Experimental and Numerical Investigation of Semi-Transverse Ventilation System During the Fire Test

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ABSTRACT: *The focus of this full-scale study is to investigate the operation of the Bosrucktunnel ventilation during the fire. In this regard, the performance of the ventilation system and all related sub-systems were evaluated in a standard Commissioning test. For this purpose, a fire test with a heat release rate of 3-5 MW was considered according to RVS standards. The mentioned capacity of the fire is equivalent to a common passenger car fire. This fire capacity can't represent a clear perspective from the ventilation operation during higher or extended fires. However, the system reaction and ventilation strategy are almost the same regardless of the size of the fire, particularly at the beginning of the fire. Furthermore, a general evaluation of control systems and the investigation of the entire process from incident detection to system response was necessary for this experimental and numerical study. Therefore, a CFD model was developed using a Fire Dynamics Simulator (FDS), an open-source software, for numerical simulation. Due to the relatively long length of the tunnel (5.5 km) and various safety equipment, simulating the fire and the system response was a big challenge. In such cases, simulation of the ventilation using the entire structure of the tunnel in the computational field is not easily possible, and it is not necessary. For this reason, a simplified calculation domain with a suitable boundary definition is assumed for simulation. The other required boundaries were defined using tunnel data, ambient, and tunnel conditions during the fire test. The performance of the ventilation was confirmed in smoke management in the specified schedule in the fire test. A numerical simulation was carried out to investigate the behavior of hot smoke, air velocity, and temperature distribution around the fire location. In addition, more useful information was obtained from numerical simulation, including the timing of related systems response in facing a fire, which is very important in emergencies. This information can help to deal with high-capacity fires.*

KEYWORDS: *Commissioning tests; Fire test; Tunnel ventilation; Experimental and numerical investigation; CFD.*

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INTRODUCTION

Nowadays, a standard full-scale fire test is considered a fundamental part of the commissioning tests to evaluate and prove tunnel safety. A standard commissioning test includes the evaluation of the operation of ventilation and safety infrastructures during normal or emergency conditions. According to guidelines, a standard fire test is necessary for traffic passage permission from the tunnel in many countries. The purpose of a fire test is usually to verify ventilation operation in handling hot smoke and the entire emergency from start to finish. Meanwhile, evaluation of the performance of the system (tunnel safety) in fire detection, arrangement of air velocity upstream and downstream of the fire, and smoke evacuation are other goals.

In the past decades, many experimental and numerical studies have been carried out in model and full scale on fires in tunnels. In the current fire test, the response process of the ventilation system started with the detection of the fire location and continued with the confirmation of the fire. After the incident confirmation stage, the next stage was to change the functional approach of the ventilation system from normal mode to emergency mode. This is recognized as an essential step to properly managing hot smoke at the start of a fire and providing critical time for rescue and firefighting activities.

Many fires have been recorded in the past decades and even in recent years in various tunnels around the world. These incidents have resulted in a loss of life, including injured and killed, as well as heavy structural damage [1-4]. Due to the rapid growth of traffic and the transportation of goods and passengers, the possibility of fire incidents and dealing with such emergencies are the most challenging issues in the design and operation of road tunnels. For this reason, extensive experimental research has been conducted on fires inside tunnels [1,2,4-7].

The first large-scale (12-70 MW) fire test was conducted in the Ofenegg tunnel in Switzerland in 1965. The purpose of the fire tests was to evaluate the performance of natural, longitudinal, and semi-transverse ventilation systems. Gathering information about the destructive consequences of fire in tunnel structures and equipment, as well as evaluating rescue activities, have been other goals of tests.

In 1970, further fire tests were conducted in the Glasgow Tunnel in England. The distribution of smoke and temperature as well as layering of smoke in the cross section of the tunnel have been investigated. In another study, a full-scale fire test with gasoline fuel combustion (8-12 MW) was conducted in the Zwenberg tunnel in Austria. Investigation of different ventilation systems, the effect of fire on tunnel structure, movement of hot smoke, and maximum temperature under the roof as well as air quality measurements for O2, CO, CO2, NOx, and visibility have been the objective. In 1980, two fire tests were carried out in a tunnel with a length of 700 and 3227 m in Japan. The idea behind it was to use tests in a long tunnel to see if it was possible to evacuate people by controlling and managing hot smoke. Evaluation of air velocity, burning rate, temperature as well as oxygen concentration, carbon monoxide, and heat transfer by radiation have been other goals 0.

A series of fire tests were conducted in the Memorial Tunnel between 1993 and 1995. Similar to previous works, the main objective of the experiment was to assess ventilation including longitudinal, transverse, and point extraction systems. Furthermore, the measurement of the ventilation parameters in fire cases like temperature, air velocity, CO and CO_2 concentration, smoke distribution, and visibility in tunnel cross-section have been the other part of the tests. According to the reports, the tests provided very important information on the fire behavior in the tunnels 0.

In 2001, in the other case study in the Shimizu tunnel in Japan, full-scale fire tests were carried out in a three-lane traffic tunnel with a large cross-sectional area. Ventilation operation in fire, as well as air velocity and smoke behavior during the fire, have been investigated. In addition to what was done in the previous works, in this research, the risk of the extension of the fire to the other vehicles as well as FFFS (fixed fire-fighting systems) system and smoke layering in the tunnel cross-section was considered 0. Another experimental study has been carried out on the second Benelux tunnel in the Netherlands. Investigation of the rescue activity possibilities during the fire incidents and the performance of the fire detection system, as well as ventilation and FFFS systems, have been the main and basic focus of the study. The fire sources were pool fire, passenger car, etc. Important information from the fire, including heat release rates, visibility, air velocity, and temperature has been collected 0.

The main and important goals of the mentioned studies have been the investigation of hot smoke and gasses behavior, smoke propagation, air velocity down and upstream, and temperature distribution in the tunnels during the different fires. The valuable outcomes from the research and studies have been compiled in national and international standards for tunnel ventilation and safety design and operation.

