UPGRADE OF A TRANSVERSE VENTILATION SYSTEM IN A BI-DIRECTIONAL TUNNEL

by

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The Karavanke tunnel forms an important link between Slovenia and Austria. The almost 8 km long tunnel is operated with bi-directional traffic and does not have dedicated escape routes. Moreover, the ventilation in case of fire does not satisfy requirements of the EU Directive 2004/54/EC that specifies the minimum requirements for tunnels in the trans-European road network. The paper present results of the research conducted regarding the possibility of upgrade the existing system in order to reach the required level of safety at lower costs possible. It is shown that with simple but novel adaptations of the ventilation system, a sizeable increase in the overall level of safety can be achieved. The methodology applied is a combination of a simple pipe model for tunnel ventilation and for detailed fluid dynamics analysis the computational fluid dynamics model is used. The existing ventilation system that in fire ventilation extracts smoke from a single duct is replaced with the smoke extraction from both ducts applying four axial fans. The analysis is focused on air/smoke flow through the vents and ducts and on pressure drops calculated over the length of the ventilation duct and its influence on the total flow. The change of the flow condition also has influence on ventilation fan operation point that is investigated in the paper as well.

Key words: *tunnel safety, computational fluid dynamics simulation, pipe model, ventilation, fire safety*

Introduction

Accidental combustion and fire modelling are attractive research topics, from the academic and from the technical point of view: in fact, while many physical phenomena related to fires are still very far from being completely translated into formulas, their full understanding is highly desirable in order to prevent fires and, more important, to plan safety procedures and rescue operations in case of fire. In particular, fire modelling in enclosures (such as railway or road tunnels) is a challenging research area with immediate practical benefits on human safety. Since closed analytical solutions are possible only in very simple cases, and experiments are often hazardous and cause material damage, recent developments received substantial contributions from the tools of computational fluid dynamics (CFD); on the other hand, theoretical approaches allow writing of improved algorithms for CFD codes, and experiments provide a large amount of information useful in tuning the code parameters [1].

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Longitudinal ventilation systems are characterized, if compared with more elaborated systems, by significantly lower investment, maintenance, and exploitation costs. Their use became more and more widespread in the recent past, in particular because of the significant reduction of motor vehicle emissions [2, 3].

The described fire model presents behaviour of fire and smoke in a road tunnel. The most interesting is the effect of air supply and exhaust system on smoke movement. Does the ventilating system accelerate or choke fire and what is the optimum ventilation regime? The correct procedure for ventilation fan operation in case of fire accident plays the most important role to ensure the longest possible evacuation time as stated by Petelin *et al.* [4] and requested by national regulations [5, 6]. This is important information for people evacuation planning.

Transverse ventilation system

Here the ventilation system in the Karavanke tunnel is shown in normal and in fire regime operation. There is also an efficiency analysis of the fire ventilation in the existing state and also with the foreseen upgraded system.

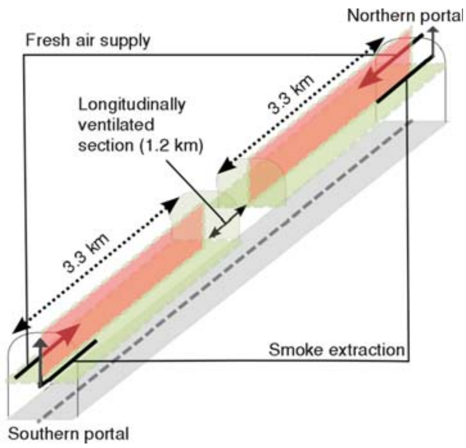

Figure 1. The south portal of the Karavanke tunnel with the air intake in the tunnel in the horizontal direction and the air or smoke exhaust through the chimney in the vertical direction

In fig. 1 description of current ventilation system can be seen. It is comprised of a combination of transversally ventilated sections and of a longitudinally ventilated section located in the middle of the tunnel.

For the Karavanke tunnel ventilation review and analysis needs, a new insight in the entire comprehensive project documentation in the archives of the Karavanke tunnel centre in Hrušica was necessary. We limited ourselves mostly on a documentation that relates to certain Karavanke tunnel project documentation in the archives that should serve for the conclusion of work on the project of a possible reconstruction of the Karavanke tunnel.

Air flow measurements on individual grate sets were first carried out on October 2008, then a second time on June 2009 (fig. 2). A comparison of the measurements with the year 2008 shows a considerable improvement in the results, because some leak problems have been solved. The grey coloured data in fig. 2 should represent the leakage of the exhausting channel itself of the Karavanke tunnel and the leak of grates installed behind the grate set where the measurements were performed.

