ABSTRACT
Investigations concerning smoke dispersion in a rail tunnel were content of a research project, which was performed in the already finished section KAT1 of the Koralmtunnel in Austria. Full scale tests were performed, covering fires with a max. heat release rate of up to 21 MW. Smoke dispersion was monitored using video cameras and related temperature distributions at various sections of the tunnel were recorded. Focus of the investigation was the smoke dispersion in the region of the cross passages where passenger evacuation will happen.

The tests shall provide supporting information for the selection of the proper escape doors (swinging doors or sliding doors) which will be installed for passenger evacuation via the cross passages. In order to provide sufficiently safe conditions during the self-evacuation phase, smoke shall not restrict the escape possibilities. The tests aimed at investigating the interaction between fire load, smoke production rate and escape possibilities as a function of the installed ventilation system and the aforementioned parameters.

Keywords: safety in railway tunnels, fire tests, smoke dispersion, egress doors for cross passages

1. INTRODUCTION
Modern railway tunnels consist of two single-track tubes, which are connected via cross passages at a maximum spacing of 500 m. As soon as their length exceeds the maximum distance to be covered by the failsafe running function, an emergency stop station in the tunnel has to be provided. The both tunnel projects Semmering Base Tunnel (SBT) with a length 27 km, as well as the Koralmtunnel (KAT) with a total length of 33 km, are currently under construction and contain one emergency stop station roughly in the middle of the tunnel. Both projects are the key elements of the new ‘Südbahn’ between Vienna and Klagenfurt and are part of the Baltic-Adriatic TEN corridor.

The most serious problem of a rail tunnel under operation is the possibility of an incident with fire. Hence the decisive scenario for the risk assessment is the case ‘passenger train under fire’. From this perspective, the protection of passengers is seen as the major goal in case of an incident. In case of a fire a passenger, train should either stop at the emergency station if it has not passed it yet or exit the tunnel. The most unfavorable scenario is given when a train is forced to stop between portal and emergency station, thus passengers have to be evacuated via the closest cross-passages.

This requirement calls for smoke-free egress ways. Mechanical ventilation has to provide a positive pressure difference between the non-affected and the incident tube in order to avoid smoke penetration into the safe area, hence maintaining this pressure difference is of utmost importance.

As part of an ÖBB funded research project full scale fire tests were carried out from October 2016 until January 2017 in the already built section KAT1 of the Koralmtunnel. The tests contained fires with a maximum heat release rate of up to 21 MW. Main objective was to gain...
knowledge about the conditions while an incident particularly with regard to the smoke propagation at the different development phases of the fire.

2. PROBLEM DESCRIPTION

2.1. Smoke-free egress ways

On the one hand cross passages are used for housing the technical equipment needed for tunnel operation and safety issues, on the other hand they are used as escape routes into the safe area in case of an incident.

The mechanical ventilation system of the SBT is designed to serve this purpose [1]. In case of a stop in the emergency station, smoke will be extracted and fresh air supplied to the rescue rooms. In case of a stop between the rescue station and the portal, fresh air will be supplied to the non-affected tube and smoke extracted from the incident tube. Figure 1 depicts an incident situation between east portal and emergency stop station. Due to the resulting pressure difference, smoke cannot penetrate into the safe area.

![Figure 1: Sketch of the ventilation of the Semmering-Basistunnel in case of fire between east portal and emergency stop station](image)

2.2. Escape doors

There are manifold and partly even contradictory requirements when it comes to railway equipment of railway tunnels. This applies in particular to the escape doors of the cross passages. On the one hand, the doors have to stay tight regarding smoke despite the constant change of pressure and suction caused by the passing trains. On the other hand, they have to keep their functionality as escape doors in case of an incident, meaning the force, necessary to open it, must not exceed 100 N.

