Instationary CFD Simulations and Smoke Tests for the Design Check of the Fire Ventilation in the Branisko Tunnel

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Abstract
The 4975 m long Branisko tunnel is situated in Slovakia between the towns of Levoča and Prešov on one of Europe's most important West-East connections, the E50 highway. The inauguration of the tunnel was in June 2003.

Based on a previously defined ventilation project, HBI Haerter Ltd. has worked out the detailed design and control algorithms, and supported the on-site supervision and commissioning of ventilation and control equipment.

A CFD study was conducted for the design check of the fire ventilation. Prior to the tunnel opening, a smoke test has been carried out, which proved the efficiency of the fire ventilation system.
The results of the CFD calculations can be compared qualitatively with the data acquired by the smoke tests.

1. Introduction

In order to validate the ventilation system of the Branisko Road Tunnel, which was designed using 1-dimensional methods, a 3-dimensional CFD study was conducted and smoke tests carried out. The reason for the detailed study and tests is that tunnel safety during emergency situations has gained increased attention. Furthermore, the equipment of the fire department has become powerful and they have various possibilities to intervene. The results provide an overview of the smoke propagation and stratification as a function of time and space. Additionally, the effects of the ventilation system on the smoke behaviour are investigated in the CFD study. The results from the CFD study and the smoke tests can be integrated into the intervention plans by the fire department such that no surprises are to be expected during an intervention.

2. Ventilation Concept

The Branisko Road Tunnel is a single tube road tunnel with bi-directional traffic. It is equipped with a semi-transverse ventilation system combined with an air-extraction station at approximately midway, see Fig. 1. Furthermore, 90 overhead dampers are situated in the intermediate ceiling. They are used for the fresh-air supply during normal operation and for the smoke extraction in case of fire. Moreover, at about the middle of the tunnel eight large dampers are integrated in the ceiling to enable a point extraction. The tunnel ventilation equipment consists of one fresh air fan at each portal and two parallel exhaust fans over a shaft near the middle of the tunnel. A parallel escape tunnel is ventilated separately by fresh air fans at each portal. This guarantees that under all circumstances, the escape tunnel is kept free of smoke, even when the escape doors are open.

