

ON THE FLOW RESISTANCE OF TUNNEL FIRES – VALIDATION BY FULL-SCALE FIRE TESTS

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ABSTRACT

The aerodynamic resistance of a tunnel fire in longitudinal ventilation, also known as “throttling effect”, is relevant for the design and operation of longitudinal tunnel ventilation systems. The throttling effect has been investigated in an extensive CFD study, as presented at the Tunnel Safety Conference in 2020 [1]. It was found that the temperature and airflow stratification downstream of the fire contributes to the pressure drop even far beyond the extent of the fire. A 1-D model of various factors contributing to the air-flow resistance of a tunnel fire has been presented.

In June 2024, we performed full scale fire tests in the test facility at the “San Pedro des Anes” Experimental Centre in Spain. The test facility allows controlled fires with a heat release rate up to 10 MW, jet-fan induced longitudinal flow and sufficient distance from the downstream portal to investigate temperature stratification. The experimental setup allowed direct pressure measurements between the tunnel and a parallel service gallery. Still, the observed pressure differentials were small and external meteorological pressures influenced the measurements in some of the tests.

It was not possible to validate the increased pressure drop downstream of the fire that was observed in the CFD simulations of the 2020 study. In this paper, an updated 1-D model for the throttling effect is presented that is supported by experimental data and by improved CFD modelling.

Furthermore, a frequency analysis of the static pressure has been performed with the goal of comparing the observed frequencies to the characteristic frequencies of the fire source and of the tunnel.

Keywords: throttling effect, tunnel, fire, flow resistance, pressure drop.

1. INTRODUCTION

The research project "Flow Resistance of Fires in Road Tunnels" ([1] to [3]) concluded that many longitudinal tunnel ventilation systems are under-dimensioned, as the flow resistance is generally underestimated. The project includes a theoretical investigation of flow resistance and its relevance for the tunnel ventilation design for smoke control.

The flow resistance of a fire consists of several contributions. Some can be determined from the one-dimensional conservation equations:

- Decrease in static pressure at the fire site due to heating, expansion and acceleration of the tunnel air,
- Increased wall friction downstream of the fire due to increased flow velocity with reduced air density,
- Increase in static pressure due to the deceleration of the air flow due to cooling on the tunnel wall.

An additional pressure loss was found due to spatial effects. It was determined from a series of 3-D CFD simulations.

- Increased flow resistance due to temperature stratification downstream of the fire.

Similar work on the flow resistance of tunnel fires has been done by other researchers ([4] to [8]). All studies were based entirely on analytical approaches, flow simulations and model experiments, since practically no large-scale experimental data was available at the time. Before the results can be applied in practice, simulations must be validated using large-scale fire tests.

Validation is the verification of a computational physical model with experimental measurements. In this case, validation pursues the following objectives:

- Measurement of the physical quantities required to validate the results of the study [2]: the pressure profile along the tunnel and the cross-sections of the flow velocity and temperature downstream of the fire.
- Comparison of the measurements with the results of the study.

This article concentrates on the fire tests and on the validation of the 1-D model. As part of the project, additional CFD simulations were done. These results are published in separate articles [9], [10] and in the project report [11].

2. METHODOLOGY

2.1. Test Tunnel

The fire tests were performed at the tunnel San Pedro de Anes near Gijon, Spain. The tunnel cross-section is shown in **Figure 1**. Key dimensions of the tunnel are:

- Length: 600 m
- Height under the false ceiling: 5.17 m
- Cross section (with false ceiling): 48 m²
- Longitudinal gradient: -1% south to north

2.2. Fire Source

The fire was formed by fire pans that were placed close to the road surface. Fire pans represent a minimal geometric pressure loss. The heat release rate was estimated from the area of the fire pans. In the test, it was measured indirectly using gas analysis of the exhaust air. The average heat release rate was also determined by the amount of fuel and the duration of the fire.

