SMOKE PROPAGATION IN TUNNELS – COMPARISON OF IN-SITU MEASUREMENTS, SIMULATIONS AND LITERATURE

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ABSTRACT

Smoke propagation in tunnel fires was and still is in the focus of intense research. The main aim of such investigations is the critical velocity required to avoid backlayering or the definition of the length of a backlayer. This paper compares results from in-situ measurements, from 3D CFD simulations, and from the application of literature-based simple equations. Since smoke propagation is strongly influenced by numerous parameters such as heat release rate, supply air velocity, temperature and humidity, the fire source itself, etc., boundary conditions have to be defined clearly when comparing results from the different types of investigations. A special focus in this paper is the behavior of the backlayering in small and mid-size pool-fires under varying conditions. The starting point was well documented full-scale fire tests performed in the Koralmtunnel in winter 2017/2018. 3D CFD models were applied, allowing for a detailed analysis of smoke propagation and a comparison with full scale fire tests. Finally, the results concerning backlayering length were compared to results achieved by application of well-known equations from literature.

Keywords: smoke propagation, hot smoke tests, CFD simulation, backlayering, critical velocity

SYMBOLS

backlayering length [m]	L_B	dimensionless backlayering length	L_b^*
heat release rate [kW]	$\dot{Q}$	dimensionless heat release rate	Q^*
supply air velocity [m/s]	V	dimensionless supply air velocity	V^*
tunnel height [m]	H	tunnel cross section area [m²]	A
supply air temperature [K]	T_0	gravity acceleration [m/s²]	g
supply air density [k/m³]	ρ_0	specific heat – air [kJ/kgK]	c_p

1. INTRODUCTION

Only a limited time frame for self-rescue is available in the event of a tunnel fire. As the presence of smoke strongly restricts escape possibilities, detailed knowledge of tunnel smoke propagation may be essential.

Smoke propagation in a tunnel fire has a strong impact on the possibility of self-rescue. This is why it continues to be the subject of investigation all over the world. In a tunnel fire, various approaches to smoke management may be applied [1]. Depending on the prevailing national philosophies, these approaches range from 'zero velocity' to venting with critical velocity. Austrian standards [3] require ventilation control with a target value of 1.5 -2.0 m/s in tunnels with uni-directional operation, and 1.0 – 1.5 m/s in cases of bi-directional traffic. As there are advantages and disadvantages to all approaches, careful assessment is called for. Table 1 summarizes the major positive and negative aspects of all ventilation strategies.

Apart from the ventilation strategy, tunnel system design is also a key factor with respect to smoke propagation and self-rescue. For example, tunnel height and hydraulic diameter are the major geometrical parameters. Smoke management (ventilation strategy) has to be adapted to the existing tunnel geometries. Thus, while large tunnel cross-sections are advantageous in controlled low air speed ventilation regimes, with respect to factors such as filling capacity, smoke stratification, and viewing conditions, critical velocity is more readily achievable in small cross sections as there is limited smoke storage capacity above head height.

Irrespective of the ventilation strategy applied, smoke propagation, in particular the phenomenon of backlayering, is of special interest in research activity all over the world. Several fire tests, at both model and full-scale size, have already been carried out (see [4] and [5]). The results from such tests have been incorporated into national and international standards.

Table 1: Advantages and disadvantages of various ventilation strategies

Ventilation strategy	advantages	disadvantages
Zero ventilation	smoke stratification lower HRR due to O_2 lack at fire seat required fan power is low	smoke propagation in both directions, high concentrations of pollutants and very low visibility in the fire region challenging requirements on ventilation control challenging requirements on air speed measurement equipment (0 m/s range)
Critical velocity ventilation	no smoke on supply air side	unfavourable self-rescue conditions downstream of the fire (smoke side) required fan power - high
Controlled low velocity ventilation	acceptable self-rescue conditions upstream and downstream of the fire event keeping smoke stratification downstream the fire longer lower required fan power than critical velocity ventilation	challenging requirements on ventilation control smoke stratification is not given in all cases backlayering occurs

The investigations presented in this paper focus on the numerical simulations of full-scale pool-fires with a maximum HRR in the range of 2 to 21 MW, carried out by the authors in 2017/2018 [5]. In addition to thermal aspects such as the temperature profiles downstream of the fire, or the heat transfer from air to the tunnel-lining, smoke propagation was also of special interest. Parameters concerning fuel consumption, supply air velocity, etc., were recorded and were taken as boundary conditions for the numerical simulations. Finally, a comparison of in-situ and numerical results to empirical approaches from the literature [4] is made and discussed.

