹).

In order to provide complete information, the simulation was also run for an airflow rate of 5 m.s⁻¹.

Smoke stratification was evaluated according to visibility, the limit criterion being the decrease of visibility to 15 m. On the basis of the given assumptions, the distance of moving individuals to a safe distance was approximately 75 m.

Table 2 shows the distance in relation to heat output, during which the airflow rate and time of fire development saw a decrease in visibility in the tunnel to 15 m or less (critical visibility level). The distances are given for time periods of 300 s and 600 s. These were representative periods that clearly showed the measured results.

Table 2. Comparison of the distance of smoke spread along the tunnel to heat output

Airflow rate [m.s ⁻¹]	Distance in the tunnel with visibility less than 15 m [m]			
	Fire heat output 5 MW		Fire heat output 30 MW	
	Time of fire development [s]		Time of fire development [s]	
	300	600	300	600
0.0	0	0	250	435
0.5	195	460	435	615
1.0	300	610	585	980
1.5	220	650	700	975
2.0	305	275	745	925
2.5	5	60	790	870
3.0	0	0	725	735
3.5	0	0	720	720
5.0	0	0	720	720

The distances of the decrease to critical visibility shown in Table 2 are charted in Figure 22.

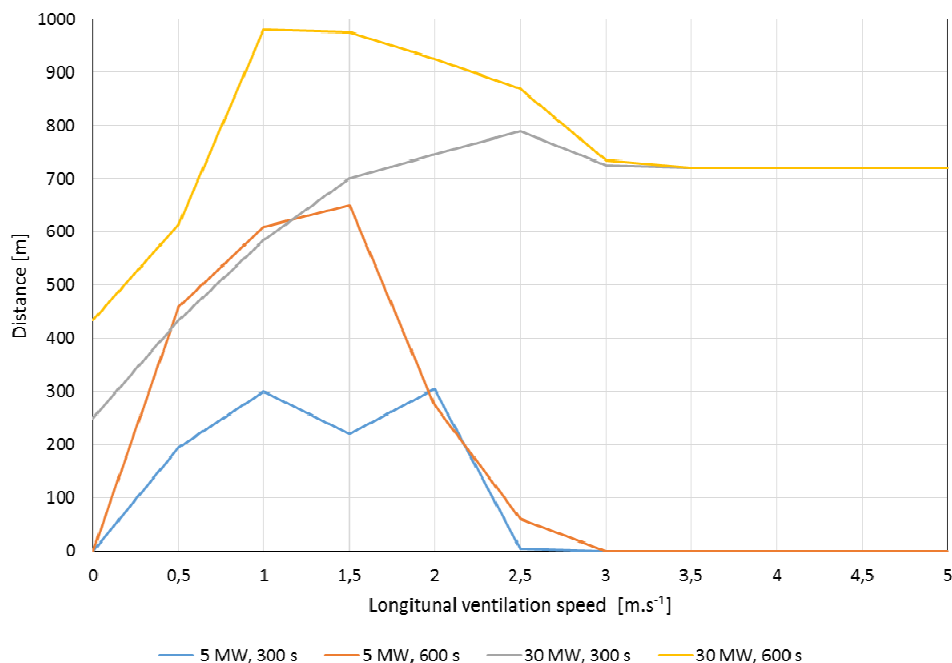


Fig. 22. Distance in the tunnel with visibility less than 15 m

Tables 2 and Figure 22 show that with a heat output of the fire of 5 MW, the distance of tunnel with a decrease to the level of critical visibility attained for a distance greater than 75 m for the airflow rate 0.5 to 2 m.s⁻¹. It is, therefore, a lower airflow rate. When the ventilation was not operating (air velocity is 0.0 m.s⁻¹) and with higher airflow rates, the visibility in the tunnel was satisfactory.

A different situation arose with a heat output of 30 MW. For all airflow rates, the threshold of critical visibility was crossed at a distance greater than 75 m. However, the results partially varied between the 300 s and 600 s periods. In the 300 s period, critical visibility distances were less when ventilation was not used and during

very low airflow rates (up to $1 \text{ m}\cdot\text{s}^{-1}$). In the 600 s period, the shortest critical visibility distances were achieved when ventilation was not used and during very low airflow rates (up to $0.5 \text{ m}\cdot\text{s}^{-1}$) and during high flow rates.

The results of the simulation show that airflow rates less than the critical rates did not lead to improving the conditions for evacuating people. In this way, it is debatable, whether the strategy of longitudinal ventilation, which is used in unidirectional tunnels with high congestion probability and bidirectional tunnels, where there are lower airflow rates designed than is the critical rate, is justifiable.

