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VALIDATION OF A MODEL ROAD TUNNEL USING FIRE EXPERIMENTS DATA

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ABSTRACT

This paper describes the validation of a model tunnel designed for investigations on the design and operation of ventilation systems in road tunnels. The model tunnel in a scale of 1:18 allows flow visualisation and velocity measurements via particle image velocimetry technique (PIV). For isothermal investigations on fire scenarios, a buoyant helium-air-mixture is injected into the tunnel. Analogue scaling based on the preservation of the Froude number is used to correlate the results to real scale.

Two experiments with mechanical longitudinal ventilation from the “Memorial Tunnel” test program were considered suitable for validation. The investigations were carried out in parallel experimentally with the model tunnel and numerically with the Fire Dynamics Simulator (FDS). The validation comprised a qualitative comparison of the smoke propagation and a quantitative comparison of vertical flow profiles in the tunnel axis to the original data.

Overall, a good agreement with the original data was found in the evaluation of the results, so that a successful validation was assumed. The results show that it is possible to obtain similar flow characteristics applying analogue scaling in fire scenarios including the operation of model jet fans.

Keywords: model tunnel, mechanical ventilation, validation, analogue scaling.

1. INTRODUCTION

The design and operation of ventilation systems for road tunnels has been the object of experimental studies since the 1960s when the number and length of tunnels started to increase considerably in industrialised countries. Usually, these kind of studies are conducted in a model scale and exploit the possibility to establish a geometric similarity of the tunnel and a kinematic similarity of the flow between model and real scale. Since real scale experiments especially on the ventilation in emergencies are costly and limited in scope, experiments in model scale have proven to be useful, even though there are limitations due to the partial nature of the physical similarity that can be achieved. For example, current guidelines on the estimation of the critical velocity are mainly based upon experiments in model scale whose results were combined with theoretical considerations afterwards [1; 2; 3].

In addition to the concept of similarity, the results from model scale should be subject to a validation with data from real scale in order to demonstrate that the model can give meaningful insight if it is applied in a reasonable way.

2. MODEL TUNNEL

The model tunnel in question was designed in a preceding research project in a scale of 1:18 [4; 5]. Numerous modular segments were constructed that allow to model two-lane tunnels with typical rectangular or arched profiles and variable slopes. In order to model mechanical ventilation systems, working jet fans in different sizes and with adjustable jet velocities were constructed. The effect of moving vehicles on the tunnel flow can be included based on a modified slot-car system. Since gravitational effects dominate the tunnel flow in emergency situations, fire plumes are modeled isothermally based on the preservation of the Froude number (section 4.2).

Multiple series of experiments addressed e. g. the blockage effect of vehicles, the positioning of jet fans and the influence of the tunnel slope during normal and emergency situations with longitudinal mechanical ventilation. In the end, the tunnel and the preliminary results were seen as a "proof of concept" for subsequent investigations.

A distinguishing feature of the model tunnel is the ability to measure instantaneous and mean flow fields by particle-image velocimetry (PIV). PIV is a laser-optical, non-intrusive measurement technique whose principle is based on the illumination and tracking of seeding particles that are added to the flow. This enables to obtain velocity distributions in the measurement plane. The model tunnel is built of transparent plastic to guarantee the optical accessibility to conduct 2C (two component)-PIV measurements. The principle of this technique is sketched in (Figure 1).