- Test 1: 4.0 m² 147 l
- Test 2: 4.0 m² 150 l
- Test 3: 6.1 m² 230 l

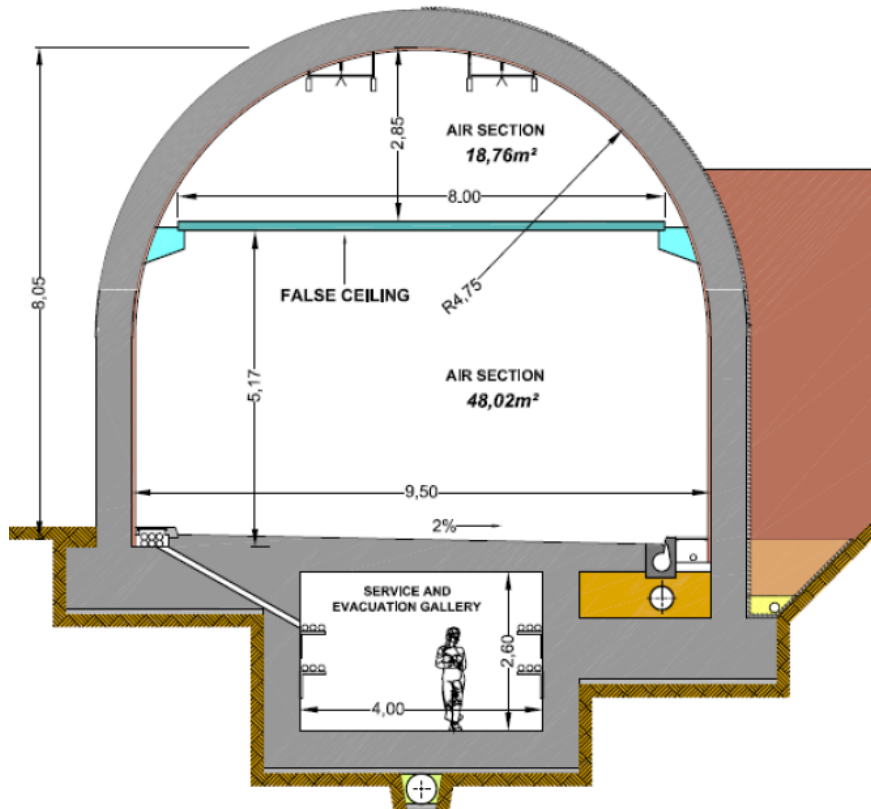


Figure 1: Normal profile of the test tunnel San Pedro des Anes

2.3. Ventilation

The target value of the longitudinal ventilation was an airflow of 3 m/s towards the fire, corresponding to the design value of the longitudinal flow according to the Swiss design code ASTRA 13001. The jet fans are supplied via soft starter on/off. The jet fans were set prior to the tests to achieve the intended airflow.

2.4. Instrumentation

The setup is shown in **Figure 2**. The airflow measurement downstream of the fire was supposed to consist of 25 independent velocity monitors to assess the average flow velocity in the tunnel as well as the flow profile in the cross-section. For the tests, however, only 6 differential pressure monitors were available. This only allowed to record a vertical flow profile with five pitot tubes recording the average dynamic pressure across the tunnel.

For temperature measurement, 25 gas thermocouples were installed at PK522 in the same grid points as the pitot tubes.

The static pressure profile along the tunnel was measured as a differential pressure between the tunnel and the service gallery underneath. The service gallery was open to ambient air at PK600 and no airflow was present. Therefore, the service gallery has been considered as being at reference pressure. In the tunnel, the pressure measurement was located at the tunnel wall, 2 m above ground. The opening of the pressure tube was arranged perpendicular to the longitudinal flow to avoid any influence of the flow velocity. In CFD simulations, it was verified that the measured differential pressure was representative of the average pressure in the tunnel cross-section.