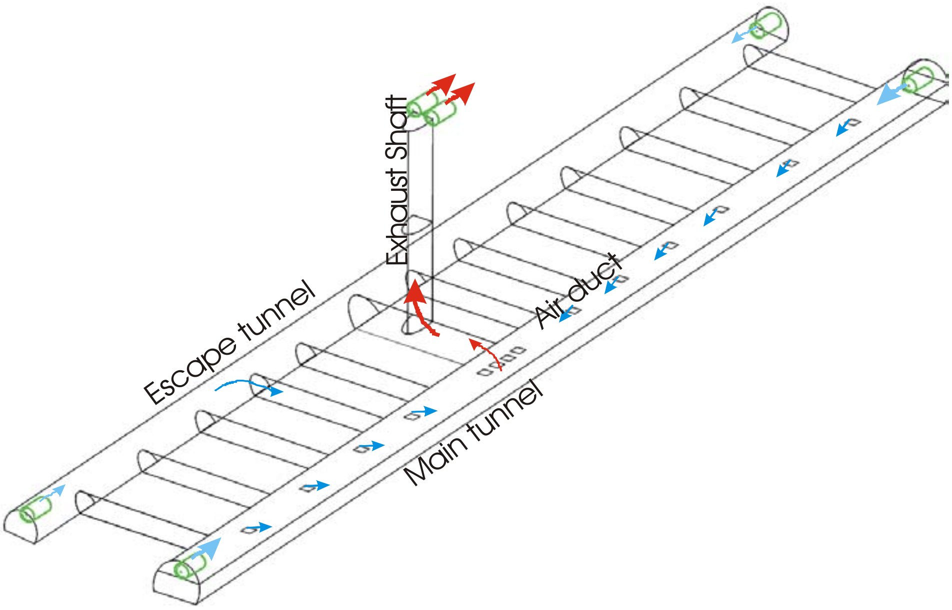

Fig. 1 Overview of the tunnel with its ventilation system

In the fan buildings at the portals and therefore at the ends of the ventilation duct, the fresh-air supply fans (VZ) are located, see Fig. 2. In the midway of the tunnel, the ventilation duct can be partitioned by closing the vertical dampers (K_K) on both sides of the midway-ventilation station. On the top of the midway-ventilation station, the exhaust fans (VA) are located. The fresh air is supplied via the ventilation duct from the eastern and the western portal through the dampers into the tunnel. The vertical dampers (K_K) are used to switch between two extraction modes: either through the ventilation duct or directly from the tunnel. In case of semi-transverse ventilation, the vertical dampers (K_K) are closed and the dampers in the intermediate ceiling (K_L) are partially opened. The air is extracted either through the eight large dampers near the middle of the tunnel (K_A) or through five open dampers in the ceiling (K_L). The exhaust air is expelled by the axial fans (VA) into the ambience through the stack at the middle of the tunnel.

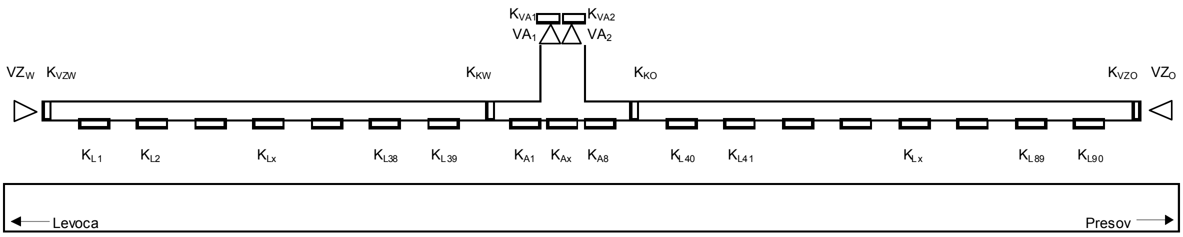

Fig. 2 Schematic of the tunnel-ventilation system

Normal Operation

The default ventilation mode is defined as air extraction through the eight dampers at the midway-ventilation station. This mode causes a longitudinal ventilation of the tunnel. The air is carried from both portals into the tunnel. When the air speed in the tunnel exceeds a certain value, the semi-transverse ventilation is activated in order to slow down the air flow, to provide sufficient visibility and to ensure a pollution level of the tunnel air below the permitted limits.

Emergency Operation (Fire Case)
In case of a tunnel fire, the ventilation concept treats four different cases that are defined according to the location of the fire. For most fire locations, the smoke is extracted through five open dampers bordering the fire, see Fig. 3. They cover a length of 200 m. If necessary, semi-transverse ventilation is also operated in the non-incident branch in order to have an airflow speed towards the fire from both sides. Also for fires near the midway-ventilation station, smoke is extracted. However, for fires located near the portals several different scenarios have been elaborated.

