Hot Smoke Tests for Smoke Propagation Investigations in Long Rail Tunnels

Peter Sturm [1), Johannes Rodler [2)], Thomas Thaller [3)], Johannes Kari [3)], Daniel Fruhwirt [1)], Patrick Fößleitner [2)]
1) Graz University of Technology, Austria
2) FVTmbH Graz, Austria
3) ÖBB Infrastruktur AG, Austria
Corresponding author: Peter Sturm, Graz University of Technology, Austria
E-mail: sturm@ivt.tugraz.at

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ABSTRACT
Smoke propagation in an enclosed facility is always a matter of concern whenever the evacuation of people is necessary. The construction of long rail tunnels has made evacuation an even greater challenge. Long rail tunnels are equipped with emergency stop stations so that evacuation may still occur even when trains are on fire and incapable of leaving the tunnel. However, should a train breakdown occur between the portal and the emergency station, passenger evacuation has to be performed via cross passages and into the non-affected (safe) tube. This requires a balanced pressure regime between the two tunnel tubes and/or across the cross passages. The paper describes field tests which were performed in order to investigate smoke propagation in tunnel tubes and over cross passages in the event of severe fires. Fire tests up to 21 MW peak heat release rate were performed, and smoke propagation was monitored, with a strong focus on the situation at cross passages.

INTRODUCTION
Smoke propagation in tunnels and especially smoke transport via cross passages into safe areas are of considerable interest in emergency cases in long tunnels. In Austria, three quite long high-speed road tunnels are under construction. These are the Koralm Tunnel with a length of 33 km, the Semmering Base Tunnel with a length of 27 km and the Brenner Base Tunnel (together with Italy) with a length of 55 km. All these tunnels have emergency stop stations for emergency passenger evacuation. However, the possibility of a train breakdown in the tunnel between portal and emergency station can never be ruled out. In such cases the evacuation of passengers has to be performed via the cross passages into the non-affected (safe) tube. In the case of a fire the safe tube is normally set under overpressure. This therefore raises the question as to which type of equipment has to be installed in the cross passages to maintain this pressure balance and to avoid smoke penetration into the cross passage. Additional ventilation equipment might be needed to maintain the overpressure and to supply clean air.

In order to assess the extent to which installation and maintenance costs might be minimized, full scale tests were performed in an existing and separately ventilated section of the Koralmtunnel. Fire tests were performed in order to monitor smoke propagation in the tunnel, and in the region of the cross passages. These tests entailed a max. heat release rate of up to 21 MW. The tests were performed with and without active water mist systems in order to estimate the influence on visibility inside the smoke-covered region downstream of the fire location. The parameters investigated concerned heat, air velocity in the tunnel, and pressure differences between the tubes etc. Smoke propagation was investigated on basis of image processing of the video data. A precise quantification of the smoke volume flow rate was intended but failed due to imprecise information from video images.

TEST LOCATION AND TEST SET-UP

The tests were performed in the Koralm Tunnel in the south of Austria. The tunnel has a length of 33 km and a maximum overburden of up to 1,200 m. Figure 1 shows a sketch of the tunnel, and of the test section in the east, KAT 1. The section has a length of roughly 3.5 km and covers the stretch between the east portal and the ventilation shaft at Leibenfeld. Within the test section, 5 cross passages connect the two tunnel tubes. As tunnel excavation and construction activities were (and are) still in progress, a clear separation of the test section from the rest of the tunnel was required.

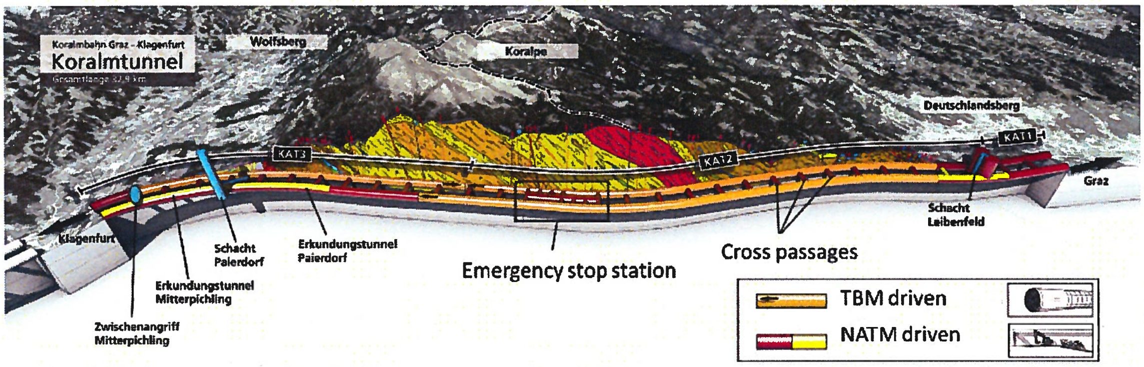


Figure 1: Sketch of the Koralm tunnel (source: ÖBB)

A detailed description of the test location and the measurement procedures can be found in reference [1]. The following gives a short overview of the most important items. Figure 2 shows the test section. The air flow was provided by two axial fans installed in the brattice at the east portal of the north tube.