This is mainly caused by the gradient of the tunnel and the ongoing fire. With a heat output of 30 MW, smoke was channelled in the main direction of the flow of the ventilators during flow rates of up to $3.5 \text{ m}\cdot\text{s}^{-1}$. This is a predictable phenomenon characteristic for airflow rates less than the critical air flow rate.

Figures 4 to 21 also show that over the course of the simulation (i.e., an uninterrupted development of fire), visibility inside the tunnel decreased and therefore deteriorated the conditions for evacuating and rescuing people. Therefore, it is important to decrease the time for evacuating and rescuing people as much as possible.

The results achieved by the case study were partly affected by the tunnel's design (e.g., dimensions, and gradient) and choice of point of fire origin (e.g. location, size, heat output). The Klimkovice tunnel examined in this case study can, however, be considered a typical tunnel in terms of design and technical equipment.

Conclusion

Road tunnel safety is currently a widely discussed issue. One of the most significant items of safety equipment is ventilation, which also ensures safety during a fire. One type of ventilation is longitudinal tunnel ventilation. The strategy of longitudinal tunnel ventilation depends on the characteristics of the tunnel according to its direction of traffic (one-way or two-way) and the probability of congestion. In one-way operated tunnels with a high probability of congestion and two-way tunnels, the selected airflow rates are less than the critical air flow rate.

The case study, however, illustrates that with low fire heat output, smoke stratification is interrupted along a significant length of the tunnel. With higher airflow rates, the results are more favourable. Higher values of heat flux show similar results in terms of smoke stratification.

The positive effect of lowering airflow rate below the critical value in terms of retaining smoke stratification is therefore debatable.

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References

- Annexe n° 2 (2000). Annexe n° 2 à la circulaire interministérielle n° 2000- 63 du 25 août 2000 relative à la sécurité dans les tunnels du réseau routier national - Instruction technique relative aux dispositions de sécurité dans les nouveaux tunnels routiers (conception et exploitation).
- ASTRA 13001 (2008). Tunnel ventilation, Design, design and equipment, ASTRA 13001 [online]. Bundesamt für Strassen Astra. 2.03 vyd. Bern, 2008. Available from: www.astra.admin.ch.
- ČSN 73 0804 (2010). Fire Protection of Buildings – Industrial Buildings. Prague: Czech Office for Standards, Metrology and Testing.
- ČSN 737507 (2013). Design of Road Tunnels. Prague: Czech Office for Standards, Metrology and Testing.
- ČSN EN 31010 (2011). Risk Management – Risk Assessment Techniques. Prague: Czech Office for Standards, Metrology and Testing.
- ČSN ISO 31000 (2018). Risk Management – Principles and Guidelines. Prague: Czech Office for Standards, Metrology and Testing.
- ČSN P CEN/TR 12101-5 (2008). Smoke and Heat Control Systems - Part 5: Guidelines on Functional Recommendations and Calculation Methods for Smoke and Heat Exhaust Ventilation Systems. Prague: Czech Office for Standards, Metrology and Testing.
- DMRB (1999). Design manual for road and bridges. Design of road tunnels. Highway structures: Design (substructures and special structures) material. Special structures. Volume 2 Section 2 Part 9 (BD 78/99). London: The Highways Agency.
- European Parliament Directive 54/ES. (2004). On minimum safety requirements for tunnels in the Trans-European Road Network [WWW Document], n.d. EUR-Lex. URL <https://eur-lex.europa.eu/legal-content/CS/TXT/PDF/?uri=CELEX:32004L0054&from=CS> (accessed 4.19.19).