The extraction blind is about 1/3 open while in normal operation. The extraction ventilator with the electric motor in the south portal used to have 450 kW of power. Namely, there is no limitation in frequency revolution regulation because it is built for electric power of around 800 kW. The actual ventilation gain and pressure loss will have to be estimated for measurements data. In the middle of the tunnel there are still $3 \times 8 = 24$ axial fans on the ceiling, each of 85 kW electric powers. In the exhaust channel there is still a vertical blind and sound dampers as an obstacle to the air flow and it presents a pressure loss (Karavanke tunnel, [7, 8]). The exhaust

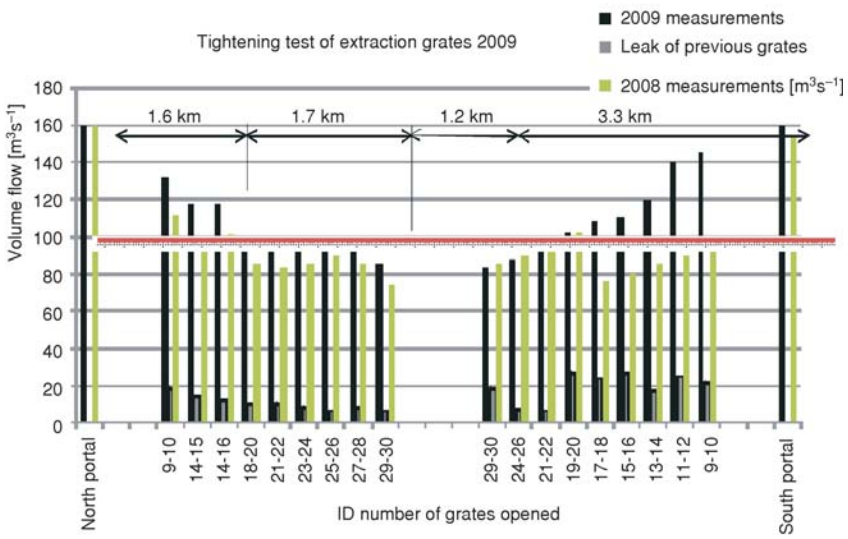

Figure 2. Air flow measurements on individual numbered grate sets. The black colour represents the air flow in front of the grate and the grey colour behind the grate measurements from 2009)

channel diverts through an angle into the vertical chimney in the portal (fig. 1). It is necessary to estimate the loss of the angle and the chimney itself – the vertical channel. It is similar in the intake channel, only the fresh air enters horizontally. The present ventilators have a variable rotational speed but they are not reversible.

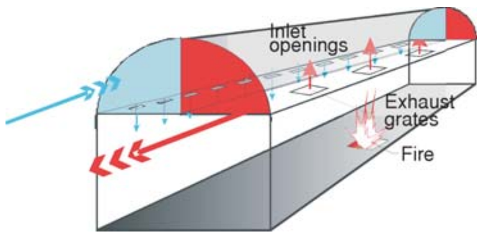

Figure 3. Overview of Karavanke tunnel ventilation system

The main reason of leakage is the construction and the maintenance of grates itself. We can see on that the leakage could be reduced by appropriate maintenance. Although the improvements are consistent the ventilation could not guarantee the desired extraction flow rate, required for different sources of fire strength.

Upgrade of fire ventilation

The new concept of ventilation in the Karavanke tunnel is proposed by the authors Brandt *et al.* [9]. They propose connecting the south and the north fresh air and waste air channels. Consequently the longitudinal ventilation in the middle section of the tunnel is abolished for the length of 1200 m (fig. 3). With this step, suction would be made possible in both directions of the tunnel at the same time and from any location in the tunnel. The proposers advocate that this upgrade will make tunnel compliant with today's safety standards and the EU Directive 2004/54/EC demands, will reduce energy consumption and assure ventilation system redundancy [10, 11].

It is important to point out that the proposed change originates mainly from the need for ventilation in case of a fire in the tunnel and based on the proposal of Brandt *et al*. [9] it assures a grater smoke suction effect. The authors anticipate connecting of the fresh air ventilation channel, closing of the side ventilation openings and installation of new grates on every 50 m. The fresh air channel could be also used for smoke extraction in case of fire by reversing the blades on the fan rotors.

The ventilation system proposal is comprised of two versions:

Version 1: Connection of the north and south extraction channel with the extraction regime in both directions, and

Version 2: Connection of both channels via a new opening (flap) in the dividing wall of the two channels.

Avoiding the specifics of different construction versions, with more or less mechanisms, we should mainly focus on the possibility of the existing ventilation channels to allow the extraction of smoke enough to achieve required safety levels. Assuming this the second version is not analysed. Instead of this in the next chapters the analyses is focused on the first proposal that is the connection of northern and southern extraction duct. The second, the connection of both northern and southern ducts is simulated, for ventilation engaging all four ventilators on portals in the extraction regime [12, 13].

Analysis of the transverse ventilation

An analysis of the connected ventilation channels, that follows, deals with the suction effect on the extraction grates regarding the location of the suction and the influence of the channel connection to the ventilation fan operation. The analysis has been carried out without considering the suction grate leakage and by taking it into account as well.