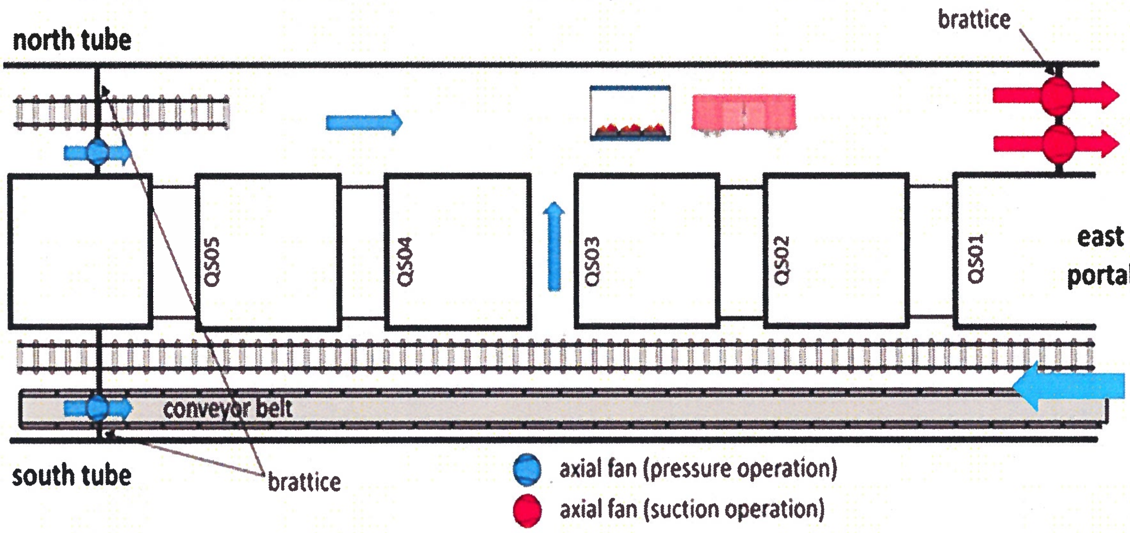
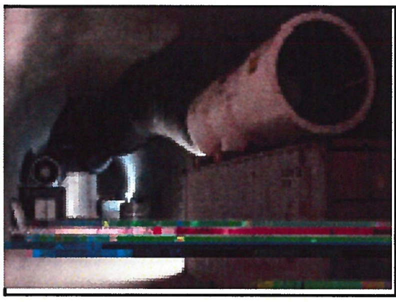


Figure 2: Sketch of the test section in KAT 1 of the Koralm tunnel (source: ÖBB)

Air was brought into the tunnel via the east portal of the south tube. The cross passage 3 (QS03) acted as a bypass to bring the air into the north tube. Hence, there was a U-shaped flow, with air flowing in via the south tube and being expelled via the north tube. The fans in the two brattices separating the test section KAT 1 from the remaining tunnel (KAT 2 and KAT3) were rarely used as they provided only little air. Hence, these fans acted mainly as a fall-back provision in case of a break-down of the main fans during fire tests.

The fact that both air streams, the fresh one via the south tube, and the polluted one via the north tube, were exchanged via the east portal resulted in some problems concerning air re-circulation. Although

between the two portals a quite a long separation wall is erected, under extreme meteorological conditions it happened that that smoke exiting the north tube was recirculated into the south tube. This resulted in increased safety provisions being provided, such as a pressurized rescue train close to the fire location in the south tube, etc.
Figure 3 provides an illustration of the fans at the brattice and also provides the most important fan parameters. The fans were capable of producing air flows of up to 150 m^3/s. However, the prevailing complexity of the aerodynamic system meant that it was impossible to adjust any steady state conditions of the air flow in the test region. There was always a quite noticeable oscillation of the air speed in the whole system. Both fans were speed controlled.



Parameter	Unit	Value
Impeller diameter	[mm]	1,600
Volume flow rate	[m^3/s]	46 to 74
Total pressure increase	[Pa]	2,750 - 820
Shaft power	[kW]	160
Number of fans	#	2

Figure 3: Axial fans and fan parameters

Air speed was monitored by ultrasonic path-averaged measurement equipment at various locations in the tunnel (see Figure 4) and temperature by PT100 sensors (Platine sensor with a resistance of 100 Ω) along the tunnel and over various heights at the measurement locations (see Figure 5). Smoke movement was monitored by video cameras. The attempted usage of smoke (opacity) sensors failed, due to their limited measurement range (in fact they quickly exceeded their measurement range as the smoke was really dense). At downstream locations, where the smoke already filledthe tunnel from roughly 1 m above road surface level, visibility was in most cases in the range of 1 to 4 m. Measurements of the pressure difference between the tubes at QS02 complemented the measurement set-up.