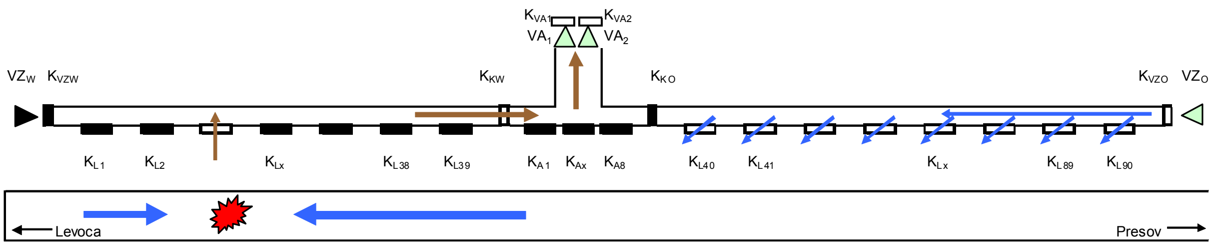

Fig. 3 Main response mode of the ventilation system in case of a fire

3. Design Fires and Heat-Release Rates for the CFD Computations

An important aspect of a ventilation design is the definition of the design fire and the corresponding heat-release rate. Applying the specifications from the responsible fire department [1], a worst-case fire scenario that concluded a maximum heat release rate of 100 MW was derived. For the current study, fires with maximum heat release rates of 100 MW, 50 MW and 30 MW were simulated.
The characteristic of the 100 MW fire, which was considered to be the worst-case scenario, was derived by superimposing several fires in accordance with [1]. The fire was supposed to be initiated by a 100 MW fire of a heavy-good vehicle using the HF1 test („Heavy goods vehicle“) from the Eureka experiment [2]. Flash over occurs as a result of the high temperatures and thermal radiations. In [1], it is assumed that a passenger car ignites every 3 to 4 min and that a lorry, bus or truck starts burning every 7 to 8 min. As a passenger car, the “Plastic Car C21” (5 MW) and as a truck the “Public Bus B11” (30 MW) from [2], were assumed, see Fig. 4, right hand diagram. Superimposing the individual heat sources results in the total heat-release rate of up to about 100 MW (see full red curve in Fig. 4, left hand diagram).
In order to simplify the characteristics of the fire, the model of Ingason [3] was applied and the specific parameters derived, see dashed line in Fig. 4. This simplification allows defining the heat release as a function of time. The parameters for the 50 MW fire were interpolated between the parameters for the 100 MW and the 30 MW fire.

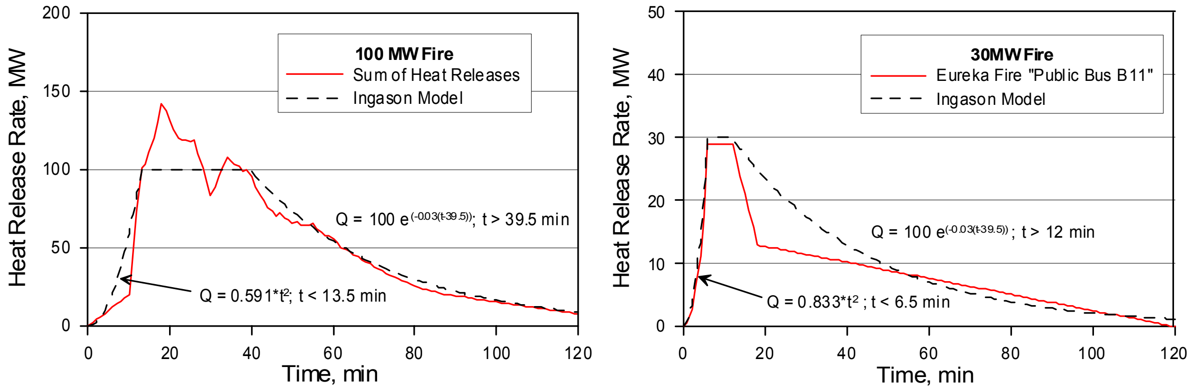

Fig. 4 The sum of the different heat releases leads to a 100 MW fire scenario (left hand diagram). 30 MW fire scenario from the Eureka test series (right hand diagram). The Ingason model [3] approximates the scenarios.

4. CFD Computations

Fig. 5 shows the domain used for the simulation. The domain represents the entire tunnel. This allows conducting a complete study of the influence of the various ventilation modes. In particular, the influence of the semi-transverse ventilation operating prior to fire detection is of interest in terms of smoke propagation and stratification. Additionally the midway-ventilation station as well as the fire source are shown in Fig. 5.

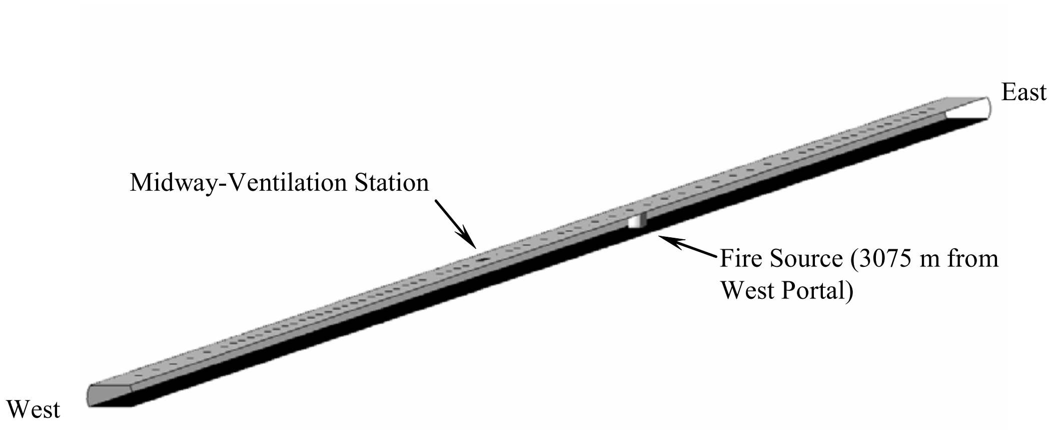

Fig. 5 Domain used for CFD Computations (entire tunnel)

Fig. 6 shows the velocities for the two default normal operation ventilation modes: central extraction with and without semi-transverse ventilation. Additionally, the volume flows are shown in Fig. 6.