- Fire Dynamics Simulator (2019). FDS-SMV [WWW Document]. URL <https://pages.nist.gov/fds-smv/> (accessed 3.22.19).
- Folwarczny, L., Pokorný, J. (2006). Evacuation of People. Ostrava: Association of Fire and Safety Engineering. ISBN 978-80-86634-92-0.
- Government Regulation No. 264/2009 Coll., on Safety Requirements for Road Tunnels Longer than 500 Meters [WWW Document], n.d. Laws for people. URL <https://www.zakonyprolidi.cz/cs/2009-264/zneni-20090901> (accessed 7.2.17).
- Government Regulation No. 344/2006 Coll., on Minimum Safety Requirements for Road Network Tunnels [WWW Document], n.d. URL <https://www.slov-lex.sk/pravne-predpisy/SK/ZZ/2006/344/20060601> (accessed 4.19.19).
- Haukur Ingason, Li, Y.Z., Lönnemark, A. (2015). Tunnel Fire Dynamics. Springer, New York. 504 s. ISBN 978-1-4939-2198-0.
- Hosser, D. (2013). Guidelines for Fire Protection Engineering, Technical Report TB 04/01., 3rd revised and amended edition. Technical-Scientific Advisory Board (TWB) of the Association for the Promotion of German Fire Protection e.V. (vfdb), Braunschweig. 419 p. Available from: <http://www.kdbrandschutz.de/files/downloads/Leitfaden2013.pdf>.
- Huijben, J.W., Fournier, P., Rigter, B.P. (2006). Aanbevelingen ventilatie van verkeerstunnels. Ministerie van Verkeer en Waterstaat, Rijkswaterstaat, Bouwdienst (RWS, BD), Utrecht.
- Hurley, M. (2015). SFPE handbook of fire protection engineering. Springer Science+Business Media, New York, NY. 2015. ISBN 978-1-4939-2564-3.
- ISO 16733-1 (2015). Fire safety engineering - Selection of design fire scenarios and design fires - Part 1 Selection of design fire scenarios. Geneva: International Organization for Standardization, Geneva, p. 31.
- Kadlic, M., Mozer, V. (2017). Uncertainties Associated with Tunnel Design Fire Scenarios. Procedia Engineering [online]. Dostupné z: doi:10.1016/j.proeng.2017.06.067.
- Kročova, Š. (2015). Protection of aquatic ecosystems against accidents in the Czech Republic. Inžynieria Mineralna. 2015, vol. 36, n. 2, pp. 225-230. ISSN 1640-4920.
- Kučera, P., Kaiser, R., Pavlík, T., Pokorný, J. (2009). Fire Engineering: Fire Dynamics. Ostrava: Association of Fire and Safety Engineering. 152 p. ISBN 978-80-7385-074-6.
- Manual 021 (2004). Road Tunnels 03.04. Norwegian Public Roads Administration.
- Marasová, D., Taraba, V., Grendel, P. (2010). Legislation and its Requirements for Tunnel Safety. Acta Montanistica Slovaca. Košice: Technical University of Košice. 15, p. 9–13.
- Ministry of Transport, Department of Roads (2013). Methodological Instruction. Ventilation of Road Tunnels. Choice of System, Design, Operation and Quality Assurance of Road Tunnel Ventilation Systems. Ministry of Transport, Department of Roads. [WWW Document]. URL http://www.pjpk.cz/data/USR_001_2_11_METODICKE_POKYNY/MP_vetrani_20132.pdf (accessed 7.2.17).
- Mozer, V. (2013). Modelling fire severity and evacuation in tunnels. Communications: scientific letters of the University of Žilina. 15(4), 85–90. ISSN 1335-4205.
- NFPA 502 (2017). Standard for Road Tunnels, Bridges, and Other Limited Access Highways, n.d. National Fire Protection Association, p. 72.
- Pokorny, J., Gondek, H. (2016). Comparison of theoretical method of the gas flow in corridors with experimental measurement in real scale. Acta Montanistica Slovaca. 21, 146–153. ISSN 1335-1788.
- Pokorny, J., Malerova, L., Wojnarova, J., Tomaskova, M., Gondek, H. (2018). Perspective of the use of road asphalt surfaces in tunnel construction, in: 22nd International Scientific on Conference Transport Means 2018. Presented at the Transport Means - Proceedings of the International Conference, Lithuania, ISSN 1822296X, pp. 290–296.
- RABT, 2006. Guidelines for equipment and operation of road tunnels. Köln: Forschungsgesellschaft für Straßen- und Verkehrswesen e.V.
- Regulation (EU) No 305. (2011). Laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC Text with EEA relevance, 2011. URL <https://eur-lex.europa.eu/legal-content/CS/TXT/PDF/?uri=CELEX:32011R0305&from=CS>.
- RVS 09.02.31, 2008. Tunnel Ventilation - Basic Principles. Austrian Research Association for Roads, Rail and Transport.
- STN 737507 (2008). Design of Road Tunnels. Bratislava: Slovak Office for Standards, Metrology and Testing.
- Tomašková, M., Vargová, M. (2018) Risk analysis of firefighting lifts and safety rules. In: New Trends in Process Control and Production Management. London: Taylor and Francis Group, 2018 S. 555-560. ISBN 978-1-138-05885-9.
- TP 049, 2018. Technické podmienky vetrania cestných tunelov TP 049. Bratislava: Ministry of Transport and Construction of the Slovak Republic Section of Road Transport and Roads.

- Yang, X. (2016). Design Environmental Protection, Energy Saving and Safety Ventilation System of Long Highway Immersed Tunnel. *Procedia Engineering* 166, 32–36.
<https://doi.org/10.1016/j.proeng.2016.11.533>.
- World Road Association | PIARC [WWW Document] (2019) URL <https://www.piarc.org/en/> (accessed 4.21.19).