In the past years (last decade), some other experimental studies have been continued with more or less the same objectives. In addition to what has been done before, heat release rate from the fires, ventilation, and FFFS performance in emitted energy from the fire combustion have been calculated. This has been done by the simulation of the real HGV fires, using wooden pallets (80 % wood, 20 % plastic) in the TST tunnel in Spain [11,12]. The same work was done by the SP group with similar objectives in the Runehamartunnel in Sweden. In this case, the maximum temperature under the ceiling has also been measured [13]. At the same time, other model-scale experiments have been conducted to find possible relationships between large-scale and model-scale ventilation parameters [14-16]. As discussed, experimental fire tests have a long history and very useful information has been obtained on the heat release rate, temperature distribution, burning rates, air velocity effects, flame length, and generation of toxic and harmful emissions from fires.

Today, tunnel safety and ventilation system, particularly during a fire, is one of the most important and interesting topics for researchers. However, ventilation control systems and dealing with the fire, particularly at the beginning of the fire with the support of some other parallel efforts for rescue and firefighting are also a concern for researchers 0. With the appropriate response of the ventilation control system from the ignition to the end of the fire, the least destructive consequences of the fire can be expected0.

However, is not easily possible to accurately evaluate fire behavior and its consequences in the tunnels on real and large scales (big fires) before the operation of the tunnel (commissioning tests). Nevertheless, as mentioned earlier, the ventilation control response can be demonstrated using a standard fire test with a limited heat release rate.

As mentioned before, the main objective of this experimental and numerical study is to investigate the ventilation and ventilation control system of Bosrucktunnel during a fire. To study the dynamic effect of smoke and heat transfer inside a certain volume (tunnel), in this study, the computational Fluid Dynamics Software (FDS) was used 0. FDS calculates radiation and conduction heat transfer in the walls and other considered solid elements as boundary conditions. However, in some cases, especially in micro scales, COMSOL Multiphysics is used for simulations. COMSOL Multiphysics is a cross-platform finite element analysis, solver, and Multiphysics simulation software [20, 21]. In the study of such an engineering process, the Navier-Stocks equations are also considered the main part of the simulation [22, 23].

It should be noted that the air pollution inside the tunnel as well as its external effects on the portals 0 is always one of the important issues in the design and commissioning process. In the present study, only the possibility of proper hot smoke management during the fire is discussed. The reason is related to the possibility of low traffic density and good emission conditions of the fleet that there is no concern about pollution. On the other hand, according to the location of the tunnel (rural tunnel), air pollution was not significantly a big problem. However, in certain situations e.g., severe local pollution in the tunnel, the required ventilation capacity, and control system are easily available to rectify the air quality.

The innovation of this work compared to previous works is the simultaneous focus on issues such as ventilation control, the reaction of the ventilation system during a fire event, and modeling the movement of smoke and temperature. Among all these parameters, combustion modeling and investigating the effect of natural fuel combustion in the process of ventilation and smoke management has a more innovative aspect than previous works.

FIRE TEST (COMMISSIONING) AND RELATED MEASUREMENTS

The Bosrucktunnel in Austria is located along the A9 highway and connects the federal regions of Upper Austria and Styria. It is a part of a vital network connection from the north to the southeast of Europe. The western tube of the Bosrucktunnel was built in 2013. The eastern tube was refurbished in 2015. On the 2nd and 9th of December 2015, hot smoke commissioning tests were carried out according

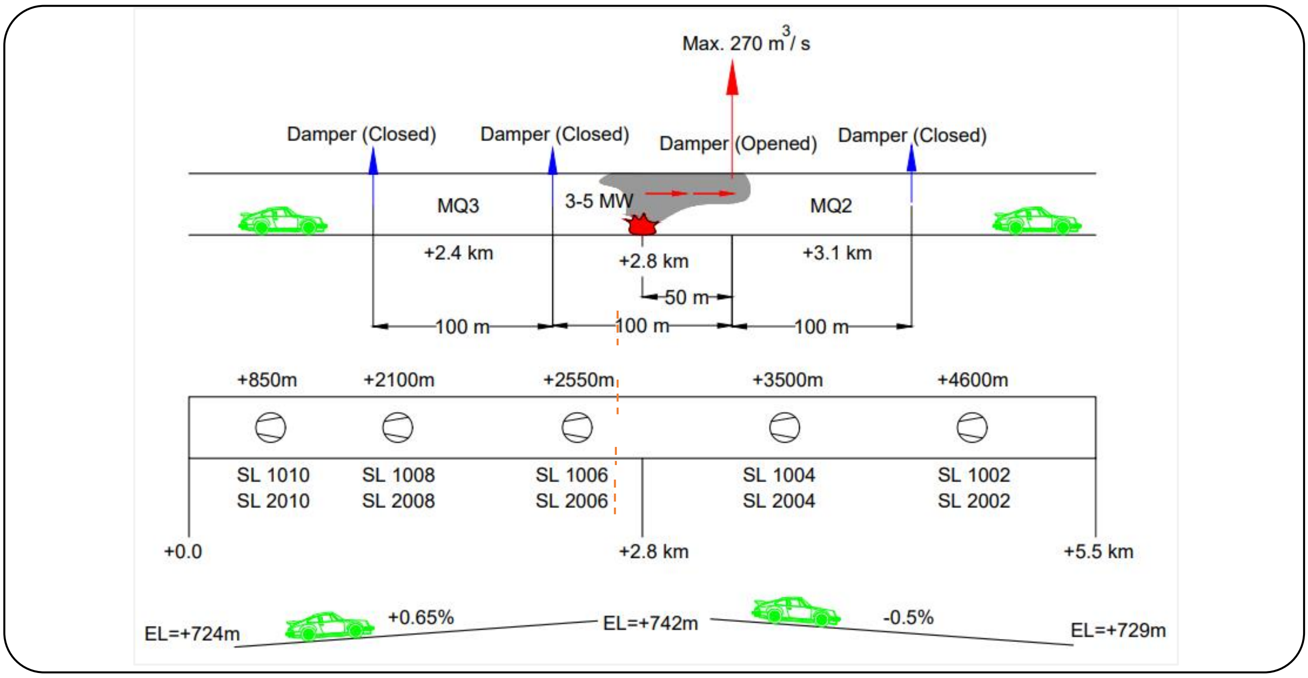


Fig. 1: Schematic view of the Bosrucktunnel tunnel equipment and some geometrical data for fire tests.

to the Austrian RVS standard 09.02.31 in the eastern tube of the Bosrucktunnel.

