Optical density of testing aerosol and fire smoke in a road tunnel with longitudinal ventilation: comparison by FDS6

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Abstract. Specific testing aerosol is used for road tunnel ventilation tests to represent steady-state movement of fire smoke downstream of the fire and to avoid the damage of the tunnel. This study investigates the spread of aerosol in 240 m long section of a road tunnel by computer simulation using the well-known FDS simulation system and compares it with the fire smoke spread. Conditions under which optical density for both cases is similar are determined, mainly the mass flux of aerosol needed to represent the smoke produced by fire and the distance at which steady-state flow of smoke is formed. The influence of the fire HRR and air flow velocity on the determined aerosol mass flux is studied as well. The determined value of mass flux increases with increasing flow velocity and decreases with increasing fire HRR. The results indicate that the aerosol can be used to represent the optical density of steady-state fire smoke spread downstream of the fire in tunnel ventilation tests.

1. Introduction
Fires in road tunnels are extremely destructive events destroying irreversibly not only tunnel facilities but also concrete tunnel walls. Therefore, it is almost impossible to perform full-scale fire tests of realistic fire scenarios in particular tunnels in operation. Although Computational Fluid Dynamics (CFD) is a very efficient tool for evaluation of fire scenarios, full-scale tests in real road tunnels, for example ventilation tests, cannot be fully replaced by simulation.

In Slovakia, several highway road tunnels are under construction or have been planned. Ventilation tests are an essential part of fire safety measures required by authorities. In order to tackle with the aforementioned difficulties, a specific kind of testing aerosol [1] is used for ventilation tests to represent smoke generated by fire. The aerosol is used for smoke visualization and must meet the following requirements:

- Optical density of aerosol is similar to that of considered fire smoke
- Heat produced during aerosol generation allows maintaining the aerosol stratification at ambient temperature
- Opacity sensors and smoke detectors respond correctly to the aerosol
- Heat does not damage the tunnel facilities
- Aerosol is not toxic and does not cause corrosion.

The aerosol is generated by a chemical reaction of 50 times lower heat release rate (HRR) than the HRR of the corresponding modelled fire. However, it is assumed that the optical density of the aerosol
in a sufficiently long distance from the modelled fire source corresponds to the optical density of the fire smoke. This way, devices installed in the tunnel are not damaged while realistic smoke movement interacting with the tunnel ventilation is achieved and practical fire scenarios can be examined experimentally.

This study compares the movement of the aerosol in a road tunnel with the movement of the corresponding fire smoke and looks for conditions under which the movements are similar. The aim is to determine the mass production of the aerosol and the distance at which a steady-state movement of the smoke layer occurs in order to obtain similar optical density profiles for the aerosol and the fire smoke. The task is solved by the widely used Fire Dynamics Simulator (FDS, version 6.3.2) [2, 3, 4, 5]. The results can be used for settings of road tunnel tests using the aerosol and may increase the confidence on capability of the aerosol to represent fire smoke in specific conditions.

2. Simulation settings
Geometrical model of 240 m long section of a road tunnel of horseshoe cross section with 20 cm resolution is used for FDS simulations. The dimensions of the cross section of the tunnel (10.8 m width and 6.8 m height) are typical for road tunnels currently under construction in Slovakia [6, 7]. The computational domain size is 240 m x 10.8 m x 7.2 m, consisting of 1200 x 54 x 36 cells. The total number of cells is 2,332,800. Variable dynamic pressure is set on the left tunnel portal to obtain and stabilize a required target velocity of the air flow in the tunnel. The initial value of air flow velocity is 90% of the target velocity.

Let us consider 1 m.s\(^{-1}\) target velocity typical for fire ventilation scenarios in bi-directional tunnels and relatively less intensive 1 MW fire with considerable soot yield of 0.2. The fire source in fire scenario is modelled as a rectangular block located 10 m from the centre of the tunnel (i.e., 130 m from the left portal). Its top surface (1 m\(^2\)) burns with the HRR per unit area (HRRPUA) of 1 MW.m\(^{-2}\). Taking into account a low HRR of the chemical reaction generating the aerosol (20 kW), the source of aerosol in aerosol scenarios is modelled as a block with 0.2 x 0.2 m top surface (one mesh cell), which corresponds to the dimensions of real aerosol generators.

Mass loss rate of 1 MW fire calculated by FDS is 24.78 g.s\(^{-1}\), i.e., 4.957 g of soot per second. Therefore, 123.9 g.m\(^{-2}\).s\(^{-1}\) mass flux of aerosol generates the same amount of smoke as the fire. However, buoyancy of the fire accelerates the spread of smoke under the tunnel ceiling while the spread of aerosol is slower, which means that a lower mass flux of aerosol is sufficient to create the same optical density as the fire smoke. In order to determine the most appropriate value of mass flux, several aerosol scenarios simulations with various values of mass flux were executed and evaluated. As preliminary simulations indicated that the spread of smoke is about 1.5 times faster than the spread of aerosol, the resulting value of mass flux can be expected in the vicinity of 84 g.m\(^{-2}\).s\(^{-1}\) mass flux. Therefore, values between 62 and 90 g.m\(^{-2}\).s\(^{-1}\) were tested. Optical density is evaluated by five
quadruples of detectors at 6.0, 5.0, 3.4 and 1.6 m height at 25, 40, 65, 80 and 95 m from the fire/aerosol source.