2. FULL SCALE FIRE TESTS IN KORALMTUNNEL

IVT carried out full scale fire tests in order to investigate smoke propagation in the Koralmtunnel (Austria). These investigations mainly focused on smoke propagation downstream of the fire source and on the effectiveness of methods designed to prevent smoke entering cross-passages. A detailed description of the measurements is given in [5]. Pool-fires as defined in Austrian guidelines [3] were used as fire source. HRRs realized ranged from 2 MW (2 pool fires) up to 21 MW (peak-value – 10 pool fires). These pool fires were situated in a sheltered fire box, made of fire-resistant panels, in order to protect the newly-built tunnel lining. Figure 1 shows the protective box (5 by 5 m) and its location within the tunnel cross-section (43 m², 7.43 m height).

In total, 14 fire tests were performed. The test duration was in the range of 8 to 21 minutes and strongly depended on the number of pools used and on supply air velocity. The HRR rate was recorded by two independent systems. One system used gravimetric measurement of fuel consumption based on load cells. This system is very reliable at small and large HRRs, as the properties of the fuel burned are well known. The second system recorded oxygen consumption which, unfortunately, was not precise enough for small fires. Temperature was recorded in multiple positions as vertical profiles and along the tunnel axis. The most important monitoring points were downstream of the fire source, and temperature stratification was measured at several distances up to 100 m from the fire protection box. Temperature stratification also provided information on hot smoke layering. Additionally, smoke propagation was recorded with video cameras situated in various positions upstream and downstream of the fire source. The measurement set-up, including all sensor positions for temperature stratification measurement and camera-positions, is shown in Figure 2.