Performed verification calculations of the fire ventilation system parameters according to the new proposals follow are analysed according the following presumptions:

– union of the north and south fresh air channel and the smoke suction channel,
– smoke suction to the north and south side of the tunnel,
– extraction only through the smoke channel,
– extraction through both channels,
– two open suction grates in the smoke suction channel before and after the fire location – the grate on the location of the fire is closed, and
– four open grates in the fresh air delivery channel that in case of fire should be used for the extraction of the smoke (the grates for the fresh air intake are 50 m apart from each other).

Goals of the analysis:

– determine the flows in the suction grates in dependence to the fire location, and
– determine the operational points of the ventilators with and without taking into account the leakage of the grates and smoke dynamics in the operation of the new fire extraction regime.

Pipe model of the ventilation duct

The model is based on Darcy-Weisbach equation applied for laminar and turbulent flows:

$$\frac{\Delta p}{\rho \mathrm{g}} = h_\mathrm{L} = f\,\frac{L}{D}\,\frac{w^2}{2\mathrm{g}} \tag{1}$$

where Δp is the pressure drop, h_L – the head losses, f – the friction factor, L – the length of the pipe, D – the hydraulic diameter, and w – the velocity of the flow.

The friction factor is further calculated with the known Colebrook equation [14]:

$$\frac{1}{\sqrt{f}} = -0.86 \ln\left(\frac{e}{3.7D} + \frac{2.51}{\text{Re}\sqrt{f}}\right) \tag{2}$$

where e is the surface roughness and Re – the Reynolds number.

From this the equation of the total pressure loss in the ventilation duct could be derived. Depending on the air flow there are three main losses influencing the total pressure drop; pressure drop along the ventilation duct, pressure drop along the tunnel, and the pressure drop on the two extraction grates:

$$p(\dot{V}) = \frac{\rho}{2}\left[\left(f_1 \frac{L}{D_1} + K_{\text{out}}\right)\left(\frac{\dot{V}}{A_1}\right)^2 + \left(f_2 \frac{L}{D_2} + K_{\text{in}}\right)\left(\frac{\dot{V}}{A_2}\right)^2 + 2K_{\text{R}}\left(\frac{2\dot{V}}{A_{\text{R}}0.9}\right)^2\right] \tag{3}$$

where $\dot{V}$ is the volume flow, K_R – the loss coefficient for the suction grate, K_{out} – the loss coefficient at the exit side of the ventilator, and K_{in} – the loss coefficient of the incoming flow from portals. The pressure drop caused by the heat looses due to the curve in the transition to the exhaust funnel is neglected in the model.

CFD model background

The fluid flow is modelled by solving the basic conservation equations. Those are conservation of mass, eq. (4), conservation of mixture fraction, eq. (5), conservation of momentum, eq. (6), and conservation of energy, eq. (7) using a form for low Mach number [15, 16]. The approximation involves the filtering out of acoustic waves.

$$\frac{\partial \rho}{\partial t} + \nabla \rho \vec{\text{u}} = 0 \tag{4}$$

$$\frac{\partial \rho}{\partial t}(\rho Z) + \nabla \rho Z \vec{\text{u}} = \nabla \rho \text{D} \nabla \text{Z} \tag{5}$$

$$\rho\left(\frac{\partial \vec{\text{u}}}{\partial t} + \frac{1}{2}\nabla|\vec{\text{u}}|^2 - \vec{\text{u}} \times \omega\right) + \nabla \tilde{p} = (\rho - \rho_\infty)\text{g} + \nabla \boldsymbol{\tau} \tag{6}$$

$$\rho c_p\left(\frac{\partial T}{\partial t} + \vec{\text{u}}\nabla T\right) = \dot{q}_c^m - \nabla \vec{\text{q}}_\text{R} + \nabla k \nabla T \tag{7}$$

where ρ is the density, $\vec{\text{u}}$ – the velocity vector, Z – the mixture fraction, T – the temperature, and D – a molecular diffusivity. $\tilde{p}$ is the perturbation pressure caused by pressure differences, τ – the viscosity stress tensor, and k – the thermal conductivity. $\dot{q}_c^m$ and $\nabla \vec{\text{q}}_\text{R}$ are the source terms of chemical reaction and radiation, respectively. The radiation term has a negative sign because it represents a heat sink.

The effect of the flow field turbulence is modelled using large eddy simulation (LES), in which the large scale eddies are computed directly and the sub-grid scale dissipative processes are modelled. The unknown sub-grid stress tensor τ is modelled by Smagorinsky model. Further the combustion model is based on the assumption that the combustion in mixing-controlled. This implies that all species of interest can be described in terms of the mixture fraction *Z*. Heat from the reaction of fuel and oxygen is released along an infinitely thin sheet where *Z* takes on its stoichiometric value as determined by the solution of the transport equation for *Z*. The state relations are calculated for a stoichiometric reaction of C_7H_{16} (oil), which is proposed by McGrattan *et al*. [16] and Heskestad [17], and called a Crude-oil reaction.