The 200 s smoke movement was simulated using Intel Core i7-4790 CPU @ 3.60 GHz. The wall-clock time depends on specifications of each scenario: 8 – 16 and 20 – 38 hours for aerosol and fire scenarios, respectively.

3. **Simulation results**

The main qualitative difference between the movement of fire smoke and aerosol is the back-layering occurring in the former case (Fig.2, top). In aerosol scenario it is not formed due to low buoyancy caused by the 20 kW chemical reaction generating the aerosol (Fig.2, bottom). Other differences can be observed downstream of the fire/aerosol source in its vicinity. Therefore, optical density differences between fire and aerosol scenarios at the first and second quadruples of detectors are the most significant for all tested values of the aerosol mass flux.

![Figure 2. Fire smoke and aerosol movement in a part of 240 m long tunnel.](image)

However, these differences are not essential for the steady-state movement of smoke being formed in a larger distance downstream, which is similar in aerosol and fire scenarios. The sum of squared differences between the time-averaged optical density values measured by the last three quadruples of detectors for the fire and the particular aerosol scenario is determined for all tested values of aerosol mass flux. The optical density values are averaged over the interval 150 – 200 s, when steady-state movement is achieved (Fig. 3, left). The minimal sum is obtained for the aerosol mass flux of 68 g.m\(^{-2}\).s\(^{-1}\) (2.7 g.s\(^{-1}\) mass flow rate; i.e., 55% of the fire mass flow rate).

![Figure 3. Optical density for 1MW fire and the corresponding aerosol scenario measured by quadruple of detectors at 80 m from the fire/aerosol source during the whole simulation (left) and after steady-state conditions are formed (right).](image)
Figures 3 and 4 show optical density values measured by 3 selected quadruples of detectors. It can be seen that the optical density profile for the fourth position of detectors (located at 80 m) is almost identical for fire and aerosol (Fig. 3, right; Table 1). There are some differences of less significance for the third position of detectors (located at 65 m) at which the optical density profile is not fully stabilized (Fig. 4, left; Table 1). This indicates that both profiles become very similar beyond 70 m from the source.

Table 1. Sum of squared differences between the time-averaged optical density values in fire and aerosol scenario for particular quadruples of detectors [m$^2$]

| Position of detectors at | 25 m | 40 m | 65 m | 80 m | 95 m |
|--------------------------|------|------|------|------|------|
| Sum                      | 0.17 | 0.38 | 0.13 | 0.01 | 0.07 |

As mentioned above, significant differences can be observed for the second position of detectors (located at 40 m), mainly for detectors located below the tunnel ceiling (Fig. 4, right; Table 1). However, for the practical purpose of smoke visualisation during tunnel ventilation tests the optical density at head level is more essential; therefore, even such smoke behaviour is acceptable. The values for detectors located in lower positions Fire/Aero 3 and 4 are relatively close for fire smoke and aerosol (Fig. 4, right).

4. The influence of fire HRR and air flow velocity

As the change of fire HRR and air flow velocity may influence the accuracy of smoke representation using aerosol mass flux, another three scenarios combining 1 and 3 m.s$^{-1}$ velocities and 1 and 3 MW HRRs were investigated. The same procedure as in the previous section was used to determine the proper aerosol mass flux. The corresponding simulation results are shown in Tab. 2.

For the scenario with parameters (1 MW, 3 m.s$^{-1}$) it is not possible to determine the proper mass flux value due to the qualitatively different behaviour of aerosol. Other results indicate that the aerosol and fire mass flux ratio decreases with increasing HRR. It is obviously due to the buoyancy of more intensive fires, accelerating the smoke spread rate in comparison with aerosol scenario. Therefore, the smaller amount of slowly moving and strongly concentrated aerosol is sufficient to achieve the
required optical density. On the other hand, the ratio increases with the flow velocity increase. For the same HRR increasing velocity becomes the main factor influencing the smoke spread rate, fire buoyancy becomes less important and the total amount of smoke becomes the main factor influencing optical density.

Table 2. Proper mass flux of aerosol / % of fire mass flux for particular scenarios

| Scenario    | Mass Flux       | Percentage |
|-------------|-----------------|------------|
| 1 MW fire   | 2.7 g.s⁻¹/55 %  | -          |
| 3 MW fire   | 6.0 g.s⁻¹/40 %  | 8.2 g.s⁻¹/55 % |

5. Conclusions

In this paper, optical density of fire smoke and testing aerosol used for ventilation tests in road tunnels was investigated using the Fire Dynamics Simulator system. The simulation results for 20 cm resolution indicate that the optical density profile for steady-state movement of the aerosol of specific mass flux is very similar to the fire smoke movement. For the tested 1 MW fire, the steady-state conditions occur beyond 70 m from the fire/aerosol source. The aerosol mass flux of 2.7 g.s⁻¹ is proper to represent 1 MW fire for 1 m.s⁻¹ flow velocity. The proper aerosol mass flux increases with increasing flow velocity and decreases with increasing fire HRR. The results indicate that the testing aerosol is suitable to represent the steady-state spread of fire smoke downstream of the smoke source in full-scale road tunnel ventilation tests.

6. References

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