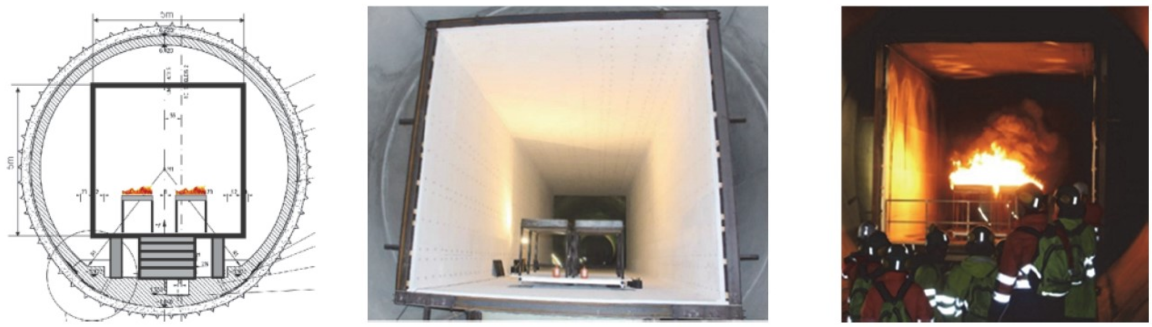

Figure 1: Housing of pool-fires

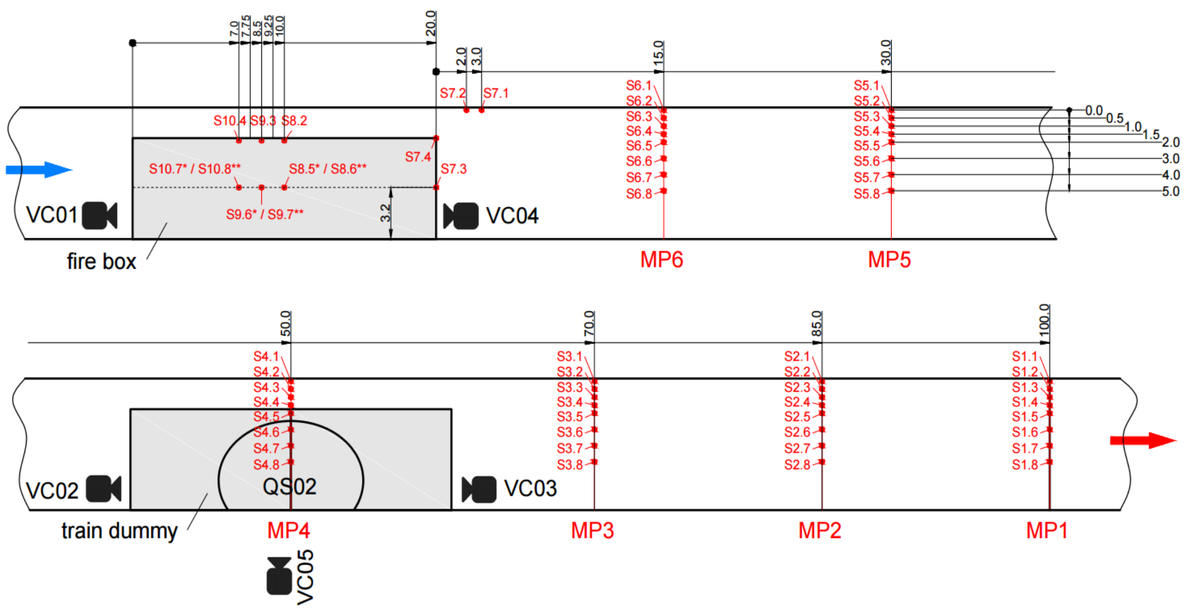

Figure 2: Sensor positions within tunnel test section for temperature monitoring

Backlayering lengths were determined visually, using the casting blocks as indicators. However, it needs to be noted that these observations concerned mainly the maximum length of the backlayer and not the variations observed during the performance of each individual test (i.e. no time dependency).

3. NUMERICAL INVESTIGATIONS OF SMOKE PROPAGATION

As smoke propagation during the hot smoke tests needs to be assessed in detail, a numerical model was generated for simulations in a 3D CFD domain. The main focus was on backlayering and its dependencies on HRR, supply air velocity, etc. In addition, convective heat transfer and thermal radiation to tunnel wall, and its impact on temperature stratification downstream of the fire source, was also investigated.

3.1. Numerical model

For calculating smoke propagation, Fire Dynamics Simulator (FDS) in combination with Smokeview was used. FDS has major advantages in modelling fire. There are different predefined models available, but user-defined models can also be used. Tunnel-geometry was defined within a 10 x 10 x 600 m calculation domain. Cell-size was originally defined at 0.5 m x 0.5 m x 0.5 m and later reduced to 0.25 m x 0.25 m x 0.25 m. Generally, the calculation domain was divided into 6 blocks, with the fire source close away from the block edges. There was no local mesh-refinement in the area of the fire source. Dimensions of the box were 5 m x 5 m x 10.5 m. Material values were given by the manufacturer of the fire protection panels. Concrete tunnel walls were defined as by two elements a 0.25m. The material property values used were those for standard reinforced concrete. The material property values used for both tunnel wall and fire protection plate are shown in Table 2.

Table 2: Solid layers - material values

	Concrete wall	Protection plate (fire box) *
Specific heat capacity kJ/(kgK)	1.04	1.0
Heat conduction coefficient W/(mK)	1.8	0.212
Density kg/m³	2280	900

* PROMATECT-T plate

When simulating tunnel fires, boundary conditions have to be well-defined since marginal changes in fuel consumption, local oxygen ratios, supply air velocity, etc. have a large influence on smoke production and propagation. The recorded supply air velocity curves from KAT fire tests served as boundary conditions. The entrance into the calculation domain was defined as a velocity inlet at a distance 25 times the hydraulic diameter upstream of the fire source. This prevented inlet momentum exerting any influence on backlayering development in the numerical model. The temperature and humidity of the supply air were considered to be constant during the individual tests.