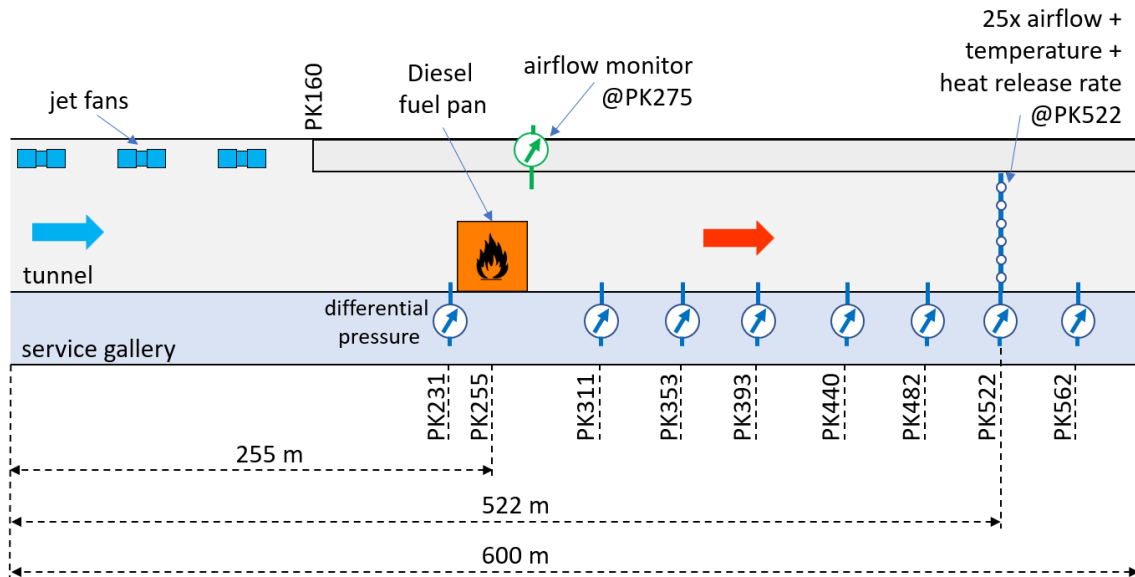


Figure 2: Test setup

An additional differential pressure measurement was located at PK231. The installation was like the installation of the differential pressure measurement described above. This pressure sensor was used to collect short time measurements at higher sampling frequencies of 100 and 2000 Hz.

The heat release rate was evaluated by measuring the total mass flow rate and various gas concentrations (CO, CO₂, O₂ and H₂O). The heat release rate was then derived from these mass flow rates.

3. MODEL

3.1. 1-D Model

A 1-D model for the throttling effect was proposed in the research report ([1] to [3]). With the assumption that fuel mass flow is neglected, the calculation model is presented in a compact formulation. Equations (1) to (5) were developed from classical fluid dynamics analysis, such as pipe flow pressure drop and momentum balance.

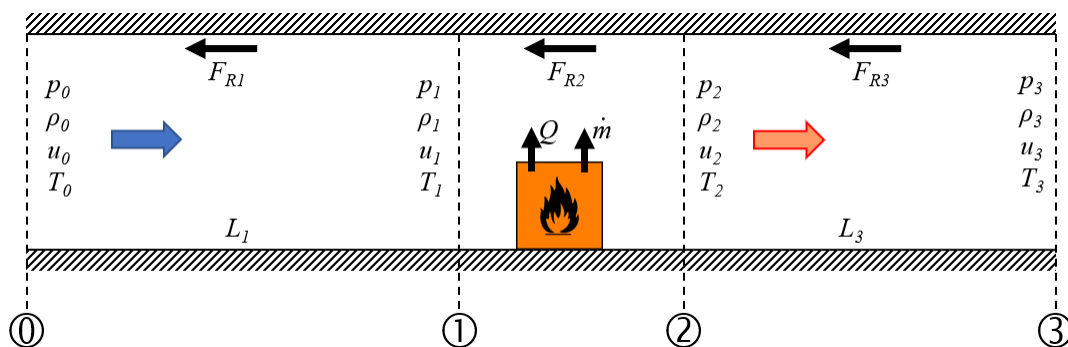


Figure 3: Definitions

The variation of static pressure due to wall friction in the inflow section results in

$$\Delta p_{0-1} = -\frac{\rho_0}{2} \cdot u_0^2 \cdot \frac{\lambda L_1}{D_h} \quad (1)$$