The length of the two-lane unidirectional tunnel (east tube) is about 5.5 km. The cross-sectional area and hydraulic diameter of the tunnel are about 50 m^2 and 6.75 m, respectively. All other geometrical data like tunnel cross-section area, hydraulic diameter, and longitudinal gradient were available from the drawings for the 3D model setup. There is the possibility of using the tunnel in bidirectional traffic mode as well.

The tunnel is equipped with a semi-transverse ventilation system with the support of jet fans, for longitudinal airflow momentum. The air extraction stations (shared with both tubes) are located at the top of the entrance and exit portals. The extraction is performed *via* remotely controlled dampers, which are located every 100 m throughout the tunnel. In addition, 10 jet fans numbered SL 1002 to SL10010 and SL2002 to SL2010 (in 5 pairs) are installed for longitudinal airflow (see Fig. 1). The tunnel is divided into 63 fire zones and a linear fire detection system as well as other multiple systems like CCTV is used for incident detection purposes. Fig. 1 presents more detailed information about the tunnel geometry, ventilation equipment, and fire test.

The fire is located in the middle of the tunnel where the longitudinal gradient is turned from a positive to negative for unidirectional traffic mode. It means that the location is a crucial position for a fire incident. Air velocity sensors are located along the tunnel roughly every 700 m. However, for the mentioned fire test, the highest priorities for the air velocity measurements belonged to sensors MQ2 and MQ3. The quality of system response and performance including sensors, extraction dampers, control system, and other safety-engaging elements were controlled and verified in cold tests before the implementation of the fire test.

According to the RVS.09.02.31 recommendations, two pools containing 20-liter diesel fuel and 5-liter gasoline each are required for a standard fire in commissioning tests. Accordingly, the size of the pool is determined as 1m ×1m and positioned at a height of about 1m above the ground level. In this case, a heat release rate of 3-5 MW is expected concerning RVS and other fire tests. The expected heat release rate for the mentioned configuration has been proved in other experimental studies as well [1, 4, 24].

Fig. 5-b depicts the fire test setup and safety equipment e.g., insulation of cables in the tunnel. This protection cover, itself, affects fire detection and recorded data for temperature. This issue was also considered in the fire test and report.

(a)

(b)

Fig. 2: Air velocity measurement installation and set-up (a) Small size 3-5 MW fire test and smoke extraction point (b).

The fire was started manually at 21:59:26. At that time the airflow was around -1 m/s. When the fire was triggered, there was a natural air flow of roughly -1.2 m/s (Fig. 9-MQ3) in the tunnel. The fire detection took place 82 seconds after the ignition, whereby the smoke extended 130 – 140 m toward the exit portal. Immediately after fire detection, the controller began to connect jet fans to set the desired longitudinal airflow. At the same time as the fire detection, the responsible exhaust fans were started the corresponding air exhaust damper was opened (Fig. 2-b) and the intended blade angle of the exhaust fans was approached. The axial fans were located in the north and south portals of the tunnel at the ventilation station. The double-sided in-flow exhaust air damper was reached after less than 2 minutes. At this condition, around 270 m^3/s of air extraction was available at the extraction point. In a short time, the smoke was controlled from both sides of the fire (see Fig. 7), and until the end of the fire, the smoke was pulled and discharged accurately through the activated damper. Eventually, the fire was extinguished naturally after about 11 min.

Ambient weather condition

A proper measuring system was installed at each portal for ambient weather conditions e.g., wind speed and direction, humidity, and pressure monitoring during the tests. The average temperature at the north and south portals was 14-16 °C. The ambient wind speed at the north portal was about 0.6 m/s in 180°-240° direction and the south portal was 0.6-1.2 m/s with relatively high turbulence in different directions. The humidity was around 92% for the south and 87% for the north portal during the test. The barometric pressure difference between the two portals amounted to 45 Pa. This resulted in a natural airflow of around -2.2 m/s without active ventilation in the tunnel. The longitudinal air velocity was measured at a distance of about 150 m (both sides) from the fire location (Fig. 2-a). Two ultrasonic converter systems, sender and receiver, at a distance of 12 m at 45° were applied for this purpose. These measurements took place to control and ensure the accuracy of the data stored by SCADA for the employed sensors (MQ2 and MQ3). The results of measurements and output of SCADA is showing very good agreement. This simultaneous measuring is validating recorded data by SCADA as well.

CFD INVESTIGATION OF THE BOSRUKTUNNEL FIRE TEST

Fire dynamics simulator (FDS) was employed for CFD simulation of the fire inside the tunnel. FDS is an open-source code that is widely used for fire simulation in tunnels. FDS solves numerically, a set of thermally driven Navier-Stokes equations for low–speed (Ma<0.3) flows. The software is appropriate for fire simulation, smoke, and heat transfer. The software has been used by many researchers in full or scale-model studies [28-31].

Fire dynamic simulator (FDS) solves numerically a form of the Navier–Stokes equations for thermally-driven flow. It includes both DNS (Direct Numerical Simulation) and LES (Large Eddy Simulation) models. The LES model is widely applied in the simulation of fire-induced smoke flow behavior in tunnels and is used in the present simulation study as well. The governing equations for mass conservation, conservation of momentum, and the conservation of energy is shown in Equations (1) to (3), respectively 0.

$$\frac{\partial \rho}{\partial t} + \nabla.\rho u = \dot{m}''' \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u) + \nabla.\rho uu = -\nabla p + \rho g + f_b + \nabla.\tau_{i,j} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h_s) + \nabla.\rho h_s u = \frac{Dp}{Dt} + \dot{q}''' - \dot{q}_b''' - \nabla.\dot{q}'' + \varepsilon \tag{3}$$

In the LES method, the sub-grid turbulence model (SGM) has been commonly used. The turbulent sub-grid model considered by FDS is the modified Smagorinsky model. Equation (4) presents the turbulent viscosity which is defined in FDS.

$$\mu_{LES} = \rho(C_s\Delta)^2[2\bar{S}_{ij}:\bar{S}_{ij} - \frac{2}{3}(\nabla.\bar{u})^2]^{\frac{1}{2}} \tag{4}$$