The fire source (pool-fire) was modelled as a 1 m x 1 m fuel surface area. The fire tests' specific fuel consumption curves (1 s resolution), measured via the gravimetric method, were implemented as boundary conditions. For modelling pool fires, the simple pre-defined chemistry model (Table 3) led to relatively good stability, convergence level and results. The major advantages of such a model are its relatively low requirements concerning numerical effort and mesh-size. As the focus of the numerical investigations was on the fire/smoke consequences and not on the fire itself, the application of a more complex combustion model was not considered necessary. The required input parameters for simulations using the chemistry model are the chemical fuel compositions in a mole-fraction mode for oxygen, hydrogen and carbon, yield factors for carbon-monoxide and soot, calorific value, and radiative fraction. The values used were either those recommended in the FDS User-Guide [2] or were taken from the relevant literature [4] (Table 3).

Table 3: Simple chemistry according to FDS, model - input parameters

Variable	Value
Carbon - mol fraction	0.344 mol/mol_fuel
Oxygen – mol fraction	0.002 mol/mol_fuel
Hydrogen – mol fraction	0.654 mol/mol_fuel
Calorific value	42.6 MJ/kg_fuel
Radiative fraction	33 %
CO – yield	0.01 kg/kg_fuel
Soot - yield	0.04 kg/kg_fuel

3.2. Solver set-up

Generally, FDS uses a LES-approach for the calculation of transient simulations. This requires a higher numerical effort and demands stricter hardware requirements than standard RANS-models. But FDS uses multiple empirical approaches in solving for the equations of change, and this allows for the use of coarser mesh-sizes. Nevertheless, the pressure solver is an essential part of the simulation set-up.

Before simulating the KAT fire tests, a study of a very simple fire within a small calculation domain was carried out in order to find an accurate pressure solver. In the present study, several pressure solvers were tested, including the standard pressure solver, GLMAT, UGLMAT, and two more solvers currently available as beta-versions. It turned out that the UGLMAT solver led to better results, but when using the solver for simulating tunnel fires, numerical stability was not sufficient. In the latter respect, the standard pressure solver showed the best performance. It was thus chosen for use in the KAT fire test simulations.

Grid independency was checked by applying three different meshes. Starting with the original mesh size of 0.5 m x 0.5 m x 0.5 m, two refinement steps were made. Once solver set-up was settled, the first step of mesh-refinement (0.3 m x 0.3 m x 0.3 m) was performed. Results with a mesh size of 0.3 m differed slightly from to the solutions using the original mesh. The second refinement step (0.25 m x 0.25 m x 0.25 m) – which was eventually used for all FDS simulations – led to only marginal differences in the variables monitored.

3.3. Results

Although simulations were performed for several KAT fire tests, the results for two representative fire tests, one small size fire and one large size fire, are discussed in detail. n this context, the simulation results of KAT fire test 3 and test 7 are shown and compared to the in-situ measurements. Important boundary conditions such as supply air velocity, number of pool-fires, average and peak HRR, and the test duration of both tests, are shown in Table 4.

Table 4: Test parameters and results

	vel_avg [m/s]	no. pools [#]	HRR_avg [MW]	HRR_peak [MW]	Duration [min]
Test 3	1.22	2	2.3	4.0	15
Test 7	1.5	8	14.5	19.5	8

Figure 3 shows temperature profiles 15 m downstream of the fire source, at different times during KAT fire test 3. The maximum temperature close to the tunnel ceiling is 15°C higher in FDS simulation than in the experiment. While temperature stratification was clearly defined in the in-situ measurement, simulation shows hot layers at lower heights. This effect indicates an under-prediction of radiative and convective heat transfer from gas to tunnel wall in FDS. In addition, the chosen calculation grid is still too coarse in order to have a better description of the heat transfer to the wall.

Figure 4 shows the results for the same sensor positions in KAT fire test 7. In this case, maximum temperature is 10°C higher in FDS simulation than in the experiment. The trend seen in results from fire test 3 is prolonged, since temperature stratification was also striking in the in-situ measurements and hot layers at lower heights can also be seen in simulation results. There appears to be more heat remaining in the simulated smoke layer (area to the left of the h-T curves). These observations confirm the suspicion of a reduced heat transfer from gas to wall.