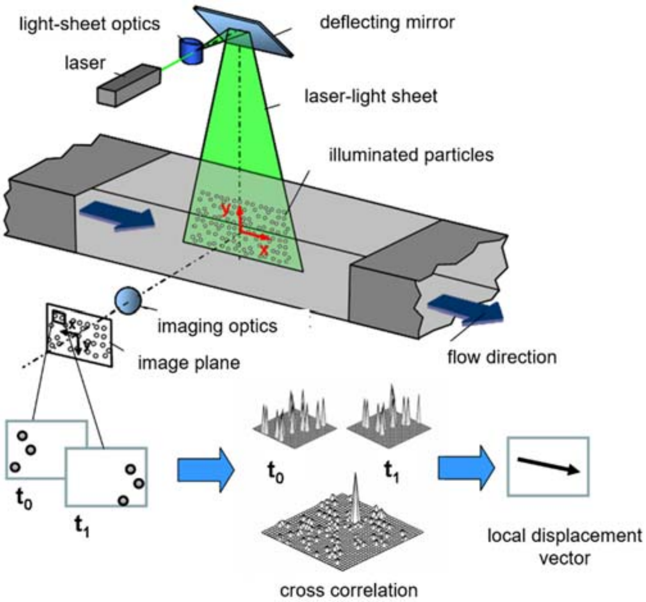

Figure 1: Principle of a 2C-PIV measurement and the subsequent data processing

3. FIRE EXPERIMENTS DATA (MEMORIAL TUNNEL)

In order to gain or derive suitable data for validation, literature on real-scale fire tests and commissioning tests in tunnels was reviewed. As expected, the number of real-scale tests that document the effect of ventilation was quite limited. Most of the tests in research projects were performed in structures that are noticeably different from typical road tunnels. In addition, they are lacking thorough data on the operation of the ventilation system and its effect on the flow field; the latter is true for commissioning tests as well.

As a result, the well-known tests on fire ventilation in the "Memorial Tunnel" [6] were chosen as the single source for validation data. These tests, conducted 1993-1995 in a disused two-lane road tunnel of 853 m length, can be considered the most extensive source on the problem at hand to this day. Out of the 98 tests in total, 15 tests were performed with longitudinal mechanical ventilation that differed mainly in fire size and jet fan activation pattern. Out of these, tests no. 606A and 608 were chosen and modelled both experimentally and numerically. This paper addresses the results for test 608.

The available data for modelling and subsequent comparison comprised the heat release rate, jet fan activation patterns, observed smoke propagation and verbal descriptions in test protocols as well as flow profiles in the tunnel axis and estimations on the volume flow at several positions distributed over the length of the tunnel.

4. EXPERIMENTAL RESULTS

4.1. Adaptations in order to model the Memorial Tunnel

The testing facility offered a free length of approximately 45 m. Considering some clearance that was necessary beyond the portals, this allowed for the assembly of the model tunnel with a length of 40 m, equivalent to 720 m with respect to the model scale. This restriction required the reduction of the real scale tunnel length that could be represented by 133 m (-15 %). Therefore, the section downstream of the jet fans between the fire site and the south portal was shortened. The slope of 3.2 % was considered by adjusting the supporting frames beneath the model tunnel. Its shell was built out of transparent polycarbonate geometrically similar to the original horseshoe profile.

The Memorial Tunnel originally featured a full transverse ventilation system with fan rooms at both portals that situated the axial fans above the traffic space. The geometry of these fan rooms reduced the tunnel cross-section from a horseshoe profile to a rectangular profile and was reproduced in the model tunnel.

The available data also shows the tunnel flow in uphill direction prior to the test due to meteorological effects (wind) and possibly natural convection; in order to include these effects a set of computer case fans was assembled and placed in front of the higher north portal that was able to generate the corresponding pressure difference.

Over the course of test 608, 7 out of the 15 installed jet fans were operated. The power supply of the model tunnel was limited to provide for jet fans or fan groups at three different longitudinal positions. Therefore, only the first half of this test could be simulated (2 minutes of natural convection after fuel pan engulfment followed by 12 minutes of forced convection; Figure 2). The three jet fans that were operated in different groups during this period were placed in the tunnel axis similar to the original test.

4.2. Analogue Scaling (Froude Scaling)

For isothermal investigations on fire scenarios, a buoyant helium-air-mixture was injected into the model tunnel (Figure 3). Analogue scaling based on the preservation of the Froude number was used to correlate the results to real scale [5; 7].

Test 608 was prepared with fuel pans that were expected to produce a nominal heat release rate of approximately 20 MW. According to the test data, the actual heat release rate reached 3.5 MW during natural convection and ranged from 7 to 19 MW during forced convection (t_{end} = 14 min = 840 s).

Adequate flow rates and compositions of the helium-air-mixture with an equivalent buoyancy were derived according to the following steps:

1. Simplification of the heat release rate by identifying key values that represent the development over the course of the test (Figure 2).