Where Δ is $(\delta x \delta y \delta z)^{1/3}$ and C_s is an empirical Smagorinsky constant. According to the validation works, the constants C_s, Pr, and Sc, are set as default values in FDS and for the current simulation as 0.2, 0.2, and 0.5, respectively. For numerical convergence justification Courant–Friedrichs–Lewy (CFL) Constraint is used in FDS. The CFL number restricts the time step for large-scale calculation where convective transport dominates. The estimated velocities at each time step are rechecked to ensure that the CFL condition is satisfied in Equation (5).

$$\delta t.\max\left(\frac{|u_{ijk}|}{\delta x},\frac{|v_{ijk}|}{\delta y},\frac{|w_{ijk}|}{\delta z}\right) < 1 \tag{5}$$

The Bosrucktunnel tunnel is too long for a full CFD numerical simulation (5.5 km). Most parts of the tunnel length were not directly affected by the fire. Therefore, only the section that is directly affected by the fire is included in the model. That part included activated dampers, active jet fans, and measuring sensors which were required in the tests. To consider the effects of removing other parts of the tunnel, such as pressure drop, meteorology, and similar issues, the appropriate boundary condition obtained in the measurements was used. However, as only the fire region has a pronounced 3D behavior of the flow field, only this region was considered in the calculations. Due to the availability of reliable data from fire test, it is possible to define proper boundary conditions for a limited length of the tunnel. The selected calculation domain involved the fire location, sensors, and activated extraction damper. Therefore, in this study, a model with a length of 800 m was enough for CFD simulation. The calculation domain covers well the whole fire test boundary and airflow measuring in up and downstream the fire (see Fig. 1 MQ2 and MQ3). This approach and domain simplification method is already applied by some researchers [25-27, 36]. *Levoni et al.*, have simplified the calculation domain of the 11.6 km long Mont Blanc Road tunnel to 300 m with proper boundary definition on both sides of the calculation domain.

The effect of the longitudinal slope was also considered in the calculations (see also Fig. ***1***). Comparison of outcomes from CFD simulation and of recorded data in the fire test gives a better understanding of the system reaction and smoke behavior in the tunnel.

Boundary conditions

The whole CFD model domain is divided into 10 separate zones with different meshes. Fig. 3-a depicts the top view of the main parts of the domain where the pool fire is located. A cross-sectional view of the tunnel CFD model is shown in Fig. 3-b. The material of the pool body, and tunnel walls was steel and concrete, respectively. As can be seen in the figures, the location of the fire has a very fine mesh size. In the region of the extraction point (damper), the mesh size is somewhat coarser. The size of the meshes in the combustion area, and also in the other part of the domain was based on the proper mesh size calculations for the FDS model [25-26, 28].

The pool fire boundary and airflow regime were the main and important boundary conditions that had to be determined in the current study. This data is taken from the experiments. Fig. 4-**a** presents the considered airflow boundary condition for the area upstream of the fire (see Fig. 1 ,MQ3). The velocity profile is taken from experimental data which was available from the measurements (Fig. 9, MQ3). After fire ignition, the velocity was around -2.2 m/s concerning the measurements. The extracted volume flow from the activated damper is shown in Fig. 4-**b**. This boundary condition and the operational schedule were also based on the measured experimental data. Air velocity on the other side of the fire (~3 m/s) is calculated by FDS in simulation. The result shows good agreement with the measurements.

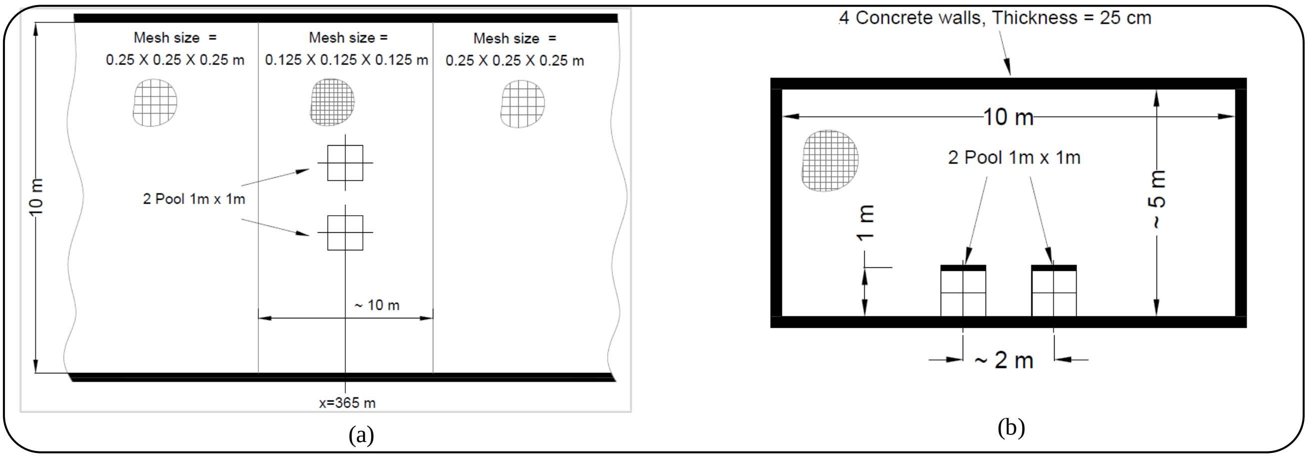


Fig. 3 : Calculation domain geometrical configuration, (a) top view of the mesh configuration in the main parts of the domain, (b) cross-sectional of the CFD model.