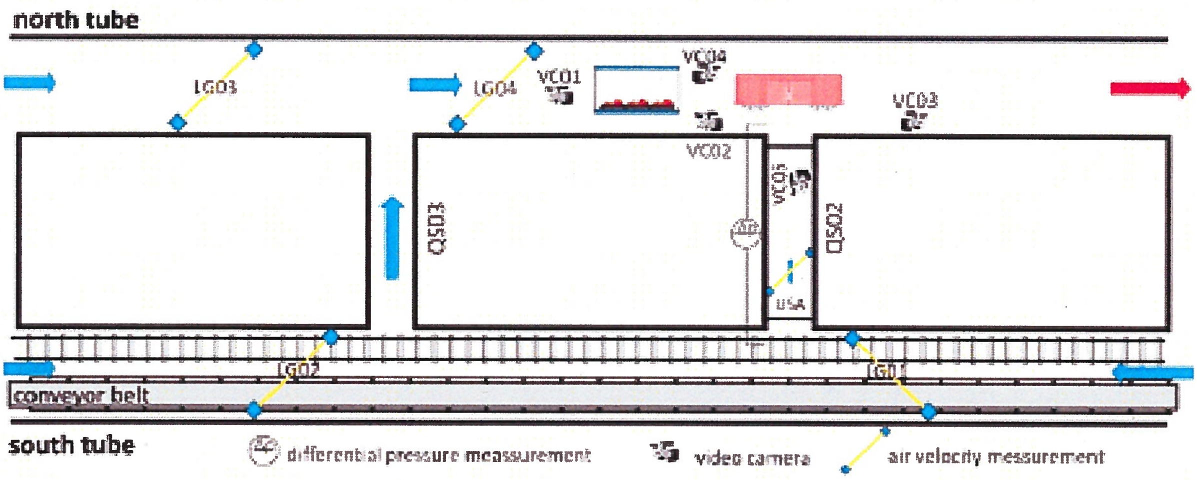


Figure 4: Measurement set-up for air velocity (LG0x), video monitoring (VC0y) and pressure difference between the tubes at the closed cross passage

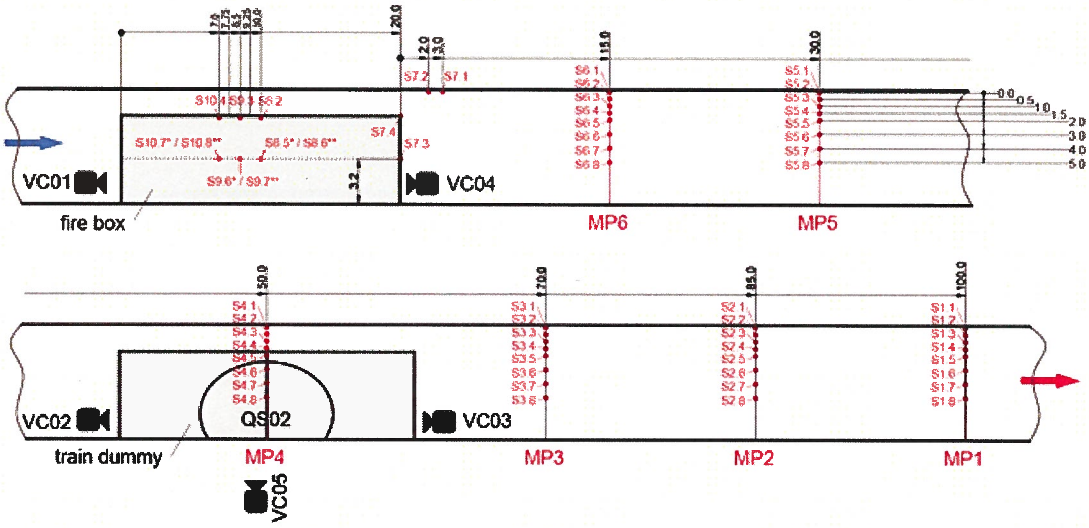


Figure 5: Measurement set-up for air temperature (Sx.y) and video monitoring (VC0x)

Two different types of doors were installed in the cross passage used for the investigations. While one side was closed with a sliding door, a swing door was used on the other side (see Figure 6.