The change of static pressure at the fire location is simplified to

$$\Delta p_{1-2} = -\frac{Q_c u_0}{c_p A_T T_0} \quad (2)$$

The change in static pressure downstream from the fire includes two components. The wall friction corresponds to the inflow section. However, the flow velocity is increased and the density reduced. This results in an increased pressure drop.

$$\Delta p_{2-3A} = -\frac{\lambda}{2D_h} \int_0^{L_3} \rho(x) \cdot u(x)^2 \cdot dx \quad (3)$$

$$\Delta p_{2-3A} = -\frac{\rho_0}{2} \cdot u_0^2 \cdot \frac{\lambda}{D_h} \cdot \left[\frac{Q_c}{\alpha U_T T_0} \left(1 - \exp\left(-\frac{\alpha U_T L_3}{\rho_0 u_0 A_T c_p}\right) \right) + L_3 \right] \quad (4)$$

The recovery of static pressure by cooling and the resulting deceleration of the flow is

$$\Delta p_{2-3B} = \frac{Q_c u_0}{c_p A_T T_0} \left(1 - \exp\left(-\frac{\alpha U_T L_3}{\rho_0 u_0 A_T c_p}\right) \right) \quad (5)$$

with

u	airflow velocity	L	length	Q_c	conv. heat release rate
ρ	air density	A_T	cross-section	c_p	heat capacity
p	static pressure	D_h	hydr. diameter	α	heat transfer coeff.
T	temperature	U_T	tunnel wet perimeter	λ	friction coefficient

The study ([1] to [3]) described an additional pressure loss due to temperature stratification. This was derived from OpenFoam CFD simulations. The evaluation of the test data made apparent that the strong flow stratification and the additional pressure loss were an artefact of the CFD simulations. It is now assumed that the pressure loss was caused by an insufficient resolution of the near-wall flow field (for the Large Eddy Simulation) and/or an inadequate application of wall functions.

For this analysis of the experimental data, the 1-D model following equations (1) to (5) were implemented in the 1-D numerical model Spitfire [12] for comparison with the experimental data and with additional CFD simulations.

3.2. CFD

In addition to the 1-D simulations, three different 3-D CFD codes were used for the preparation of the fire tests and for a comparison with the collected data

- RANS, Star-CCM+
- LES, Fire Dynamic Simulator
- DES, ANSYS Fluent

A detailed documentation of the CFD simulations, i.e. geometry, sub-models, boundary conditions etc. are described in the project report [11].

The Star-CCM+ version v2302 was used for the RANS simulations. The simulations were carried out in stationary mode with 2nd order coupled flow and energy. Due to the expected high temperature gradients, the air is assumed to be compressible. Viscosity, thermal conductivity and heat capacity of the air are calculated as a function of temperature using Sutherland's Law. The gravity term is included to take account of buoyancy forces. For inclined tunnel geometries, only the gravity vector is modified.

Fire Dynamic Simulator FDS v6.8.0 was used for the LES simulations. For analysis of the pressure curve of fires in long tunnels, the transient Very Large Eddy Simulation VLES in combination with the standard FFT-based solver has been used, as recommended in the FDS user manual.

Detached Eddy Simulation (DES) is a hybrid turbulence model that combines RANS and Large Eddy Simulation (LES). Near solid boundaries and close to the fire, where turbulence scales are small and resolving them is computationally expensive, DES applies RANS to model turbulence efficiently. Away from walls, in regions with large turbulent structures, DES switches to LES, which directly resolves unsteady eddies. DES provides a balance between accuracy and cost, capturing large-scale turbulent motions in separated flows while avoiding the excessive computational demand of a full LES.