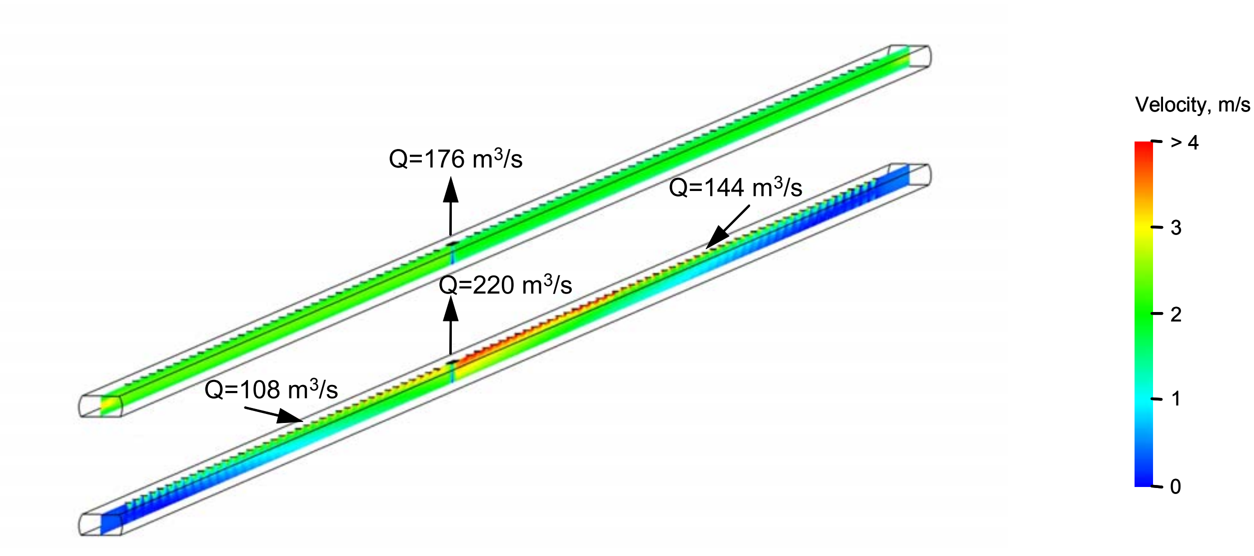

Fig. 6 Velocities in the tunnel resulting from the ventilation mode and the specified volume flows: extraction (above) and extraction together with semi-transverse ventilation (below)

In case of additional semi-transverse ventilation, the velocity profile depends on the longitudinal position of the profile, whereas for the case of pure extraction the velocity profiles are similar from the portal to the extraction point (Fig. 6).
A detail of the zone close to the midway-ventilation station has been chosen for comparison of the velocity profiles in the cross sections for the two ventilation modes, see Fig. 7. These are results of normal operation (without a fire).