Heat release and soot formation

In order to calculate the radiation accurately, soot must be considered. Due to the extreme complexity of soot formation process, no very good model is currently available for soot prediction in the combustion of solid fuel. In this paper the soot was considered by assuming a constant soot conversion factor, 10%. The soot formation rate was simply assumed to be proportional to the fuel supply rate. The fire is assumed a heat release source with a specific power of 1800 kW/m^2, where the oxygen and fuel consumption and the release of combustion products depend on the stoichiometric equation $11O_2 + C_7H_{16} \rightarrow 7CO_2 + 8H_2O$. Here C_7H_{16} is a heptane, which burns very similar to a crude-oil just with less soot release. Soot release is additionally added to the combustion model. The model includes other combustion products (H_2, N_2, H_2O, O_2, ...) that are default considered and are not matter of our research.

Detailed description of hydrodynamic, thermodynamic, and combustion model is explained in the McGrattan *et al.* [16] FDS technical manual and will not be repeated here.

Geometry and setup of the model

The geometry, initial, and boundary conditions are arranged to the tunnel geometry and fire parameters. Figure 4 shows the geometry of the tunnel from the external view. The physical size of the domain is 1000 m in length, 10 m wide and 7.8 height. The fire in located 700 m from the south portal and in symmetrical to the cross-section. The applied numerical grid is non-uniform. The geometry is divided in three sections over the tunnel length. The reason is the requirement of the combustion model, which compute the reaction and the heat release in the second section where the fire is located. Other parts of the geometry do not require such a dense grid because of lower velocity gradients. The total number of computational cells is $1.2 \cdot 10^6$.

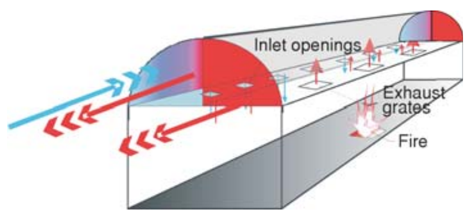

Figure 4. Overview of the proposed solution for fire emergency ventilation

Initial and boundary conditions are divided to geometry obstacle conditions and fluid initial conditions. Walls of the tunnel are defined as thermally thick walls in the model, where heat transfer is computed to and through the walls. The initial temperature of any obstacle is defined the same as ambient (20 °C) temperature. The velocity beside the wall is calculated as the average value of the velocity in the first cell touches the wall and zero velocity on the wall cell (zero velocity). Thermal radiation initial conditions are defined with radiation intensity based on the initial temperature of objects (ambient temperature) and the air wavelength that is mostly formed by nitrogen. Heat of radiation emitted from walls is calculated as black wall radiation intensity. The tunnel has 0% slope and portals are defined as open boundary conditions that link the tunnel domain with the ambient [18].

Comparison of results from two models

The first are analysed the operating points of the ventilator with a complete seal of the suction grates and with the opening of two consecutive grates regarding the location of suction is shown in fig. 5. The opening of two grates is a standard procedure that comes from the emergency ventilation procedure. We can see that already after 3000 m of channel the operational point of the ventilator would move into the unstable region.

The real operation deviates from the ideal because of the leakage in the suction grates. Measurements of the leakage from 2009 and real flows in the suction grates are shown in fig. 2. The sealing of grates was still slightly improved in the following years. In spite of this it is clear from the picture that the difference between the flows in the portals on the distance of 3300 m is almost half. Hence it follows that the flow of suction decreases by almost half or less then 80 m^3/s in the middle of the tunnel.

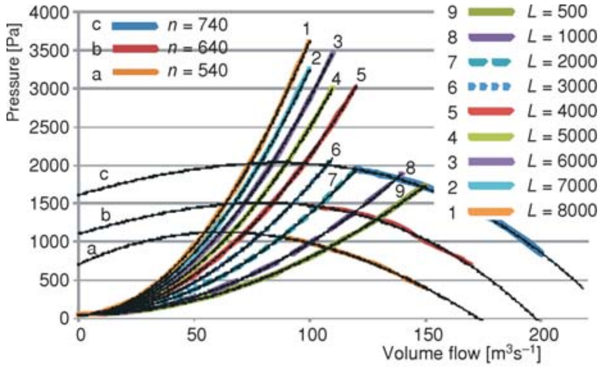

Figure 5. Operational points with complete seal of the suction flaps for different suction locations while one ventilator is working
(color image see on our web site)

The quantity of smoke produced and a minimal required extraction rate is described in tab. 1 and resumed from the German guidelines for the equipment and operation of road tunnels.