3.3. Oscillations

The study ([2], [3]) describes pressure oscillations in the fire-affected tunnel, affecting the time averaged pressure profile in a tunnel. Physical oscillations may cause difficulties with the convergence of numerical models. They can be initiated by flame oscillation and amplified with the frequency of the air column in the tunnel. The flame frequency is correlated to the size of the fire pan [13]. In Test 1 it is estimated as 1.3 Hz from the 4 m² square pan. The natural frequency of the tunnel is given by the ratio of twice the tunnel length and the speed of sound. For the test tunnel, this gives a first natural frequency of 0.29 Hz and higher order frequencies as multiples $n \cdot 0.29 \text{ Hz}$.

4. RESULTS

4.1. Pressure Profile Test 1

Figure 4 shows a comparison of the four pressure profiles along the tunnel with the measured differential pressure. Three of the pressure monitors (PK231, PK482 and PK562) showed erratic behaviour in the dynamics of the test as well as in the time averages for the pressure profile. The installation has been re-checked after the test, but no explanation has been found. The data are shown in the graph but disregarded in the analysis. The measurement at PK231 is replaced by the high-frequency monitor.

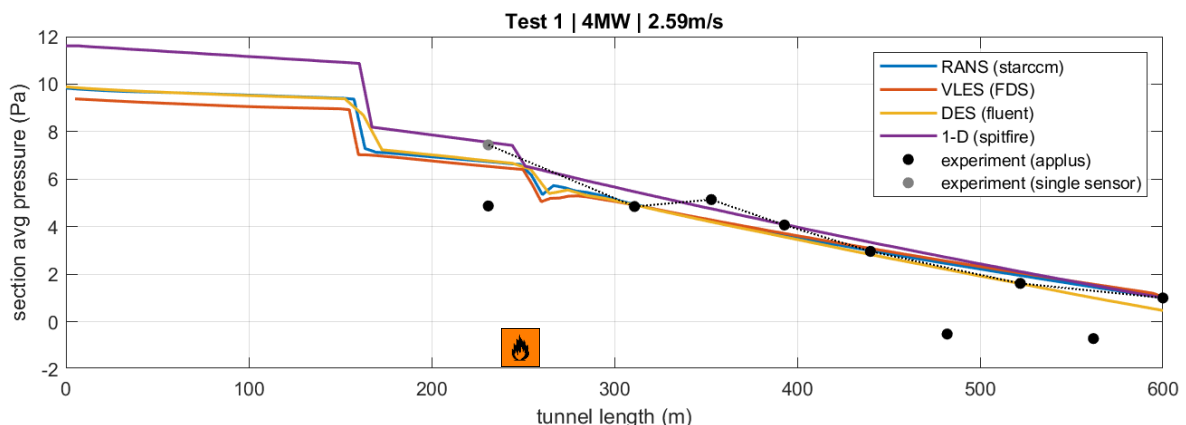


Figure 4: Pressure profile along the tunnel Test 1

The three CFD simulations show very good agreement with the measurements, while the 1-D simulation shows a slightly increased wall friction downstream, and an increased pressure drop at the cross-section change at PK160. The agreement with the measurement is surprising given the difficulty of the pressure measurement between the tunnel and the service gallery.

4.2. Pressure Fluctuations Test 1

The dynamic pressure data is best represented by a frequency analysis for a longer period with developed fire. For Test 1, this is shown in **Figure 5**. The oscillations include the dominant oscillations as well as the turbulence frequency spectrum. A dominant oscillation is visible at ~ 0.30 Hz, which represents the fundamental frequency of the tunnel tube with open portals. Higher order natural frequencies ($n \cdot 0.29$ Hz) are not visible.