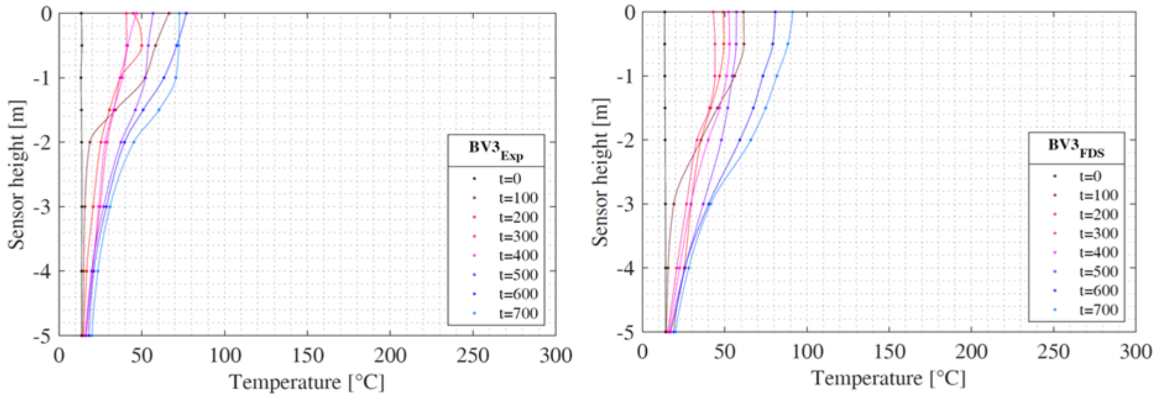

Figure 3: Fire test 3 - temperature stratification (left: experiment, right: FDS simulation)

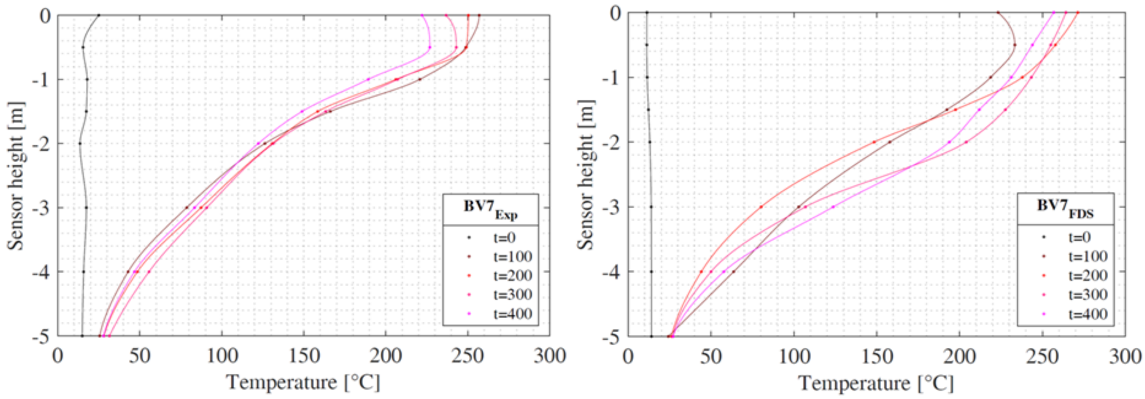

Figure 4: Fire test 7 - temperature stratification (left: experiment, right: FDS simulation)

It seems that FDS underestimates the heat transfer from the hot gas to the tunnel wall. This was also demonstrated by the application of another CFD model (Fluent from ANSYS) [7]. Due to the widespread usage of the FDS solver, the FDS model was used for further investigations. However, this discrepancy in heat transfer has to be kept in mind when analyzing the simulation results.

4. BACKLAYERING

Irrespective of ventilation strategy, backlayering is always given special consideration in a tunnel fire. In the KAT fire tests, supply air velocity was in a range of 1.1 to 2.0 m/s, which was definitely lower than critical velocity. Hence, backlayering was to be expected. Table 5 provides an overview and comparison of backlayering values, from the experiments, the FDS simulations, and from two separate approaches based on simple equations from the literature. It turned out that backlayering length is over-predicted in FDS simulations[1] for HRRs lower than 10 MW (145% - 156%). For HRRs higher than 10 MW, FDS simulations showed shorter backlayering lengths than the experiments (84% - 97%).

Approaches from the literature were taken from Thomas [6](also illustrated in [4]) (equation (1)) and Li/Ingason [4] (equations (2) and (3)). Both approaches generally led to an under-prediction in backlayering lengths compared to the experimental data. However, any comparison has to be done carefully, as empirical approaches from literature require constant supply air velocities, which were definitely not given in the experiments. Supply air velocities and backlayering lengths shown in Table 5 occurred right before reaching peak-HRRs. In addition, it has to be noted that the monitoring of the backlayering length during the field tests was made having every 10 m a mark, i.e. there is an uncertainty of several meters when comparing these values to the numerical results.