Table 1. Smoke production and minimal quantity of extraction by RABT [13]

Heat-release rate [MW]	Smoke-production rate [m^3s^{-1}]	Minimal smoke-extraction rate [m^3s^{-1}]
30	80	120
50	120	180
100	200	300

For a large fire of 50 MW the requited smoke extraction is close to the maximum capacity of a single ventilator installed. Only if the extraction grates would tight perfectly all along the extraction duct a single ventilator should produce enough volume flow. But in practice not a smaller fire could be ventilated as required.

Although ventilators are working as designed, the operational area of the ventilator remains within the characteristic ventilator curve because, mainly because of leakage on grates along the duct. Figure 6 shows the operational area of the ventilator for the extraction distance from 1000 to 7000 m.

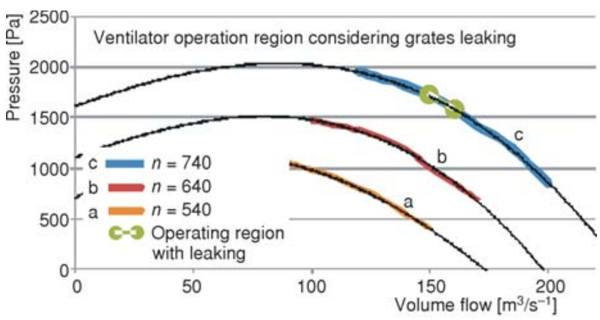

Figure 6. Operational area of the ventilator considering the leakage of the suction grates
(color image see on our web site)

Although the operational area is very narrow and presents relatively

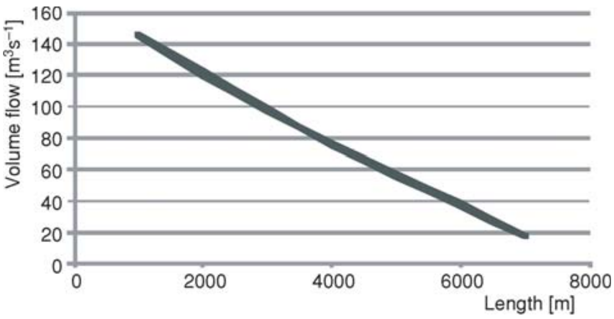

Figure 7. Calculated flows on grates along the tunnel considering grates leaking

large flows, the real extraction effect in the grates along the tunnel is fundamentally different and corresponds to measured data or as calculated and presented in fig. 7. Calculated flows correspond to the measured in fig. 2 and extrapolating the extraction rate on the entire length of the tunnel would results in the extraction on leaking grates rather than on open grates.

As follows some improvements could be reached by better maintenance or replacement of the grates, but also this solution would not give the overall solution. The 1.2 km of tunnel in the mid-tunnel is still ventilated by axial ventilators applied mainly for the velocity reduction of natural ventilation. In case of fire in this mid-tunnel zone the fire ventilation regime does not give required smoke stratification and the zone could be completely exposed to smoke [19].

General findings of the north and south channel union

The union of the north and south ventilation channel means a change in the geometry of the channel for which the now operational ventilators had been dimensioned. In simultaneous operation of both ventilators (north and south) in suction regime, united to the same channel, the operational point of each ventilator changes. Resistances in the channel, in the suction grates and partly also resistances of the air movement in the tunnel, numbers, types and position of vehicles, all influence the operational point of a ventilator. These resistances, except those of vehicles, are considered in the previously presented model that calculates flows in the ventilation channels.

In ideal seal conditions of the suction grates the ventilators would work in an area of lower efficiency and with high negative pressure according to the characteristic of the ventilator. The calculation is made with two methods, namely with a program Pipe Flow Expert [20] and by comparative with a presented pipe model. Both models are based on the pipe flow theory. Although by characteristic the ventilators somewhat differ from each other, they are all the same in the presented model. The results obtained are comparable and shown on fig. 8. The figure shows flows on suction sides of the ventilators regarding the location of extraction point in the tunnel and the altogether quantity of the extracted air (smoke).

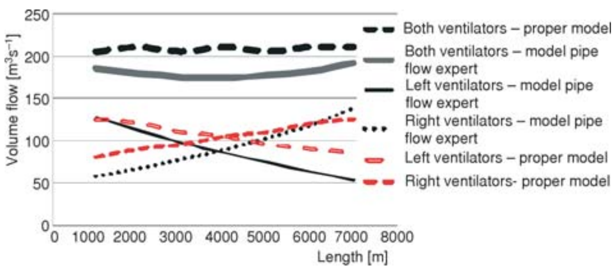

Figure 8. Flows in simultaneous operation of two ventilators for smoke extraction from the tunnel with two open suction grates and the total seal of the rest of the grates

The comparison of results on is satisfying and give the idea that a simple model could give results good enough for the first estimations of smoke extraction possibilities. The operational area of the ventilators is for the most part in an unstable area because of the ventilators characteristic, the length of the suction channel and the local and linear resistances. Figure 9 shows the ventilators characteristic in maximal revolution number (n = 740 min.$^{-1}$) and the operational area regarding the suction location in the tunnel. The more distant the suction location from the ventilator more does the operational point move to the left – unstable area.