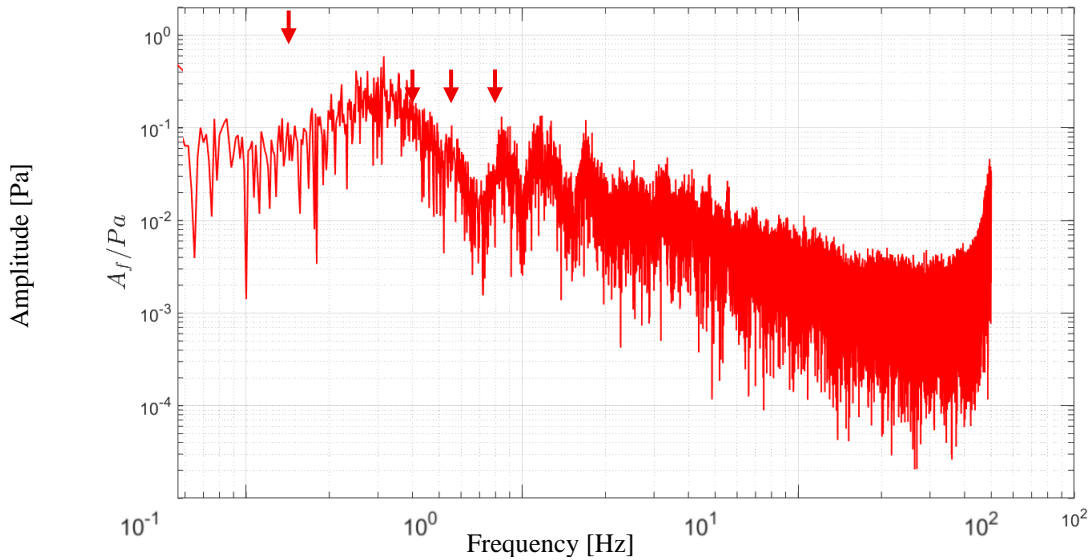


Figure 5: Frequency analysis Test 1, Sampling Rate 100 Hz

The graph also includes three distinct maximums at 0.85 Hz, 1.1 Hz and 1.5 Hz. Although these do not match the frequency of the flame oscillation according to [13], the oscillations are most likely driven by the fire. Further research is required to evaluate possible causes, such as eddy separation of the plume in crossflow.