2. Derivation of suitable smoke flow rates and temperatures for these key values by applying the model by Mégret/Vauquelin [8]. Assuming ideal gas conditions, flow densities could be deduced from the general gas equation.
3. Application of analogue scaling for the smoke flow rates. With respect to the model scale, the underlying relations equate to:

$$\mathrm{Fr} = \frac{v_R}{\sqrt{g \cdot L_R}} = \frac{v_M}{\sqrt{g \cdot L_M}} \quad \Rightarrow \quad v_R = v_M \cdot \left[\frac{L_R}{L_M}\right]^{\frac{1}{2}} \quad \wedge \quad \dot{V}_R = \dot{V}_M \cdot \left[\frac{L_R}{L_M}\right]^{\frac{5}{2}}$$

The analogue scaling was applied to the jet fans as well, i. e. the original jet velocity of 34.2 m/s was scaled to 8.1 m/s.

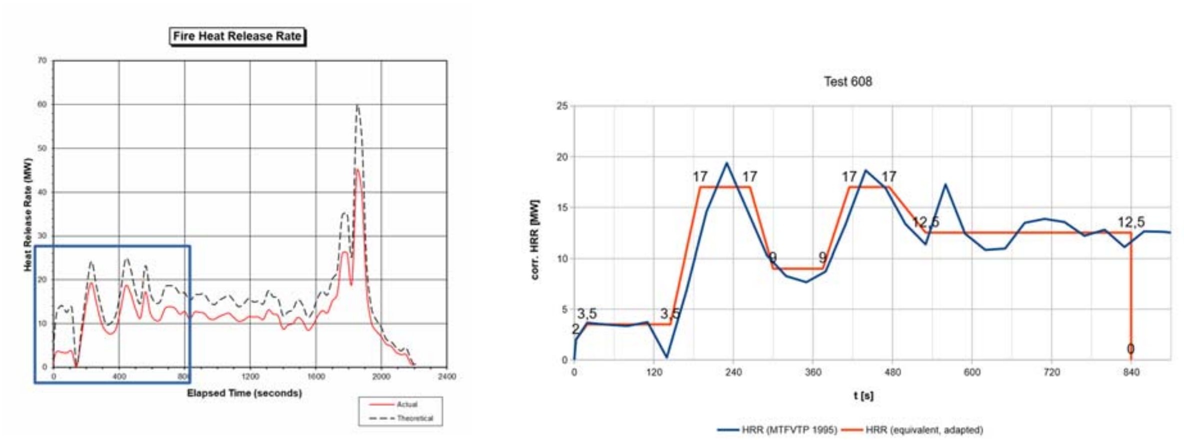

Figure 2: Measured heat release rate (left; [2]) and simplified heat release rate used to model the composition and flow rate of the helium-air-mixture (right)

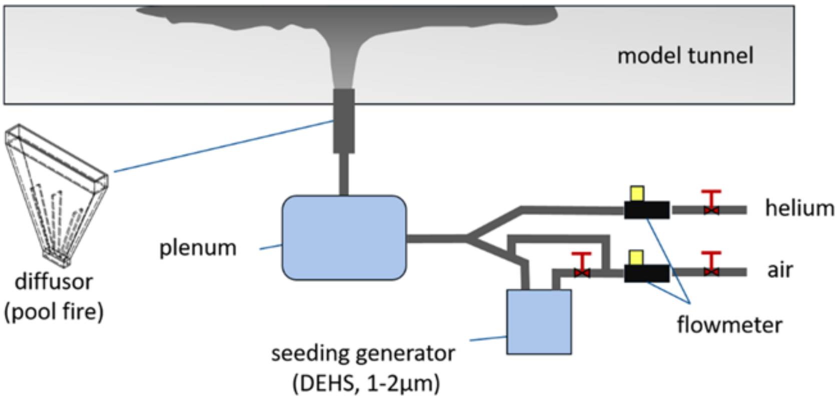

Figure 3: Seeding and injection of the helium-air-mixure into the tunnel

4.3. Comparison of flow profiles

The 2C-PIV measurements were performed in the tunnel axis at three different positions that correspond to the original tests (named Loop 207-209 in [6]). These positions were located 1,90-2,61 m downstream of the operated jet fans (equivalent to 34-47 m in real scale). Over the course of the test, the motion of the tracer particles was recorded with a sample frequency of 2 Hz. The processed profiles extracted from the velocity distributions show the development of the flow (Figure 4). The diagrams therein include the standard deviation so that fluctuations due to the inherent turbulent nature and more prominently due to the flow reversal after jet fan activation become apparent.