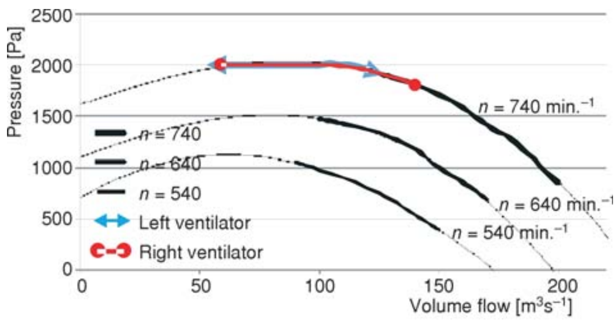

Figure 9. The operational area of the ventilator without the leakage of the suction grates

The real conditions differ from the ideal ones, namely the leakage in the suction grates fundamentally changes the suction channel characteristic.

Real conditions considering the suction grate leakage are carried out from the flow measurements in the extraction channel of the Karavanke tunnel (fig. 2). It is clear that the suction effect is reduced to almost half the flow through the ventilator at the half of the tunnel. 8 to 10 m^3/s of air leaks to the suction channel every 500 m that means 5 closed grates, during ventilator operation. The flow changes regarding the suction location and as expected is at the lowest in the middle of the tunnel (fig. 10). Curves of flows on left and right grates are closely covering each other, however there are both plotted on the graph. The total flow of extracted air (smoke) in the grates is about 140 m^3/s, extracting from a single duct and applying two ventilators for extraction. The total flow through both ducts using four ventilators for extraction could therefore be 280 m^3/s. The difference presents the leakage in the closed grates.

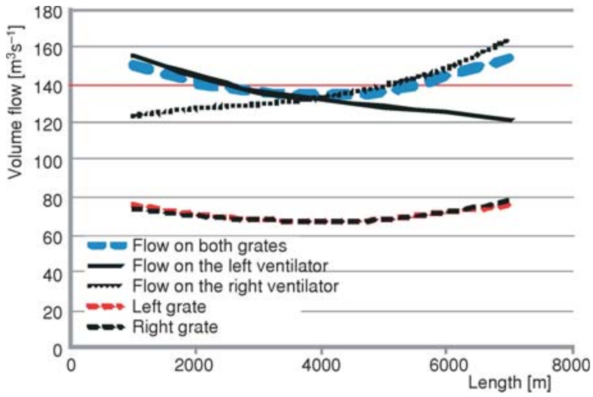

Figure 10. Flows in simultaneous operation of the ventilators considering the leakage of the grates

This extraction flow could be enough for proper ventilation of larger fires up to heat power of 100 MW (tab. 1).

Assuming the leaking on grates as a fact that occurs also on new grates or at least after a certain time in operation, the ventilation system should

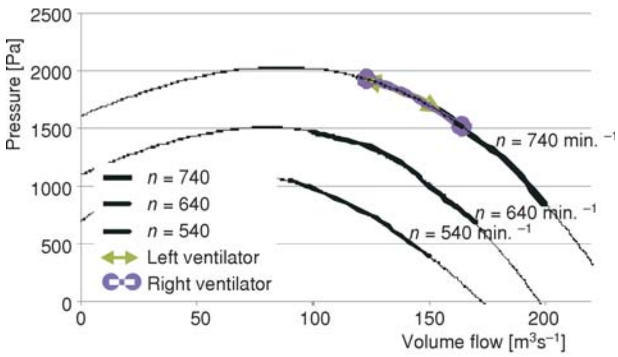

Figure 11. Ventilators operational area considering the leakage of the suction grates

be dimensioned for the less suitable operation conditions. In this sense the second version of the fire ventilation regime proposed, which assumes the extraction in both directions with four ventilators, considering extraction grates leakage as measured in 2008 before maintenance repairs, is acceptable for upgrade operation. The ventilators operational area in dependence to the suction location is therefore calculated with the pipe model described in the section *CFD model background* and presented in fig. 11. The ventilator operates within the optimal area with efficiencies between 75% and 85%, the operation area coincides with the operational point defined by the original project of the ventilation system.