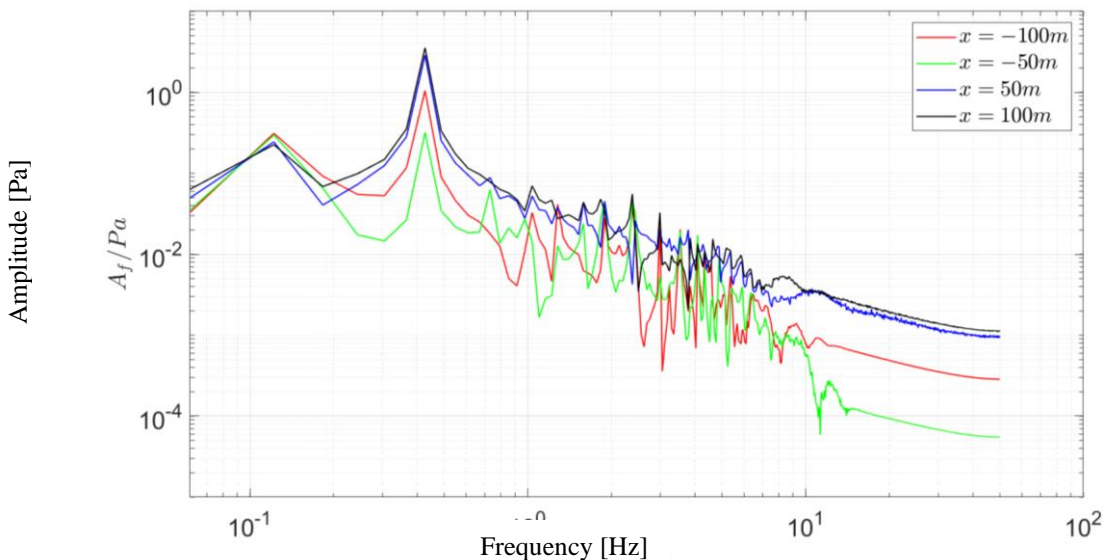


Figure 6: Frequency analysis Test 1, DES simulation

Figure 6 shows the frequency analysis for the DES simulation. We observe a peak frequency at 0.43 Hz, which matches the second harmonic frequency of a tube with one closed and one open end (0.425 Hz). The boundary conditions of the CFD model cause the tunnel oscillations to behave like a tube closed at one end (i.e. fixed flow rate).

4.3. Scaling to Higher Heat Release Rates

While the different models agreed well for the fire tests, the simulations must be scaled to typical tunnel design fires in the range of 30 to 50 MW. These simulations were done with the 1-D model, RANS and VLES.

For the scaled simulations, the tunnel geometry is changed to represent a tunnel with constant cross-section of 65 m². The shape of the cross-section varied from a wide rectangular tunnel to a high arched tunnel. A 900 m long tunnel with 1% gradient was modelled. The upstream airflow was set to 3 m/s and the heat release rate to 4 to 50 MW. **Figure 7** shows the static pressure profile along the tunnel for the RANS, VLES and 1-D simulations for a 30 MW fire.

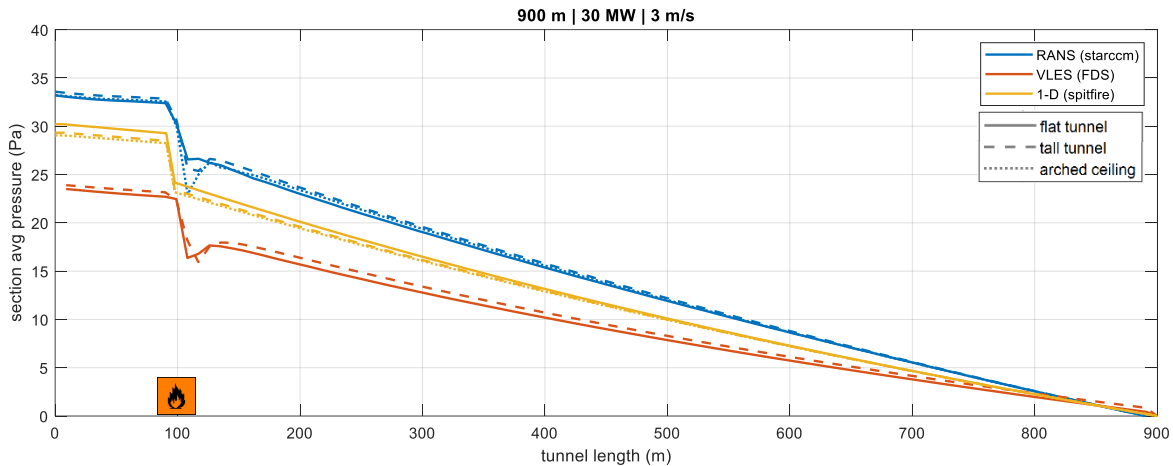


Figure 7: Pressure profile along the tunnel for a 30 MW fire

For all models, the shape of the tunnel cross-section appears to have a minor effect on the pressure drop. But, although the models agreed well for conditions of the fire tests, there is a significant difference for the larger fire with RANS giving the highest and VLES giving the lowest pressure drop.

It was the intention to conduct further simulations without gradient to separate the throttling effect from buoyancy on a downward gradient. At the time, new versions of FDS (v6.9.1 and v6.10.0) were published. The pressure profiles were significantly different from the previous version. These differences are visible in the respective user manuals chapter 21.3 [14]. It does not appear useful to validate a CFD model with such significant changes between versions. The differences in **Figure 7** can be attributed to temperature driven buoyancy on the gradient.