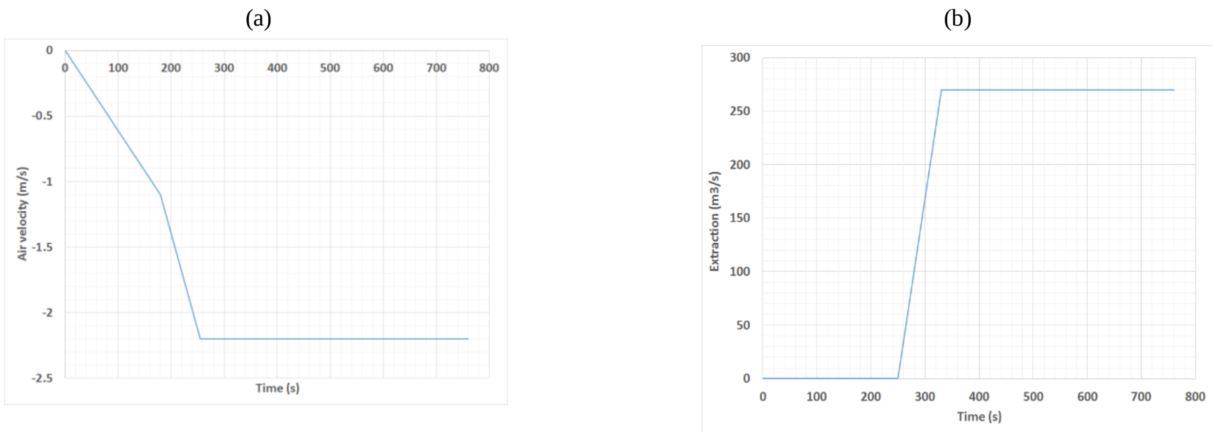


Fig. 4: Air velocity boundary condition according to the measurements, (a) air velocity at upstream the fire (MQ3), (b) Hot smoke extraction volume flow through the damper

The ambient temperature was 13°C according to the achieved experimental data from the tunnel. Table 1 summarizes the applied boundary condition in the simulation.

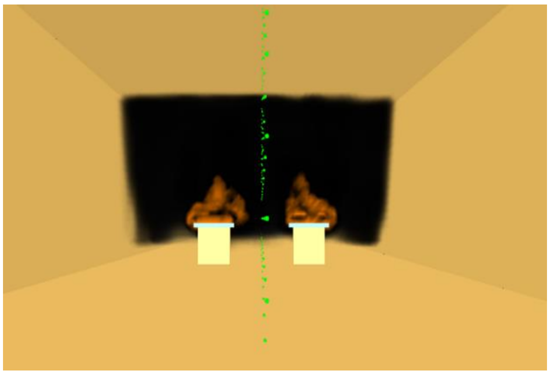
CFD simulation of fuel combustion

The assumed liquid fuel for the combustion model has the same technical specification as the burned fuel in the test. Due to the same airflow and ambient conditions, the flame showed good adaptation by test (see Fig. 5). The presence of gasoline (5 liters) was for better and faster ignition of the fire in the test. For simplicity, the gasoline part of the fuel (5 liters in each pool) was ignored in simulations. For this reason, the fire ignited after about 180 seconds in the FDS simulation. The reason is that, for combustion initiation, the required amount of heat (ignition temperature) is achieved 180 seconds after the start of the fuel chemical reaction. That means the FDS model needs 180 seconds for fuel combustion initiation (see Fig. 6). Before that time, combustion is running with a very low heat release rate and can be ignored. Within the mentioned 180 seconds, a stationary flow condition is achieved. Also, airflow reached the current limit at the moment of starting the fire in the fire test. Therefore, the condition of fire initiation and airflow in the simulation was similar to the measurements (see Fig. 8, Fig. 9).

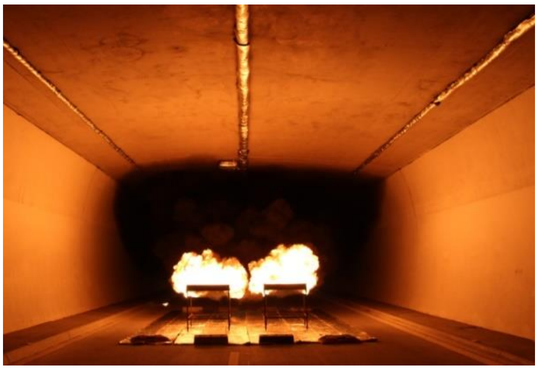
The calculated heat release rate (Fig. 6-a) is the result of real combustion. The fuel combustion is based on an oxygen consumption model. Fig. 6-b depicts the total amount of the burning rate for assumed 2×1 m ^{2} pools. According to previous studies, the fuel-burning rate or the reduction of fuel mass over time (0.045-0.055 kg/s.m^2) shows very good adaption. The combustion process reached its maximum heat release rate within about 300 seconds after the initiation. This continued for about

Table 1: A summary of the boundary condition used in the simulation.

No.	Boundary discription	Values
1	Air velocity upstream (m/s)	- 2.2
2	Air velocity dowstream (m/s)	~ 3
3	Selected calculation domain length (m)	800 m
4	Fuel pool for fire combustion modeling (m^2)	2×25 litter (1×1×0.15 m)
5	Extraction from smoke damper (m^3/s)	270
6	Tunnel cross section area (m^2)	~ 50
7	Tunnel hydrolic diameter (m)	~ 6.75



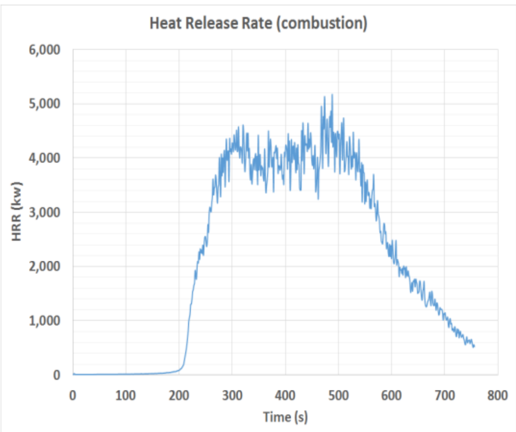
(a)



(b)

Fig. 5 : Pool fire combustion, FDS simulation model (a) and pool fire burning during the Bosrucktunnel fire test (b).

(a)



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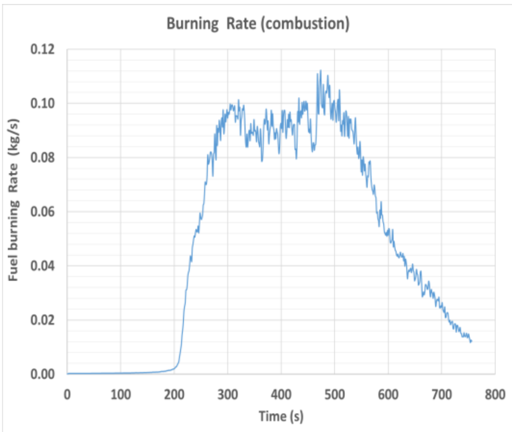

Fig. 6: Calculated heat release rate (a) and burning rate in CFD simulation of the fire (b).