Smoke flow dynamics analysis during fire with fire ventilation system operation

As presented applying the pipe model, the fire ventilation system operation with a connected north and south extraction channels and the fresh air channel (version 1) is analysed with Fire Dynamics Simulator (FDS). The extraction is performed through the suction channel towards the north and south side of the tunnel. The purpose of the CFD analysis is above all the overview of the flow dynamics and the effectiveness of the smoke suction from the tunnel. Because of the testing of the extraction effect the fire assumed in the model is of greater heat power, namely around 100 MW. Doing so the time when the suction capacity is not sufficient any more can roughly be determined. The initial air speed in the tunnel is 1 m/s towards the north direction. The location of the fire is 700 m from the south portal and the suction ventilators turn on 120 s after the start of the fire, in the mean time two suction grates open, one in front and one behind the fire. Both ventilators are simulated as a pressure boundary condition [21]. The south portal appears like it is, on the left side in fig. 12. This is also the physical position of the left extraction ventilator with the maximal under pressure produced of 1700 Pa. On other hand the right side of the tunnel domain in fig. 12 not represent the end of the tunnel. Considering this the under pressure produced by the north suction ventilator should be found in advance [22, 23]. Applying again a pipe model described in chapter explicitly the under pressure of 1530 Pa is calculated, and used as a pressure boundary condition on the right side of the extraction channel. Boundaries on the lower, driving part, of the tunnel are considered as open boundaries [24].

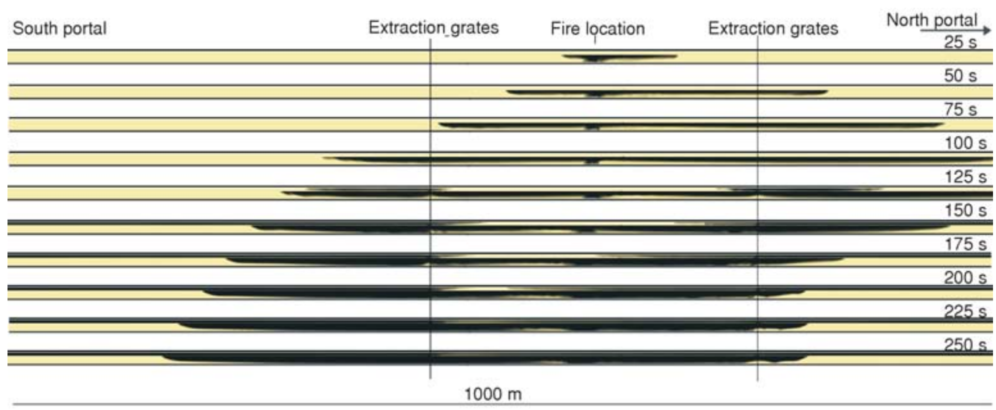

Figure 12. Smoke dynamics in the tunnel at 25 seconds time intervals

From the comparison of the fire heat force dynamics, smoke dynamics in the tunnel and the suction channel it is possible to determine the maximal suction capacity regarding the heat force of the fire that amounts to around 170 MW. With further increase of fire heat force the smoke spreads along the tunnel despite the suction (fig. 12), what occurs around the time 180 s.

The second version assumes the fire ventilation system operation with the north and south suction channels connected and the fresh air channel. The extraction in performed through both connected channels towards the north and south side of the tunnel. The fire scenario is similar to the previous. A fire of increasing heat power from 0 to 250 MW is presumed. In the suction channel there are two grates opened after 120 s in front and behind the fire and in the fresh air channel that now acts as a extraction one there are four grates opened. The size of the grates is chosen after the proposal of Brand [9] because we estimate that it is adequately chosen.

The initial air speed in the tunnel is 1 m/s towards the north direction. The location of the fire is 700 m from the south portal and the suction ventilators starts the extraction 120 s after the start of the fire.

Figure 13 shows the smoke spread dynamics in 25 s intervals. The suction effect is noticeable already after 3 minutes (time 175 s) because the north side of the tunnel ventilates completely up to the grates. The smoke spreads towards the south portal partly because the increasing force of the fire and partly because of the greater negative pressure in the south suction channels which causes a change in the flow direction in the tunnel. The suction flow is adequately greater in the operation of all of the ventilators but in this way greater air speed is also created in the tunnel and so longitudinal smoke movement in the opposite direction of the natural flow is caused.