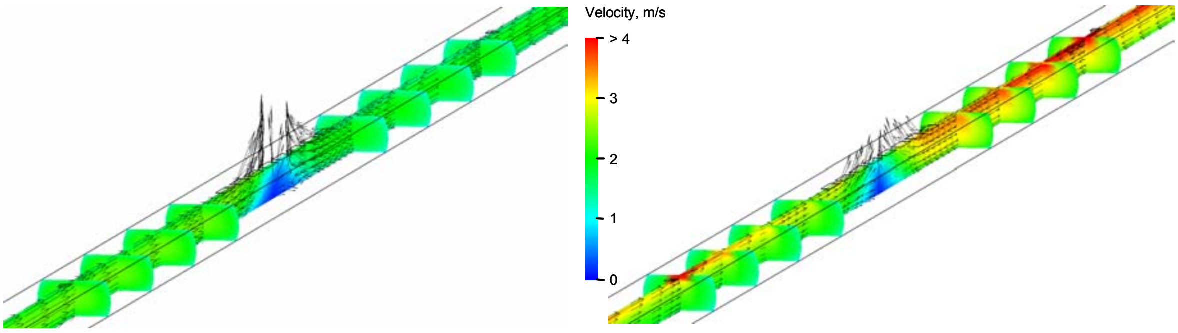

Fig. 7 Velocities around the midway-ventilation station

In the following, smoke propagation in the 30 MW fire scenario is presented. Calculations were conducted for both initial ventilation modes. The heat source was located at 3075 m from the west portal, according to [1] (see Fig. 5).
The ignition of the fire is set at t=0 s. After 180 s, it was assumed that the fire is detected and that the ventilation switches from **Normal Operation Mode** to **Emergency Operation Mode**. Fig. 8 shows the smoke propagation and Fig. 9 the smoke stratification at t=150s.

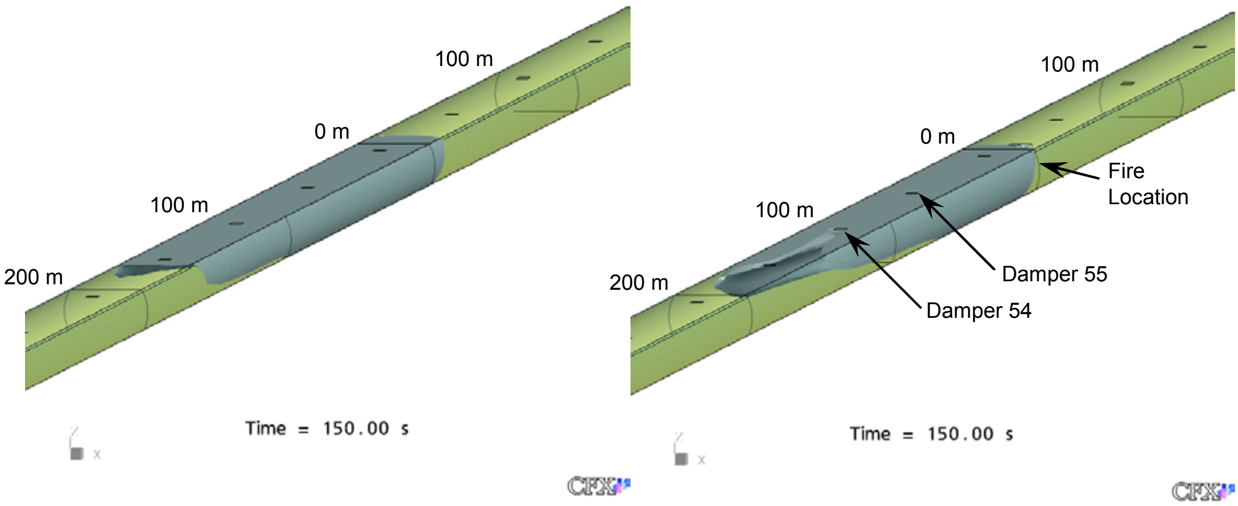

Fig. 8 Smoke propagation of the 30 MW fire at t=150 s. Initial ventilation mode: extraction (left hand picture) and extraction with semi-transverse ventilation (right hand picture).

Due to the similar flow velocities near the fire, the smoke propagates approximately at same rate, see Fig. 6.