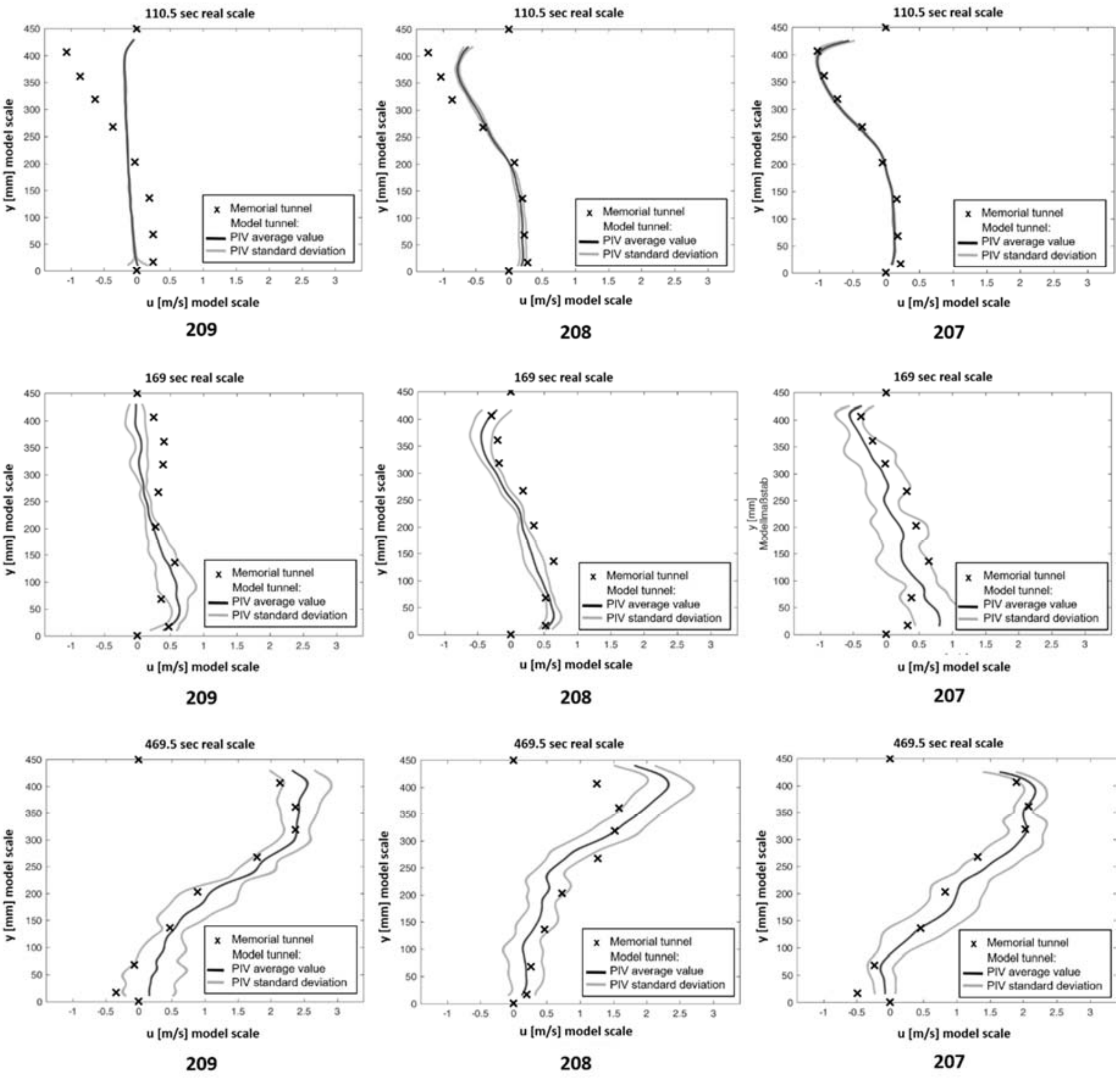

Figure 4: Flow profiles in the tunnel axis at 110.5 s, 169 s and 469.5 s compared to the original data at loops 209, 208 and 207 (original flow velocities scaled to model scale). Model tunnel values were averaged over 3.5 s, equivalent to 15 s in real scale. Reading direction of diagrams correspond to flow direction during forced convection (downhill towards south portal).

At 111 s during natural convection, there is very good agreement at loop 207 closest to the fire site, but progressively weaker agreements at the loops uphill. According to the test report, the smoke front moved over a distance of almost 300 m within 60 s (from t = 60 s to t = 120 s), equivalent to a very fast propagation velocity of approximately 4.5 m/s. However, this is possibly an overestimation since there is an offset of 53 s between the fuel pan engulfment as referential point in time in the original data and the preceding ignition of the fuel pan when smoke started being produced. The implications of this offset are difficult to account for whether it be in experiments or simulations.

At 169 s, 49 s after the activation of three jet fans, flow reversal is imminent. With respect to the transient nature of this process, there is convincing agreement between original and experimental data at all loops.

At 469 s, there is a good agreement as well with the exception of loop 208 where the original velocities are lower in the upper half. There are two possible reasons for this discrepancy: first, assumptions had to be made regarding the longitudinal jet fan positions because they are not clearly stated in the report. Second, the report mentions the positioning of test equipment upstream of the fire site that partially obstructed the flow. Because they are not disclosed in detail, they could not be modelled [cf. 9].

5. NUMERICAL RESULTS

In order to bridge between the original and the experimental results, the tests were modelled numerically with the Fire Dynamics Simulator (FDS V6.5.2) both in real scale and model scale. Boundary and initial conditions were modelled as closely as possible to the original test and the experiments, respectively (e. g., wall roughness, fan thrust, initial flow prior to the test). The only exception from that was the length of the real scale model which was reduced to 720 m corresponding to the restricted length of the model tunnel (section 4.1). In real scale, a gas burner was specified with the heat release rate depicted in Figure 2. In model scale, the injection of the helium-air-mixture was identical to the experiments.

An evaluation of the flow velocities showed that the numerical velocities are rising faster than in the original tests (Figure 5). However, the actual discrepancy is hard to determine since the temporal resolution in the original data is quite low (1/60 Hz) with an undisclosed averaging interval. Another contributing factor to this effect might be that the original jet fans require longer start-up times. In addition, the numerical velocities are approximately 10 % higher in quasi-stationary conditions both in real scale and model scale. This difference is probably mostly due to additional flow losses in the original test related to the test equipment upstream of the fire site that could not be modelled.