Figure 6: Escape doors; sliding door (left), swing door (right)

FIRE SITE AND HEAT RELEASE RATE

Pools with an area of 1 m² were used as fire sources. Variation of the heat release rate (HRR) was achieved by varying the number of pools. A mixture of 20 l diesel and 5 l gasoline per pool [2] was used as heat and smoke source. The heat release rate was derived from high quality measurements of the fuel mass loss. A set of four pools were placed on a platform, weighing the loss of fuel mass. The recording was done on a 1 Hz basis. The heat release rate was calculated from the loss in fuel mass and a calorific value of 44.4 MJ/kg fuel. Figure 7 shows, by way of example, the course of the fuel mass values in the pools. The scales were calibrated several times during the various experiments

Table 1: Test parameters

Test	No. of pools	HRR average	HRR maximum	Duration	Air velocity at start	Air velocity average
[#]	[#]	[MW]	[MW]	[min]	[m/s]	[m/s]
BV 1	2	2.3	4	00:15	1.54	1.3
BV 2	4	5.5	8	00:13	1.12	1.75
BV 3	2	2.3	4	00:16	0.6	1.22

Test	No. of pools	HRR average	HRR maximum	Duration	Air velocity at start	Air velocity average
[#]	[#]	[MW]	[MW]	[min]	[m/s]	[m/s]
BV 4	4	6	8	00:10	1	1.49
BV 5	6	7.2	11.5	00:12	1.2	1.74
BV 6	8	9.5	14.3	00:12	1.5	2.16
BV 7	8	14.5	19.5	00:08	1.37	1.77
BV 8	4	4.1	7	00:14	0.64	1.32
BV 9	4	6.0	8	00:10	1.23	1.54
BV 10	8	11.0	18.1	00:10	1.4	1.54
BV 11	6	5.0	9.3	00:17	2.3	2.21
BV 12	6	8.8	11	00:11	2.4	2.13
BV 13	10	9	21	00:16	2	1.91
BV 14	10	7.9	18.5	00:21	1.2	1.38

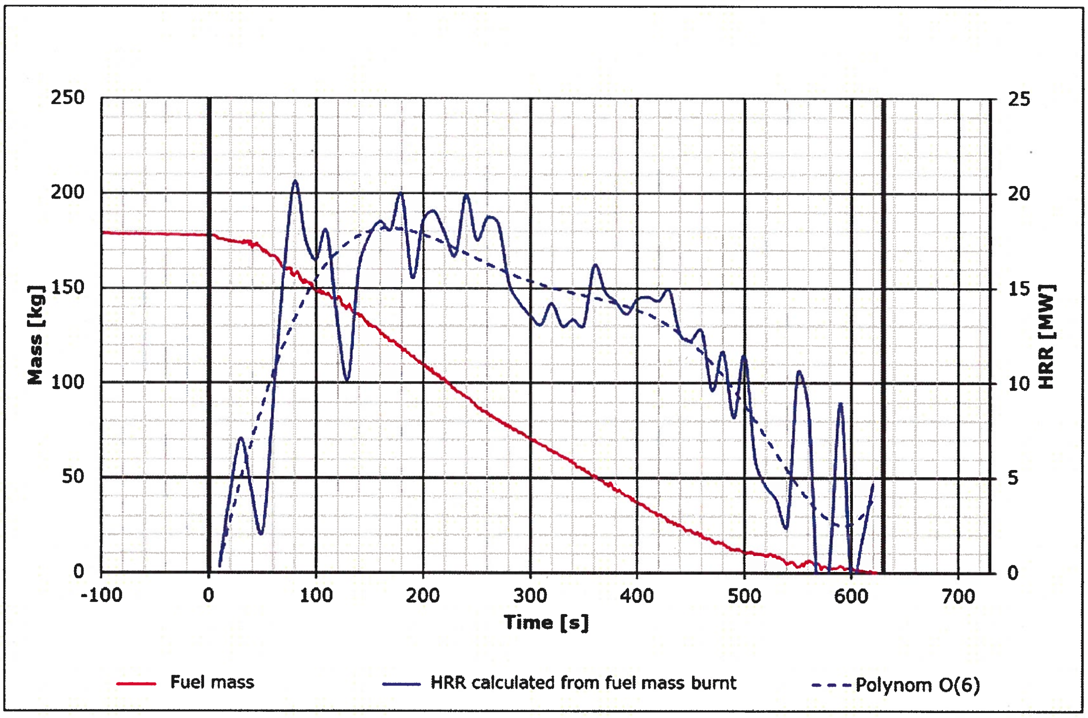


Figure 7: Measured fuel mass and calculated heat release rate

Due to the fact that the inner tunnel lining had already been fitted in the test section KAT1, damage to the existing surface had to be avoided. Hence, it was necessary to construct a 5m x 5m x 20 m fire box in order to prevent temperatures exceeding 120 °C at the concrete surface. The box consisted of two layers of fire protection boards. These can withstand surface temperatures above 600°c without any problem (Figure 8).