370 seconds (or up to 550 seconds after the simulation initiation) with a heat release rate of about 4 MW. The assumed fuel quantity in the pool is burnt within about 10 minutes. As can be seen in Fig. 6 the simulation

is stopped before the completion of the combustion. The reason is that the fire load is reduced to around 500 KW which is not considerable. However, the main parts of the HRR and burning rate diagram are quite close to what happened in the fire test. Also, the heat release rate and burning rate show good adaptation compared to what was estimated in other experimental studies [1, 4, 24] and it is comparable to RVS 09.02.31 for recommendations such as fire test configuration (3-5 MW).

Combustion model

FDS simulates fuel combustion using two different models. The default combustion model is the single-step – mixing control or elsewhere, known as the mixing-controlled combustion model. The second combustion model is the finite-rate reaction model. The latter requires a very fine mesh, which is not usually practicable for the combustion simulation of a tunnel fire. The method which is applied here uses a different concept from the numerical simulation methods that have been used to study the reaction and improve the fuel cell performance 0. The reaction scheme of the fuel for the "simple chemistry" in the mixing-controlled combustion model in FDS is shown in Equation (6).

$$C_xH_yO_zN_v + (v_{O_2})O_2 \rightarrow (v_{cO_2})CO_2 + (v_{H_2O})H_2O + (v_{CO})CO + (v_{Soot})\,Soot + (v_{N_2})N_2 \quad (6)$$

The chemical composition of the fuel as well as the yield factors for soot and CO have to be defined by users in combustion modeling. These yield values were available for real diesel combustion. The values amounted to 0.011 and 0.04 for CO and soot, respectively (SFPE). The other parameters are automatically calculated by FDS.

The heat release rate from the fire is the most important factor in the fire combustion simulation. FDS calculates the heat release rate from Equation (7). Where, $\dot{m}_a$, $\Delta h_{f,a}$, $\dot{q}'''$ are mass of species, the heat of formation of species, and corresponding heat release rate per volume unit, respectively.

$$\dot{q}''' = -\sum \dot{m}_a{}''' \,\Delta h_{f,a} \quad (7)$$

The combustion of diesel fuel is defined as a "simple chemistry" combustion model for the simulation of the pool fire in this study.

The goal of the simulation of the combustion in this study was not only to simulate the combustion process. Rather then, the goal was to bring the fuel burning time and the heat release rate profile as close as possible to the real situation of the fire test. In this case, the evaluation of smoke behavior, temperature, velocity profiles, and, in general, say, system reaction compared with a real fire test will be possible.

RESULTS AND DISCUSSION

The output of this study should be considered from important aspects such as smoke management by the ventilation system, smoke and temperature distribution in the cross-section and length of the tunnel, and fuel combustion process (combustion time and maximum heat emission rate). Also, in all the above cases, the timing which plays a vital role in rescue is analyzed.

Fig. 7-a depicts smoke distribution in the tunnel during the combustion process. As previously mentioned, from the beginning to 180s the fire appears as a very small fire in simulation. This period was required to earn the combustion heat in the considered simulation model. After about 180 seconds from the beginning of the chemical reaction, the main ignition process of the fuel is started. According to the referred fire test, the fire was detected after 70 seconds (about 250 seconds after the start of the fire in simulation) and in that time, due to the -2.2 m/s airflow, the smoke was extended about 150 m (Fig. 7-a). The longitudinal extension of smoke during the fire test was similar to the simulation. However, as is shown in the simulation results and was also observed in the fire test, the hot smoke is diffused on the lower level of the road. After about 280-300 seconds from the start of the simulation, the maximum heat release of around 4MW is obtained. This is also the time at which smoke propagation is limited due to the proper reaction of the emergency ventilation system. Similar to the fire test, after another 70 seconds (350 seconds), a hot smoke extraction (damper opening) is achieved. Fuel combustion at maximum HRR lasts until 550 seconds. Within this time (350-550 seconds), the fire is burning with a maximum heat release rate, and smoke in the tunnel is confined between the fire location and the extraction damper. From 550 seconds onwards, the heat release rate is showing reduction behavior (combustion power reduction) and within 200 seconds (750 seconds) is closed to 500 KW. According to the qualitative observation of the test (burning time, smoke movement, recorded by video

systems), the simulated combustion process was quite similar to the experimental fire test.

Longitudinal air velocity is another parameter for comparison with the experimental data. Fig. 8 presents the cross- sectional averaged longitudinal air velocity from the CFD calculation. As mentioned previously, air velocity upstream of the fire and extraction volume flow boundaries were assumed based on experimental measurements during the fire test. According to CFD calculation and taking into account ± 0.3 m/s the accuracy of the measurements, air velocity shows good adaption with experimental measurements (Fig. 8 and Fig. 9).