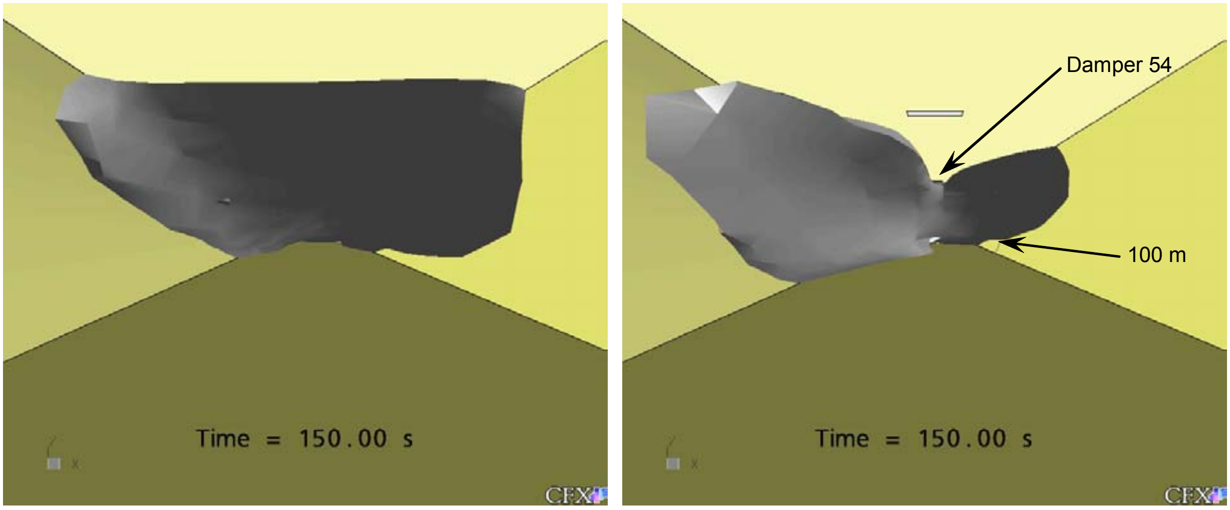

Fig. 9 Smoke stratification of the 30 MW fire at t=150 s. Ventilation modes: extraction (left hand picture) and extraction with semi-transverse ventilation (right hand picture). Position of observer: 180 m from the fire source, looking east.

While in case of the initial extraction mode, smoke stratification can be achieved. In contrast, the semi-transverse ventilation partly destroys the smoke layer at the ceiling of the tunnel and spreads the smoke, Fig. 9. Depending on the fire location (the velocity field vary with the distance to the portal, Fig. 6), the supply volume flow and the supply angle, the smoke spread can exhibit quite different behaviour.

The air-supply streamlines departing from the dampers give more insights, see Fig. 10. The picture on the left shows the streamlines of damper 54 and damper 55. The position of the observer is at a distance of 225 m from the fire, looking east. On this picture mainly two phenomena can be observed. First, the zone close to the fresh-air supply is free of smoke due to dilution (see as well Fig. 8 and Fig. 9). Second, the streamlines near the fire zone are deflected towards the walls of the tunnel. Consequently depending on the distance to the air-supply dampers, the main effect of the fresh-air supply either assists the smoke propagation or causes smoke dilution, see Fig. 10 left hand picture. Alternatively if the fire had been located closer to the portal, smoke would spread over the entire cross section as can be deduced from Fig. 10 (right hand picture). In this case, the observer is placed at a distance of 600 m from the east portal, looking west. The reason is the large eddy whirls of the streamlines.

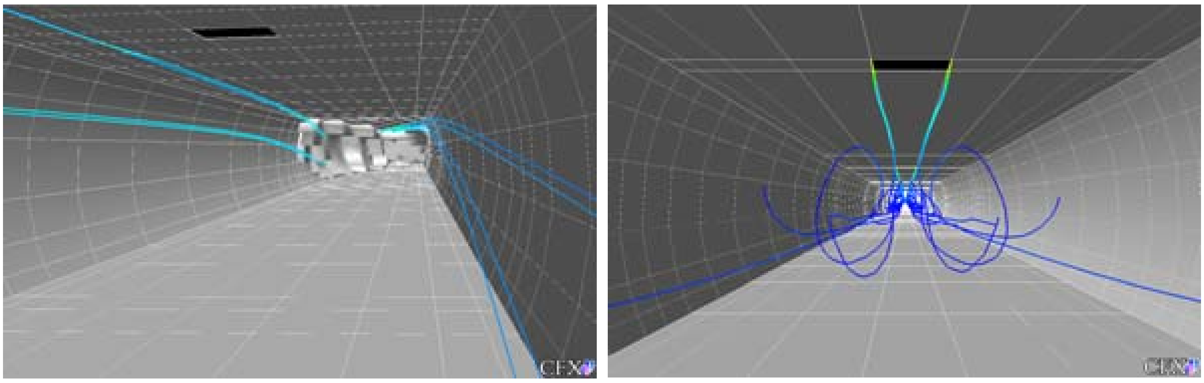

Fig. 10 Left hand picture: Streamlines departing from dampers 54 and 55. Position of the observer: 225 m from the fire source, looking east; Right hand picture: Streamlines departing from various dampers. Position of the observer: 600 m from the east portal, looking west.