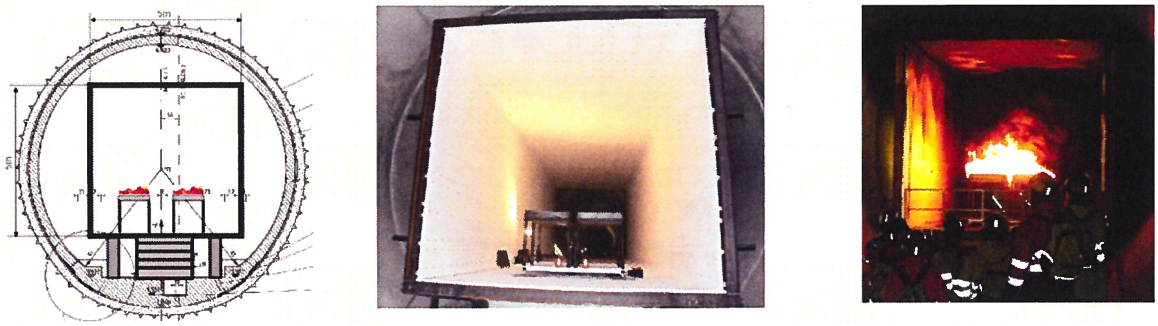


Figure 8: Fire site in a sheltered box

Two tests were performed applying a high pressure water mist system (HPWMS). The original purpose of this system was to act as an additional protection device in situations where the acceptable temperature levels for concrete were exceeded. The parameters of the water mist system were: water pressure, 30 bar; water volume flow rate 400 l/min; the area covered by the HPWMS was the full box plus one meter upstream, resulting in a water droplet density of 0.8 l/min/m³.
The prevailing conditions meant that the HPWMS could not be mounted and activated as it would be in the case of a real fire. Normally in such a system the zone upstream of the fire site is already activated. However, as this zone didn't exist in the experiments the water mist was released directly above the fire and only within a zone of 20 m in length.

RESULTS

The tests were performed between December 2016 and February 2017. In total, 14 tests were performed and the respective data recorded. The data concerned mainly temperature profiles, air velocities and images of the visibility and smoke propagation. The original intention to measure the extent of the backlayering had to be abandoned due to problems with the distance measurement upstream of the fire location. As a result, only a rough estimation can be given concerning the length and thickness of the backlayer in the individual cases.
Most of the data processing, especially that concerning dependency of the backlayer length on heat release rate and parameters of the upstream air (air velocity, temperature and humidity) is still ongoing.

Figure 9 shows as an example the profile of the temperature curves at various distances downstream of the fire box and at various times during the test. As can be seen, there is strong layering of the smoke/air over height. Figure 10 gives a closer look at the single locations. At MP6, 15 m downstream of the fire box (i.e. roughly 30 m downstream of the last pool), the fire produced, at the most elevated sensor, air/smoke temperatures of up to 260 °C as soon as 150 s after ignition. During the course of the fire temperatures were in most cases between 180°C and 240°C.
As soon as the majority of the fuel was burnt the temperature dropped rapidly. It has to be mentioned that the burning behaviour of the fuel in the individual pools varied. In most cases the pools most downstream were the first to be empty. This is probably due to some extent to the higher temperature of the air streaming over the pools enhancing fuel evaporation, and therefore directly related to the external flame radiation. On top of that, the high turbulence generated by the flames of the upstream pool additionally enhanced the burning process. Another reason is the incident heat radiation towards the fuel surface, as it increases downstream the fire. Whatever the exact case, the amount of oxygen was always sufficient to burn the fuel in the pools further downstream without any problem.