In the design phase for the approval of the railway authorities for both projects SBT and KAT, swing doors were planned. These double wing swing doors – the wings open in both directions – meet the requirements regarding escape routes best because they can be used as escape doors in both directions depending on which tube is affected. Alternatively, the use of sliding doors should also be possible (see Figure 2).
3. FULL SCALE FIRE TESTS

3.1. Objectives

Full scale fire tests with maximum heat release rates of up to 21 MW and a smoke / exhaust air volume flow of up to 150 m³/s were performed to investigate the interaction between fire size, smoke production as well as smoke penetration into cross passages with open doors.

The activation of the incident ventilation in the SBT causes partially high pressure differences (>200 Pa) between both tubes, thus preventing smoke penetration from the affected tube into the escape routes (QS). As a consequence of such high pressure differences, mechanical equipment (doors, dampers ...) might be restricted in its functionality, respectively require extra force to be handled.

The performance of cross passages doors (swing resp. sliding doors) at this high pressure differences, was another issue to be observed within the tests. Furthermore, the technical equipment needed in order to keep the cross passages free of smoke should be determined. Simultaneously, it was examined whether the max. tolerable door opening force of 100 N was not exceeded.

3.2. Test setup and ventilation

The tests were performed in the section of the Koralm Tunnel KAT 1 where the carcass works are already completed.

Figure 3 shows a schematic sketch of the Koralmtunnel with tunnel section KAT 1 between the eastern portal and the shaft Leibenfeld.
Cross passage QS02 was used for the tests. A swing door was mounted into the existing shear wall at one side and a sliding door at the other as a boundary to the test tunnel. The fire source was situated approx. 60 m away from the cross passage in western direction. Figure 4 shows the test setup.

Because of the high tested heat release rates with fire loads of up to approx. 21 MW a structural fire protection was necessary in order to avoid damage to the inner lining of the tunnel. A maximum allowable wall temperature of 120°C was defined by the tunnel owner. A fire protection box, double lined with fire resistant boards, served for this purpose (see Figure 5). It was 20 m in length and had a cross-section of 5 m by 5 m. In order to simulate the reduction of the tunnel section resulting from a train, an obstacle having the size of a train wagon was erected on a scale of 1:1 and situated directly in front of the access point to the cross passage.

**Figure 3:** Sketch of the Koralm Tunnel

**Figure 4:** Sketch of the test section
As an additional safety measure – and as a further test object – a high-pressure water mist system (HPWMS) was installed at the ceiling of the fire protection box, which should ensure a reduction of the temperature of the hot combustion gases if necessary.

The ventilation of the tunnel was mainly performed via the eastern portal of the southern tube and the cross passage QS03, which was opened to the northern tube. The suction of the smoke was ensured by axial fans in the brattice at the east portal of the northern tube. At the boundary, the two sections KAT1 und KAT2 were aerodynamically separated by brattices. A detailed description of the test setup can be found in [2] and [3].

### 3.3. Measurement and monitoring system

To get the major important testing parameter such as pressure difference, temperature profile, longitudinal flow velocity, oxygen content in the air, etc. a sophisticated measurements and monitoring equipment was implemented at the tested areas in both running tunnels. The following parameters were monitored:

- pressure difference between cross passage and both tubes employing measuring transducer (pressure measurement Δp in Figure 4)
- air velocity at various regions within the tunnel employing ultrasonic anemometers (sensors LGxy in Figure 4)
- temperature profiles at various locations downstream of the fire, employing PT100 sensors (see temperature sensors Sx,y in Figure 6)
- temperature distribution in and at the concrete surface and in the fire resistant boards within the fire box using PT100 sensors (see temperature sensors Sx,y in Figure 6)
- smoke dispersion via video cameras (see video camera VCxy in Figure 6)
- CO and CO₂ concentrations downstream of the fire (only within special tests)

Figure 6 shows the location of the temperature sensors and the video cameras.
3.4. Heat release rate

The heat release rate was measured on basis of a high precision measurement of the loss of mass (high precision scales) and then multiplying the mass burnt by the calorific value of the fuel. In order to get a sophisticated visualization of the smoke distribution, a mixture of gasoline (5 liter per pool) and diesel (20 liter per pool) was used as fuel. This mixture was burnt in pools with a size of 1 m² at the surface. An increase in the number of pools resulted in an increase of the fire size.