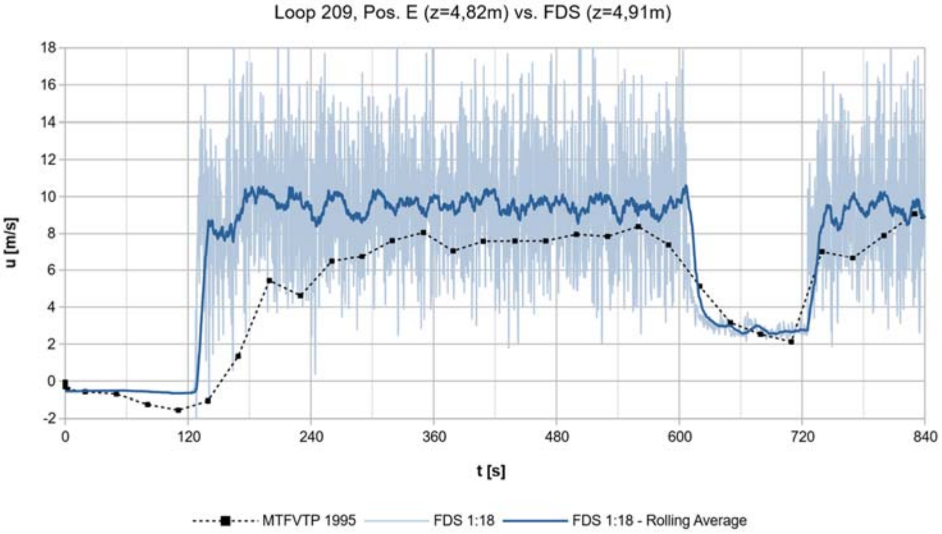

Figure 5: Comparison of the velocity development at loop 209, Pos. E (z = 4,82 m) - original data vs. scaled numerical data

The flow profiles generally show the same trends as in the experiments (Figure 6). An additional characteristic is that the numerical peak flow velocities tend to be 20-25 % higher. This can be attributed to the grid resolution which was derived with the goal to resolve the buoyant plume appropriately (cartesian grid with $\delta x = 280$ mm in real scale and 15.6 mm in model scale; $D^*/\delta x \approx 9.4$ for $\dot{Q} = 12.5$ MW). While all loops are located at the beginning of the self-similar zone of the jet, the momentum is mostly transferred within the mixing zone that is closer to the jet fan. In order to realistically resolve the entrainment in this zone that causes the jet to decay quickly, a smaller grid size would have been necessary [9]. As a result, the momentum transfer is stretched over a longer distance.

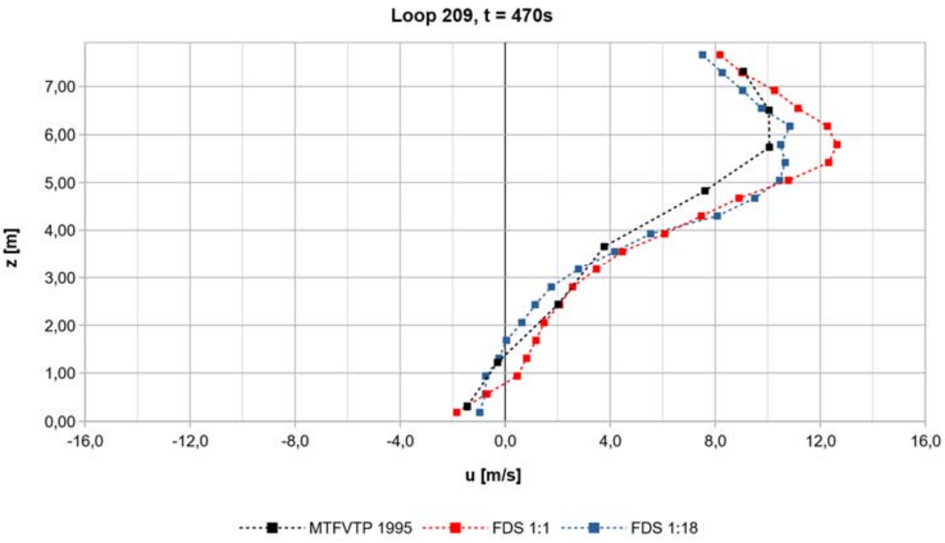

Figure 6: Comparison of the flow profile at loop 209 at 470 s - original data vs. numerical data in both real scale and model scale

6. CONCLUSION

Overall, a good agreement with the original data was found in the evaluation of the results, so that a successful validation was assumed. This is true for the other points in time that are not shown in this paper as well. The results show that it is possible to obtain similar flow characteristics applying analogue scaling in fire scenarios including the operation of model jet fans.

Residual discrepancies to the original data were mostly small or moderate and could be attributed partially to the limitations of scaled model tests in general as well as to additional adaptations that were necessary for these particular tests (section 4.1). Equally important, the incomplete documentation of the original experiments and the available scope of data limited both the experimental and the numerical model. The spatial and temporal resolution of the original data is too low in order to be able to compare transient processes in detail. In addition, some ambiguities and discrepancies were found in the original data. These results also correspond to the preliminary findings of Ingason/Li who were able to consider details not disclosed in the original report; they concluded that there is a level of uncertainty in the data that still needs to be fully analysed [10].

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