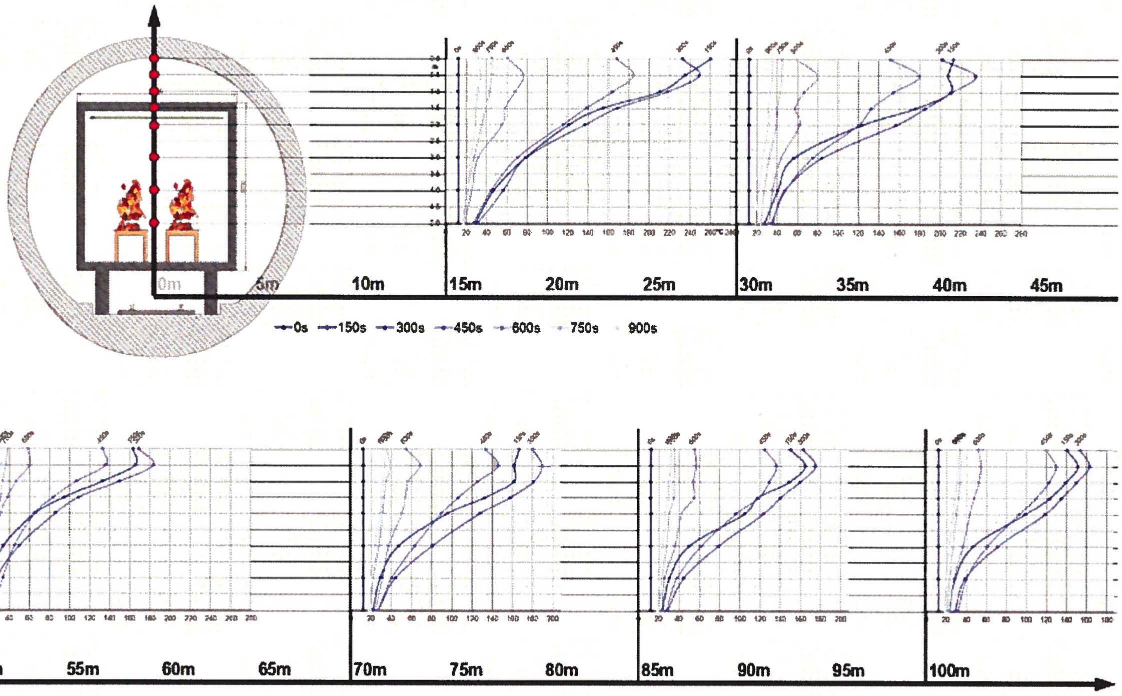
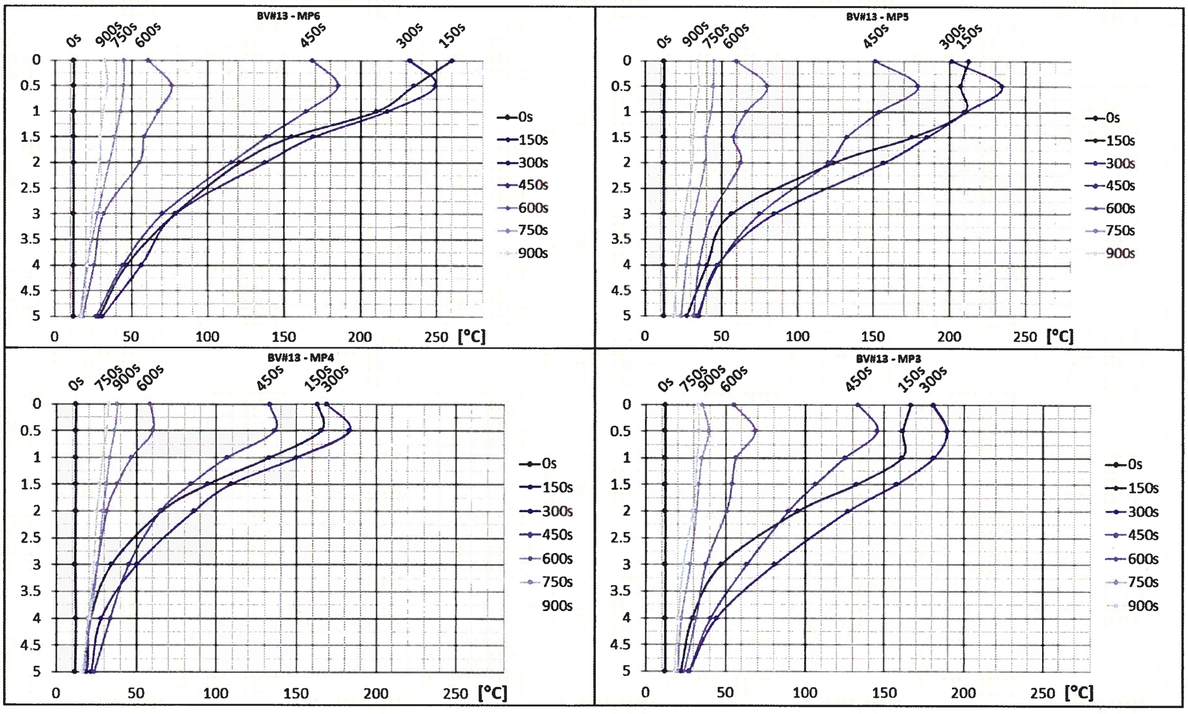


Figure 9: Fire test #13, 10 pools, max. HRR 21 MW, av. HRR 9 MW



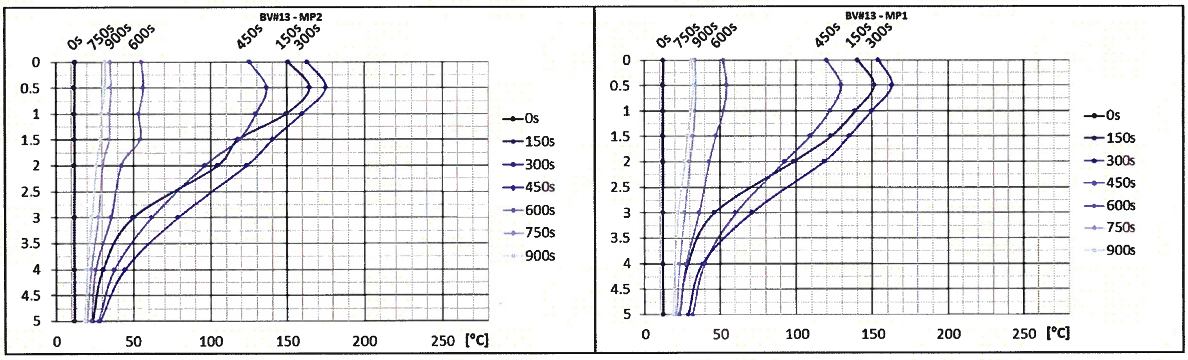


Figure 10: Fire test #13, Temperature profiles at the various measurement locations

In the lower regions (~5 m below the highest point) temperature rarely exceeded 40 °C. This is approximately the height of the head of an adult. However, it has to be mentioned that heat radiation at that location can be very high. The further downstream the temperature profile is measured, the less pronounced the profile.