Table 1 shows the major important parameters of the respective tests. The highest fire load was reached at test #13 with a peak heat release rate of 21 MW. It was tried to keep the air velocity upstream of the fire source on a constant level. Nevertheless, the values changed permanently because of the local conditions.

Table 1: Parameters of the respective tests

<table>
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<tr>
<th>Test No.</th>
<th>No. of pools</th>
<th>HHR average</th>
<th>HHR maximum</th>
<th>Duration</th>
<th>Air velocity at start</th>
<th>Air velocity average</th>
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<td>1.30</td>
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<td>1.12</td>
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<td>1.00</td>
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4. RESULTS

The air speeds achieved during the tests upstream of the fire location, were in the range of 1.5 to 2.2 m/s. These quite moderate air velocities resulted in clear smoke and temperature layering downstream. Even the dummy wagon structure at QS02 did not induce any relevant increase of turbulence.

The maximum gas temperature in the fire box amounted to 615°C, the maximum gas temperature outside the box, measured 15 m downstream of the box (MP6), did not exceed 300°C (test #14). At the same time, the maximum concrete wall temperature did not exceed the critical value of 120°C (sensor S7.1, see Figure 7) although it has to be mentioned that during test #14, the HPWMS had to be activated in order not to exceed this value. Temperatures in the tunnel downstream the fire did not exceed 40°C at the height of approx. 2 m above ground (head level).

Ventilation was activated in such a way that at the cross passage QS02 a pressure difference of some 60 Pa between the two tubes was maintained in most cases. In this cross passage, the sliding door towards the clean tube was always kept closed while the swing door towards the smoke-filled incident tube was always kept open. This pressure difference resulted, due to the leakage through the closed door, in a small air flow of approx. 1 m/s towards the incident tube. This velocity was sufficient, despite the open door to the incident tube, to prevent any smoke from entering the cross passage.

Especially at tests with very high fire load, the relatively low air velocities in the upstream area of the fire (< 2.5 m/s) resulted in the formation of a backlayer with lengths > 100 m.

Before the fire tests #13 and #14, the door opening forces were examined at different pressure conditions in both tubes. These tests showed that even without any pressure difference between the two tubes the door opening force for the swing door already adds up to approx. 100 N. As expected, the door opening force increased with the increase of the pressure difference between the tubes.
The door open force for the sliding door, also without a pressure difference between the running tunnels, is approx. 120 N. Although it can be expected that this value can be significantly reduced by an elaborate adjustment of the door. In contrast to the swing door, the door-opening force did not change with the increase of the pressure difference.

Table 2 shows the measured door-opening forces for swing doors and for sliding doors at various differences of air pressure.

<table>
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<th>Differential pressure</th>
<th>Force</th>
<th>Date</th>
<th>Time</th>
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</table>

5. CONCLUSION

It can be concluded that an air speed of >1 m/s in the open cross passage (egress) door is sufficient in order to avoid smoke penetration into the safe area. This was demonstrated during the tests. However, in realistic cases running trains in the tunnel could negatively influence the pressure situation during the first phase of the incident. However, as running trains in the non-affected tube have to reduce their velocity remarkably in case of an incident situation, this effect shouldn’t be too strong.

The design fire size for a passenger train incident is 28 MW. The tests performed with a maximum heat release rate up to 21 MW resulted in regions where passengers would be in acceptable temperatures due to convective heat downstream the fire (max. 40 °C at head level) and visibility conditions were maintained acceptable.

The activation of the HPWMS resulted in a massive decrease of the temperature downstream the fire location. However, it has to be mentioned that the momentum of the injected water spray resulted in increased turbulence and hence in a strong downwash of the smoke which reduced visibility remarkably.

The necessary air velocities ≥ 1 m/s require pressure differences between both tubes in the range of 60 Pa and more. Due to this fact, sliding doors seems to be preferable as the requirement of keeping the door-opening force <100 N can be achieved more easy.

6. REFERENCES