The simulations for larger fires indicate that model validation for experimental data from small fires has limitations regarding regular design scenarios. More data is required for larger fires.

5. SUMMARY AND CONCLUSION

Full size fire tests with heat release rates of 4 to 10 MW have been performed. The tests include measurements of downstream temperature and flow profile as well as pressure profiles along the tunnel. Although the measurement of small pressure differentials between the tunnel and the service gallery proves difficult, the data can be used for the validation of tunnel fire simulations.

The measurements are compared to 1-D simulations and to various 3-D CFD simulations. While the models agree well with the test data, upscaling the models to larger heat release rates shows significant differences, mostly to the temperature and buoyancy downstream of

the fire. FDS versions v6.8.0, v6.9.1 and v6.10.0 show significant differences in the pressure profile for tunnel fires.

Equations (1) to (5) give a good 1-D approximation for the throttling effect of tunnel fires in longitudinal ventilation. The equations can be implemented in dynamic 1-D models for the simulation of tunnel fires.

The fire tests are documented in “Flow Resistance of Fires in Road Tunnels – Validation” [11]. The documentation including the raw measurement data is available as download:

<https://doi.org/10.5281/zenodo.17938708>

6. REFERENCES

- [1] I. Riess, D. Weber, M. Steck, “On the airflow resistance of fires in longitudinal ventilation – the throttling effect” in *10th International Conference Tunnel Safety and Ventilation*, Graz, 2020.
- [2] I. Riess, D. Weber, M. Steck, “Strömungswiderstand von Bränden in Strassentunneln” in *Report 1679 Project AGT 2017/005*, 2020.
- [3] I. Riess, “Aerodynamic Resistance of Fires in Tunnels”, *Riess Ingenieur-GmbH Report 1904002*, Dezember 2020.
- [4] E. Ang, I. Riess, J. Peiro & G. Rein, “Understanding and modelling the fire throttling effect in longitudinally ventilated tunnels”, in *12th Asia-Oceania Symposium on Fire Science and Technology*, Brisbane, Dezember 2021.
- [5] R. Hansen, “Modelling the throttle effect in a mine drift” in *Journal of Sustainable Mining*, Volume 20 issue 4, <https://doi.org/10.46873/2300-3960.1329>, 2021
- [6] E. Ang, J. Peiro, I. Riess & G. Rein, “Analysis of fire throttling in longitudinally ventilated tunnels with a one-dimensional model” in *Fire Technology Volume 58*, pp. 2925-2947, 2022
- [7] D. Gay, “CFD Simulation of the Throttling Effect in Tunnels”, *MSc Thesis, Imperial College London*, September 2022
- [8] E. Ang, “Engineering simulations in the design and analysis of tunnels for fire safety and smoke ventilation”, *PhD Thesis, Imperial College London*, March 2024
- [9] R. Deb, A. Weber, I. Riess, “Numerical investigation of flow resistance of fires in road tunnels” in *20th International Symposium on Aerodynamics, Ventilation and Fire in Tunnels*, Copenhagen, October 2024
- [10] R. Deb, A. Weber, I. Riess, “Numerical modeling and experimental investigation of flow resistance of fire in longitudinal ventilation along a tunnel”, submitted for publication in *Journal of Wind Engineering and Industrial Aerodynamics*, July 2025
- [11] M. Friedl, A. Weber, R. Deb, I. Riess, “Flow Resistance of Fires in Road Tunnels – Validation”, *Project BGT 20_00A_01*, report submitted for publication.
- [12] I. Riess, “On smoke stratification in a 1-D tunnel ventilation model” in *11th International Conference Tunnel Safety and Ventilation*, Graz, 2022.
- [13] H. Ingason, Y. Zhen Li, A. Lönnemark, “Tunnel Fire Dynamics”, *Springer, DOI 10.1007/978-1-4939-2199-7*, 2015
- [14] Fire Dynamics Simulator User’s Guide, Versions v6.8.0, v6.9.1 and 6.10.0