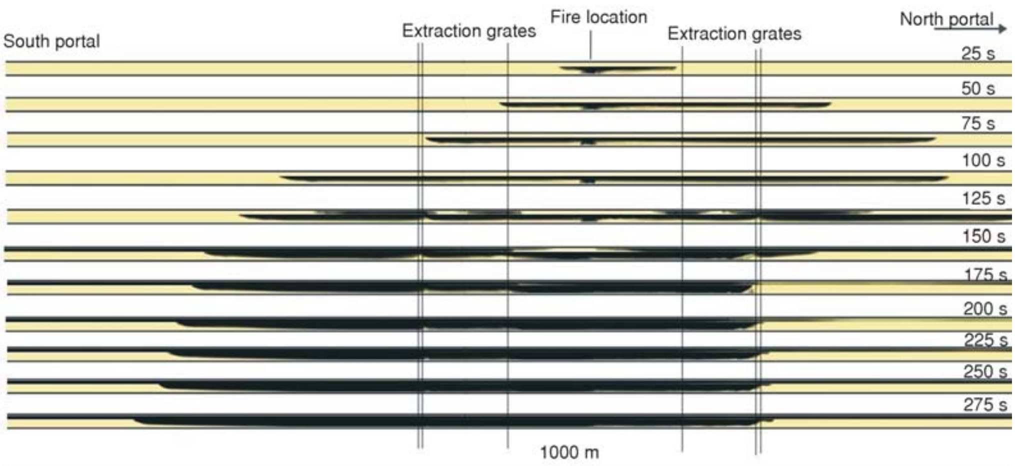

Figure 13. Smoke dynamics in the tunnel at 25 seconds time intervals

The test scenarios performed show that the direction of the fire ventilation with all four of the ventilators is not simple because we cannot easily foresee the flow dynamics in the tunnel. While two or all of the four ventilators are operating in suction regime the flow movement in the tunnel is dependent on the suction location and the heat power of the fire. A certain degree of flow direction could be assured with the adaptation of each of the ventilators revolutions regarding the suction location and the fire heat force. In any case such change in the fire ventilation regime or ventilation algorithm demands a more detailed analysis of the flow dynamics in the tunnel [25].

The last scenario tested regards a real fire possible and should represent a fire of a truck with non flammable cargo. The fire ventilation system operation with the north and south suction channel connected and the fresh air channel. The extraction is performed through both channels towards the north and south side of the tunnel as in a previous example. The fire heat power of the fire is limited to 30 MW. In this scenario the location of the fire remains unchanged as also does the initial and boundary conditions in the tunnel. The fire ventilation turns on 120 s after the start of the fire.

Despite the smaller fire in comparison to the previous scenarios the flow dynamics in the tunnel are very similar (fig. 14). The suction effect is greater because of the lower quantity of smoke formation. Once again the redirection of the air flow to the south can be noticed as a result of a greater negative pressure in the south channels. After establishing partly stationary conditions in the tunnel and the suction channels (after 200 s) mostly clean air coming from the portals is extracted through the north channels. The altogether suction effect is generally good because the smoked area remains for the most part confined between the suction grates. Intervention would be possible in this case from both sides. Access to the fire in this case is better from the north side because owing to the suction dynamics and the longitudinal flow movement appears towards the south suction grate.

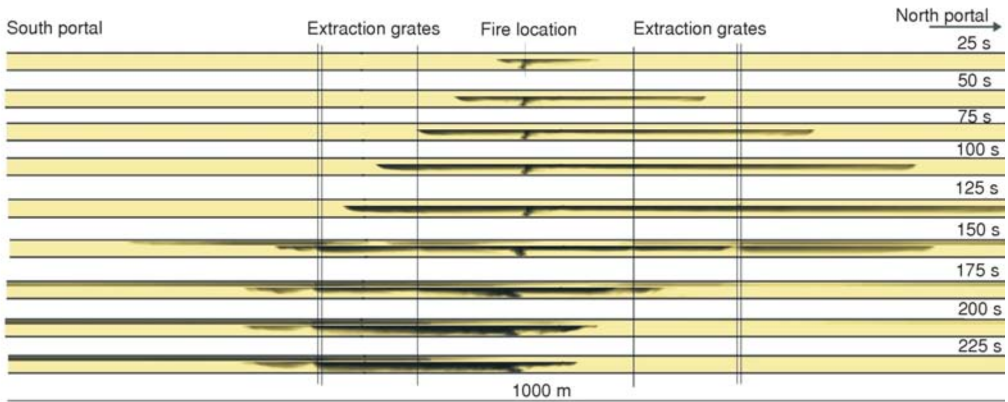

Figure 14. Smoke dynamics in the tunnel at 25 seconds time intervals

Conclusions

The described operational scenarios are general and allocated on the tunnel Karavenke ventilation system. The installation of the system requires additional investigations of ventilation effects including fire ventilation. Detailed analysis should include detailed particular properties of the tunnel construction and ventilation ducts that could be investigated with a CFD model or on the physical tunnel model. Nevertheless the paper conclusions gives the indication that the upgrade of the ventilation system improve smoke extraction in case of fire and indicates basic requirements for system regulations during the fire. The main is the requirements to keep the longitudinal velocity below the speed of evacuation in case the smoke is not fully extracted by the ventilation system. How to provide this with a cross ventilation is not still solved, but findings from the CFD models conducted indicates that it should be possible with a proper distribution of pressure in the extraction channels in dependence of the fire location and fire heat power. However the first goal of the research was not to create a fire ventilation plan, but to analyse the ventilation efficiency of the connected ventilation channels. From the research arise that the overall extraction capacity is obviously higher than in present situation and covers the extraction possibility from any point on the entire length of the tunnel. The installation of new grates on the channels floor would require new measurement of leakage and based on overall leakage of grates the selection of proper ventilators or the upgrade of existing ones. Still an uncertainty arise about the requirements of additional axial ventilators for the regulation of the longitudinal air velocity although there is a possibility to regulate it with a cross ventilation, as pointed out. But from the point of view of reliability and safety, nevertheless should be better to include them for the normal operational ventilation regime.

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