Table 6 describes qualitatively the deviations of the recorded backlayering length, taking the observations from the field tests as reference. FDS tends to overestimate backlayering length for smaller fires (<10 MW) and to underestimate it for medium size fires (> 10 MW), while the in 2015 published equations from Li/Ingason underestimate it. The old equation from Thomas has no clear tendency.

$$L_B = H * 0.6 * \left(\frac{2 * g * H * \dot{Q}}{\rho_0 * c_p * T_0 * V_0^3 * A} - 5\right) \tag{1}$$

$$L_B = H * 18.5 * ln\left(0.81 * {Q^{*1/3}}/{V^*}\right); \quad Q^* \leq 0.15 \tag{2}$$

$$L_B = H * 18.5 * ln\left({0.43}/{V^*}\right); \quad Q^* > 0.15 \tag{3}$$

Table 5: Backlayering lengths - comparison experiment/FDS/literature

Test	**Experiment**			**FDS simulation**		**Thomas [6]; [4]**		**Li/Ingason [4]**	
no.	Peak. HRR	supply air velocity	**Backlayering length**	**Backlayering length**	% from experiment	**backlayering length**	% from experiment	**backlayering length**	% from experiment
[-]	[MW]	[m/s]	**[m]**	**[m]**	[%]	**[m]**	[%]	**[m]**	[%]
3	4.0	1.10	**90**	**130**	*145*	**85**	*71*	**77**	*86*
4	7.7	1.30	**90**	**140**	*156*	**103**	*114*	**83**	*92*
5	11.5	1.61	**120**	**100**	*84*	**79**	*66*	**74**	*94*
6	14.3	2.00	**110**	**100**	*90*	**43**	*39*	**57**	*52*
7	19.5	1.25	**160**	**150**	*94*	**256**	*160*	**103**	*64*
8	6.7	1.32	**100**	**140**	*140*	**82**	*82*	**76**	*76*
13	21.0	1.72	**140**	**135**	97	**124**	89	**75**	54

[1] Radiative heat transfer was always kept at the percentage for all simulations

Table 6: Qualitative consideration of backlayering lengths, deviations from field measurements

Peak heat release rate	FDS	Li/Ingason	Thomas
< 10 MW	+	-	+/-
> 10 MW	-	-	+/-

5. CONCLUSION

Establishing the critical velocity needed to avoid backlayering in a tunnel fire has been the subject of intense investigation over the last few decades. Investigations by Li and Ingason came up with a set of equations concerning critical velocity and backlayering length. Another approach entails the use of CFD codes. These allow one the possibility of calculating relevant parameters dependent on tunnel geometry. While the information from Li and Ingason is based on model tests, CFD calculations contain uncertainties with respect to parameter settings, solver selection, etc. Full scale experiments are rare. They are costly and, in most cases, focus on specific research targets which might be different to those investigated above. Full scale tests performed by the authors a few years ago were used as reference case here for model validation.

Numerical simulations were performed applying Fire Dynamics Simulator and Smokeview software. Comparing temperature profiles downstream of the fire source, FDS showed higher maximum gas temperatures at the tunnel ceiling and hot smoke layers at lower heights from the tunnel floor. This effect results from under-predicted heat transfer from hot gas to tunnel wall, and was observed in 3D CFD simulations using ANSYS Fluent.

When discussing backlayering lengths and the comparison of the results of the different approaches (field test, CFD, analytical solutions), it has to be noted that some parameters, such as supply air velocity and temperature, changed during the course of the individual fire tests. In addition, the backlayering length was monitored within a 10 m spacing grid, resulting in an uncertainty of several meters. Generally, calculations using equations from the literature led to shorter backlayering lengths compared to observed values from field tests. Results from FDS simulations varied. For HRRs lower than 10 MW FDS tends to over-predict backlayering lengths by a factor of up to 1.5. Where HRRs are higher than 10 MW, simulation results exhibit a better fit but tend to underestimate the observed values.

6. REFERENCES

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