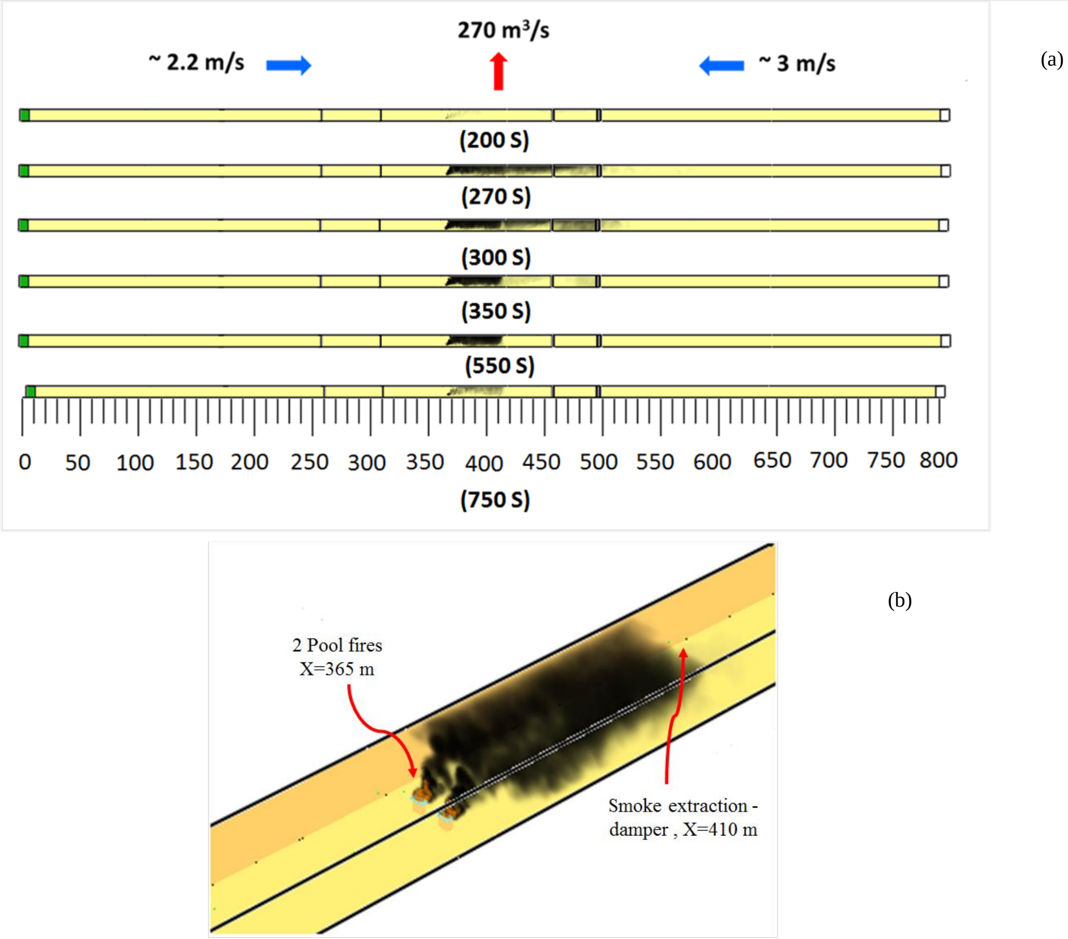

Fig. 7: CFD simulation results for smoke distribution along the tunnel length with respect to the time (a) longitudinal smoke propagation during the fire (b) Smoke view when it is blocked between fire and extraction point).

Fig. 10 shows the temperature course 10-15 cm below the ceiling at different distances downstream of the fire location. As it is clear from the temperature profiles, at the beginning of the fire (until 300 seconds) the maximum temperature is increased to about 25°C. This increase covers a length of up to 60 m downstream of the fire. This was due to the extension of the hot smoke downstream from the - not yet operating - extraction point. In addition, the temperature at the distance of 30 is increased to 40-50°C. The temperature profile in the area between the fire and the extraction damper (e.g., 40 m and before) shows similar behavior to the heat release rate during the combustion. The ambient temperature was 13 °C, based on the experimental data from the tunnel and it was taken into account in the boundary definition for the FDS calculation as well.

According to the test outcome, the maximum recorded temperature was about 37°C during the fire test. This temperature level is slightly lower compared with the simulation. The difference between measurements and simulations can be explained by the part insulation of the linear heat detector cable during the fire. The isolation was employed to prevent any possible damage to the LHD cable and other tunnel equipment during the tests (Fig. 5-b). However, in the other tests with more or less the same fire and boundary configuration, the measured temperature is quite close to the current CFD calculations results 0.

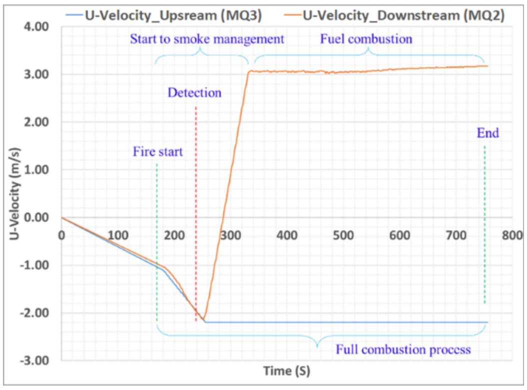

***Fig. 8:* Longitudinal air velocity upstream and downstream the fire – CFD calculation.**

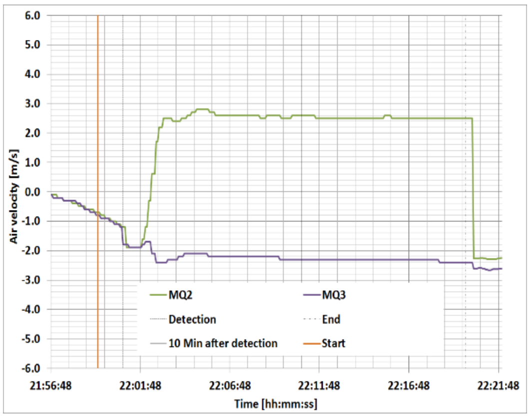

***Fig. 9:* Longitudinal air velocity profile upstream (MQ3) and downstream (MQ2) the fire –fire test.**

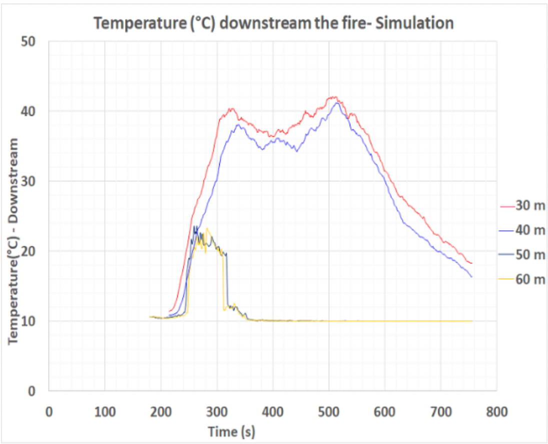

Fig. 11 depicts the cross-sectional distribution of temperature at specific distances from the fire. Hot smoke is confined between the fire source and extraction point and this has resulted in relatively higher temperature levels.

***Fig. 10:* Air temperature profile downstream at different distances from the fire in 10-15 cm under the ceiling– CFD calculation.**

Temperature distribution and smoke layering in the central axis of the tunnel are shown in Fig. 12.