In the course of test #14 the HPWMS was activated roughly 4 minutes after the start of the fire. As Figure 11 shows, temperature at MP 6 drops immediately after the activation, but mainly at the upper layers. Due to the mixing of hotter air and steam the lower layers even experience a small increase in temperatures. It took the water mist roughly five minutes to reduce the HRR effectively and bring the temperatures down to below 35°C on average. Figure 12 shows some images of the test before, during, and after the activation of the HPWMS.

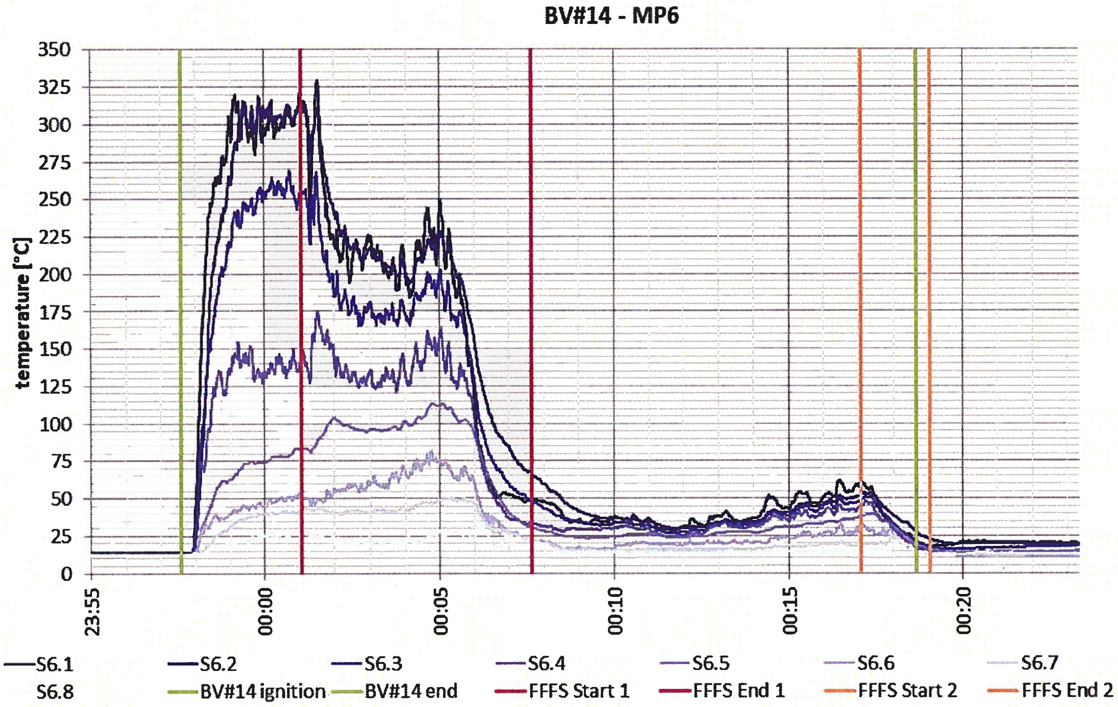


Figure 11: Fire test #14, 10 pools, max. HRR 18.5 MW, av. HRR 7.9 MW (FFFS = HWPMS)

Figure 12: Images from test #14 with HPWMS, w/o activation (left), with activation (middle), activation turned off (right)

Figure 13 shows the development of the temperature profiles along the tunnel at two distinct time steps. The first one is at 100 s after ignition, without activation of the HPWMS, while the second one, at 350s, has already experienced the active HPWMS. The interesting thing is, that at 15 m downstream of the fire box, the positive effect in terms of temperature reduction is clearly visible, but at 30 m downstream the effect diminishes, or is not visible at all.