For both ventilation modes, the smoke propagates up to a distance of 235 m from the fire and is at a later stage driven towards the extraction zone, Fig. 11. Then the smoke remains within the range of the five exhaust damper. The zones outside this range are being kept free of smoke, as requested in the design.

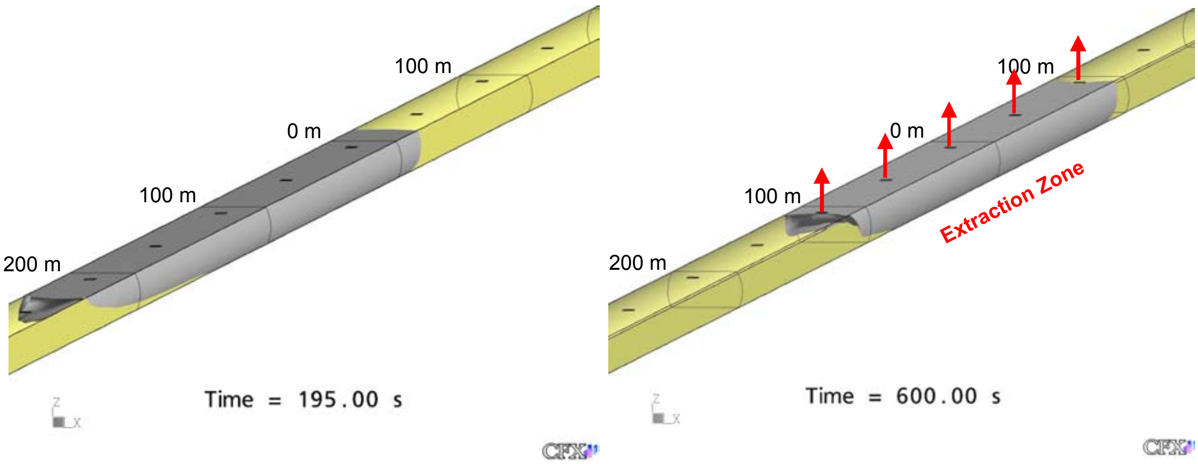

Fig. 11 Maximum smoke propagation (left hand picture). Due to the smoke extraction, the smoke remains within the range of the five exhaust dampers (right hand picture, red arrows). In both cases, the initial condition during normal operation was extraction.

5. Smoke Tests

Two smoke tests in the tunnel tube have been carried out on 20th June 2003. For the smoke production, two types of military fog grenades have been used. The grenades were placed at a distance of 1900 m from the east portal. The location coincides with the location used in the CFD computations.

First Smoke Test

Prior to the beginning of the test, the ventilation had been switched off. A natural airflow with direction west to east was measured. The according velocity was approximately 1.2 m/s. The traffic room was entirely befogged by 5 personal and 2 tank fog grenades which were ignited sequentially, see Fig. 12. The total smoke-production rate was estimated at 45 m^3/s. This value corresponds to the smoke-production rate of a lorry without dangerous goods. The smoke production ceased after approximately 20 min.

Fig. 12 Fog grenades producing smoke

Prior to the smoke detection (and therefore prior to the operation of the fire ventilation), the smoke spread along the tunnel as a result of the natural airflow. Due to the low heat-release rate, only a limited smoke stratification in the vicinity of the fog grenades was observed. Further downstream, the smoke filled the whole tunnel section. Maximum smoke production was reached 5 min after the ignition of the grenades. One minute later, the smoke was automatically detected by the opacity measurement which was situated approximately 135 m in the east of the smoke source. As a consequence, the fire alarm responded and activated the fire ventilation. At that time, the smoke had already propagated up to a distance of 200 m from the smoke source. Two minutes later, the fire ventilation was in full operation. The smoke front came to halt at a distance of approximately 400 m from the smoke source. From then on, the smoke was driven back.