Fig. 12 presents temperature and hot smoke distribution in a vertical plane along the tunnel center for steady-state calculation (s=480 s). In this way, 480 s after the start of the simulation and steady-state calculation, the maximum temperature is calculated at around 50 °C. One of the results of the correct reaction of the system and the proper discharge of smoke is the prevention of the increase in the temperature level, which can be seen here. The maximum temperature level is calculated in the area close to the fire under the ceiling. Furthermore, hot smoke and gases are washed down near ground level in the locations close to the fire and extraction point. This can be due to the effect of two opposite and relatively high (higher than critical velocity) forces from the air pressure. This situation was observed almost similarly during the whole steady-state combustion calculations.

CONCLUSIONS

The Bosrucktunnel ventilation and control system was confirmed in a full-scale experimental and numerical study. In this regard, the whole tunnel's safety was shown successful reaction during the fire test. Furthermore, good smoke management and evacuation from the single extraction point without any back layering were observed. This was possible by the mentioned proper reaction and air velocity set upstream and downstream of the fire. Air velocity arrangement was achieved by jet fans and axial fans activation. In general, smoke was blocked between the fire and the extraction point in a short time after detection and the situation was almost the same during the test. This situation is necessary for good rescue activities during a fire.

The whole fire test process, including combustion and airflow, and smoke behaviour was simulated in a full-scale simplified CFD model. The simulation model was applied to calculate some parameters like the combustion process, heat release rate, burning rate, and duration of the burning. Furthermore, the distribution of hot smoke, temperature contour, and air velocity profiles was also simulated. The mentioned calculated parameters show good agreement with the current experiment and also previous works and standards. This was helpful to validate and prove the simulation of pool fire in the test. Hence, the extraction of some information about the fire behavior in the commissioning test was possible.

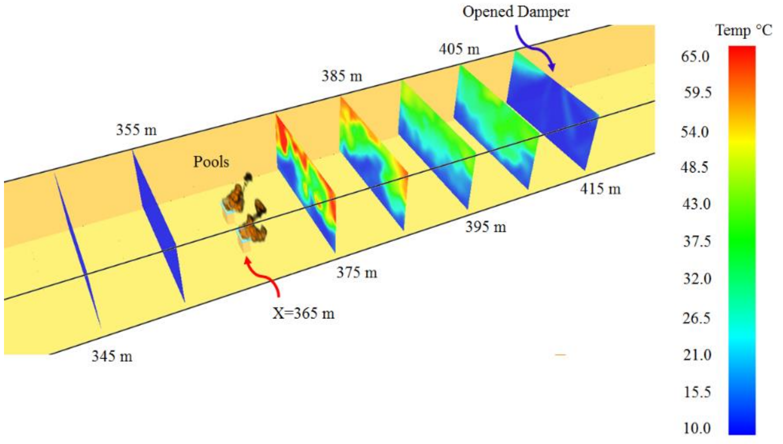

***Fig. 11:** Air temperature at the different distance downstream the fire, steady-state CFD calculation (t=480 s).*

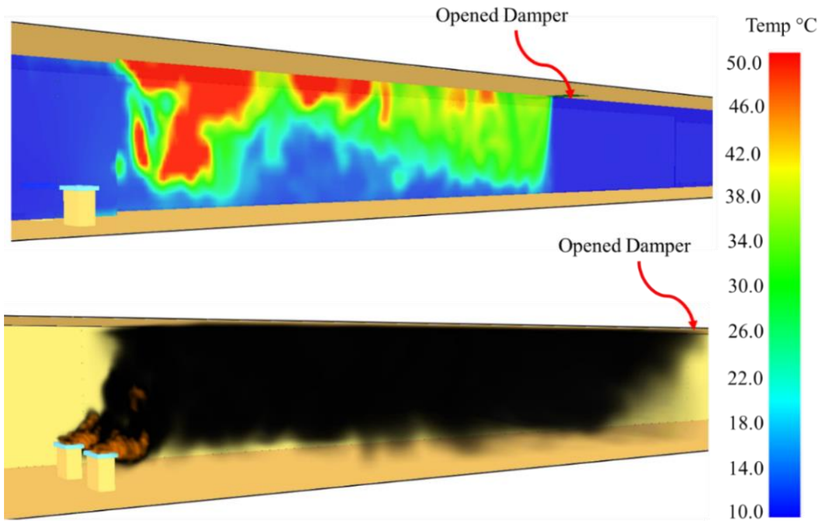

***Fig. 12:** Air temperature at the central axis of the tunnel downstream the fire, steady state CFD calculation (t=480 s).*

It has to be mentioned that fire with a higher heat release rate shows completely different behavior. The temperature contour and the area and level of smoke coverage are the main differences. This would be seen from the ignition of fire until the reaction of the ventilation system and also after that. However, the important point (and outcome of this study) is that the current ventilation system showed a proper response in creating a target airflow on both sides of the fire and extraction. The mentioned airflow and velocities that are created in the fire test can easily cover smoke extraction up to 30 MW fires and even higher. This will create a very good opportunity for rescue and firefighting for the rescue forces. However, a rapid response of rescue services and firefighters in a bus or HGV fires will be much more important compared with small passenger cars. In such conditions, only a proper system reaction can help to deal with very high temperatures and prevent casualties and the destruction of tunnel equipment.

The study of safety and ventilation systems in traffic tunnels on a real scale is a difficult and expensive task, and usually, the main goal of such studies is to check and confirm tunnel safety systems. For this reason, there are many limitations in repeating the tests, a deeper examination of the results, and the effect of different parameters. Therefore, it is suggested that in the continuation of this work, the process used in this study should be carried out on a model scale, or, if possible and conditions exist, more tests should be performed.

Abbreviations

CFD	Computational fluid dynamics
RVS	Austrian road tunnels ventilation standard
FDS	Fire Dynamic Simulator
MW	Megawatt
CO	Cicerone monoxide
CO2	Carbone dioxide
FFFS	Fixed firefighting system
HGV	Heavy good vehicles
Km	Kilometres
SFPE	Society of Fire Protection Engineers
HRR	Heat release rate
EU	European union
TST	TST tunnels in Spain
LHD	Linear heat detector

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