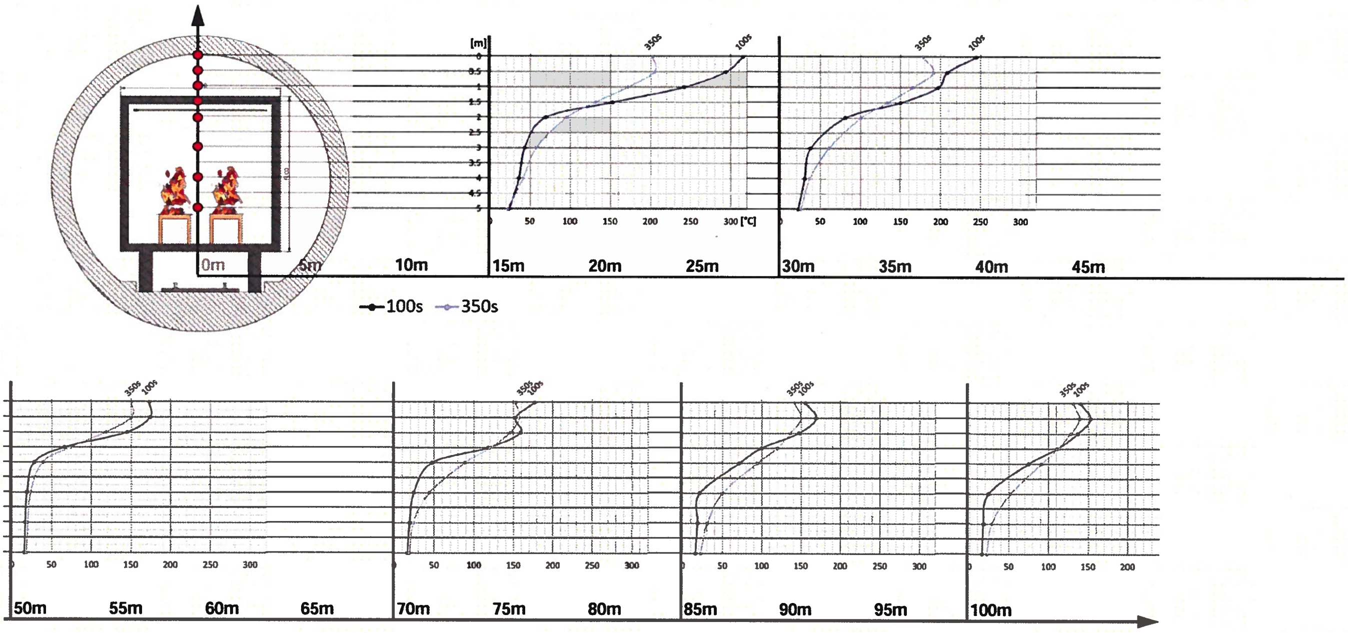


Figure 13: Temperature profiles from test #14 with HPWMS

Figure 11 shows clearly the positive effects of an active HPWMS. However, one also has to note that visibility at a height of 1 m above the floor dropped from a few meters at the location of MP6 to almost zero. Hence, for the case of the pool fire the positive effect of the temperature reduction was counteracted by the negative effects of the full loss in visibility. As the velocity of the air on the upstream side (cold) was well below critical velocity, a backlayer of considerable length was established. However, in contrast to test #13, which was performed without activation of the HPWMS, the backlayer was much thicker due to the high content of moisture in this smoke-filled layer. Hence, even upstream of the fire, visibility at head height was reduced. It has to be mentioned that those findings were derived for pool fires and the results might be different for solid fuel fires. In addition it has to be mentioned, that for demonstration purposes the activation of the HWPMS was very late. Hence the fire had time to grow and to produce a thick smoke layer. It is well known, that one of the major benefits of any kind of fixed fire fighting systems (FFFS) is to keep the fire small, but therefore a very quick activation is required.

CONCLUSIONS

The tests performed in the Koralm tunnel were designed to monitor the smoke propagation within the tunnel and through cross passages in the case of fire. The tests performed covered various heat release rates, starting small, and ending at 21 MW (maximum). A HRR in that range represents the typical HRR employed for passenger trains in the ventilation design process. Although the tests were finished in February 2017, data processing is still ongoing. However, the following qualitative results can already be stated:

- The tests with more than 6 pool fires (max. HRR > 10 MW) resulted in quite severe smoke production rates and strong restrictions in visibility downstream of the fire. However, visibility downstream of the fire was in all cases sufficient for persons to see the nearest escape signs, except in those cases with active FFFS.
- Temperature at a height of some 1.5 m to 2 m above floor level (height of head) never exceeded 30°C to 40°C.
- As the air velocities upstream of the fire never exceeded 2.5 m/s, backlayering was apparent. For smaller fires (< 10 MW) the smoke layer was stable and stayed at heights posing no problem whatsoever for people underneath. For bigger fires, the smoke layer upstream grew strongly in depth – not so much in length. For example, during the 20 MW tests (10 pools), the smoke layer extended down from the ceiling to some 1.5 m above the floor.
- The application of the HPWMS resulted in a clear decrease in downstream temperature and in HRR. However, visibility downstream of the fire was strongly restricted (note: the activation of the HPWMS started 6 minutes after the fully developed fire and the installation set-up was not as it would be in reality).
- Full data sets concerning the main parameters of the individual tests have been produced for model validation. These data are available for research purposes (e.g. model validation) on request.

Acknowledgements

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