The fresh-air supply aiming to support the smoke extraction was not activated. The local smoke extraction solely determined the longitudinal flow. Nevertheless, the smoke front in the tunnel was driven back towards the open extraction dampers, and then sequentially from one to the other damper, until the last skirts of smoke vanished through the first open damper. By this time, the smoke production had already ceased. The effectiveness of the smoke extraction was proved successfully.

The ventilation of the escape tunnel showed its ability to prevent the ingress of smoke through the escape door, even when the door was open, see Fig. 13.

Fig. 13 Open emergency exit in the smoke zone. The escape route is entirely being kept free of smoke.

Second Smoke Test
The location of the grenades for the second smoke test was at a distance of 300 m from the west portal. Prior to the beginning of the test, the ventilation had been switched off. A natural airflow with direction west to east was measured. The according velocity was approximately 3 m/s, caused by strong buoyancy forces. The smoke was automatically detected by an opacity measurement, like in the first test. Again, the fire alarm responded and activated the fire ventilation. At that time, the smoke had already propagated up to a distance of approximately 500 m from the smoke source.

In order to support the smoke extraction in driving back the smoke towards the extraction zone, the fresh-air supply fans were activated in the east branch of the tunnel.

During the first minutes, the pattern of the smoke propagation in this test was similar to the first one. The smoke extraction worked as expected. The smoke had almost been driven back towards the first open damper, limiting the smoke zone to a length of approximately 200 m, when something unexpected happened. Due to a shortcut in the electrical supply, the frequency converters of one of the exhaust fans and of the eastern fresh air supply fan failed and could not be restarted immediately. From this moment on, the smoke extraction worked only on a very limited level. As a consequence, the smoke started to spread again along the tunnel towards the eastern portal. Within 25 min, the operability of the two exhaust fans was recuperated. The extraction point was changed to the middle of the tunnel in order to reach a higher extraction capacity. At that time, the smoke production had ceased and the smoke covered a length of approximately 2000 m. After the recuperation of the exhaust fans, the fans could again extract the smoke until, after another 20 min, the tunnel was free of smoke. Smoke exiting the exhaust shaft is shown in Fig. 14. Incidentally, the problem with the electrical supply was analysed and solved immediately afterwards in order to ensure the correct operation of the fire ventilation.

Fig. 14 Smoke exiting the exhaust shaft

Real test fires or fog grenades produce toxic, corrosive smoke. This may cause health problems and may as well affect the equipment in the tunnel.
Nowadays, non-toxic smoke substitutes are available. HBI Haerter Ltd. uses these substitutes already for tests in Swiss tunnels. As an example, an impression of the smoke tests in the Flüelen tunnel, which opens on 10th June 2005, are shown in Fig. 15. These smoke tests were being realized successfully.

Fig. 15 Non-toxic smoke extracted through the extraction damper in the Flüelen tunnel (Switzerland)

6. Conclusions

The 3D CFD computations have successfully validated the ventilation design. Smoke is prevented from propagation beyond the extraction zone in the tunnel and is completely extracted through the five exhaust dampers at the extraction zone. The conditions for egress of the tunnel users and fire intervention are optimal.
Furthermore, 3D Simulations revealed insights into the smoke behaviour, especially when using semi-transverse ventilation during normal operation. During the first couple of minutes after fire ignition, the ventilation at normal operation influences the smoke spread. This is a result of the time lack between fire ignition, fire detection and operational fire ventilation. Applying the fresh-air supply from the ceiling during normal operation has the inherent disadvantage that it disrupts and possibly destroys smoke stratification. Whenever feasible, it is therefore recommended to use exclusively extraction through the dampers at the midway-ventilation station during normal operation without operating the semi-transverse ventilation.
In the smoke tests, the opacity devices detected the smoke as requested. The tunnels should be equipped with such devices. Furthermore, short distances between these devices are recommended, as defined in the German and Swiss guidelines.
In order to ensure a correct operation of the fire ventilation, functionality and performance tests in the tunnel should be worked out. Since an escape tunnel is of utmost importance regarding the safety of the tunnel users, a test of its ventilation must be included. The tests should be planned already at an early stage of the project. In reality, most tunnel-fire incidents produce a lot of smoke at a low heat-release rate. Stratification cannot be guaranteed, especially not under traffic conditions. Tests with cold smoke are therefore recommended in order to test the performance of a smoke extraction.

7. Literature

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