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CFD STUDY OF FIRE PROTECTION SYSTEMS IN TUNNEL FIRES

Abstract: *Field modelling based on the Computational Fluid Dynamics methodology plays an important role in fire research, and in the fire safety design and risk assessment of buildings: CFD codes can potentially be used to evaluate the effects of different designs and of emergency systems, and to assess the performance of safety measures over a wide range of fire scenarios. In this study the NIST Fire Dynamics Simulator version 5 (FDS5), a computational fluid dynamic (CFD) model, was used to simulate a series of full-scale fire tests of ventilation and sprinkler systems conducted in a test tunnel.*

Key words: tunnel, fire, ventilation, sprinkler, simulation.

INTRODUCTION

Fires in road and railway tunnels are particularly dangerous because the amount of firing material can be huge and the length of the way to escape outside the enclosure can be in some cases several kilometres. Fire accidents in road tunnels have proven to be extremely costly in terms of human lives, increased congestion, pollution and reparation. Development of fire and smoke spread are affected by the fire set-up and ventilation conditions in the tunnel. To prevent fires in road and railway tunnels existing tunnels should be upgraded and new tunnels should be equipped with efficient fire protection systems. One of a the adequate methods that may be used to prove the characteristics of a fire safety measures is fire simulations.

PROBLEM DESCRIPTION

The ventilation system is used for controlling smoke, hot and toxic combustion gases during a fire emergency, in order to allow safe evacuation and rescue. Ventilation may be provided by natural means (Fig. 1), or by mechanical equipment (longitudinal, semi-transverse or full transverse ventilation systems, (Fig. 3).

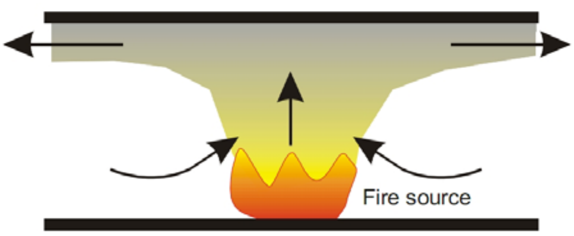

Figure 1. *Natural ventilation*

With no air current in the fire zone, the smoke progresses in a symmetrical way on both sides of the fire. The smoke remains stratified until it cools down due to the combined effects of the convective heat exchange with the walls and the mixing between the smoke and the fresh air layer, [1]. A natural ventilation system depends on the pressure differential that is created by atmospheric conditions and differences in elevation (Fig. 2).

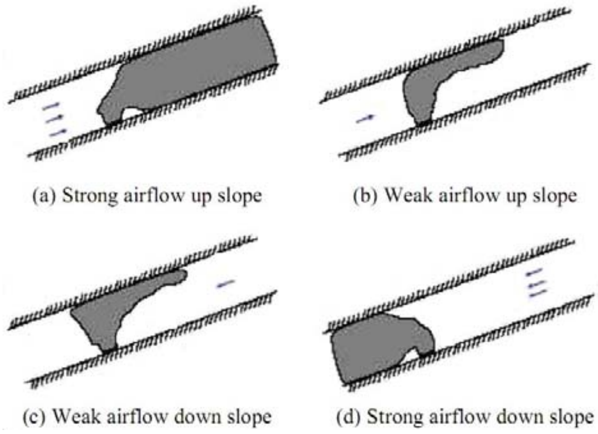

Figure 2. *Smoke behaviour in a sloping tunnel*

The longitudinal ventilation system (Fig. 3) creates a longitudinal flow along the roadway tunnel by introducing or removing air from the tunnel at a number of points. Longitudinal flow is provided by jet fans.

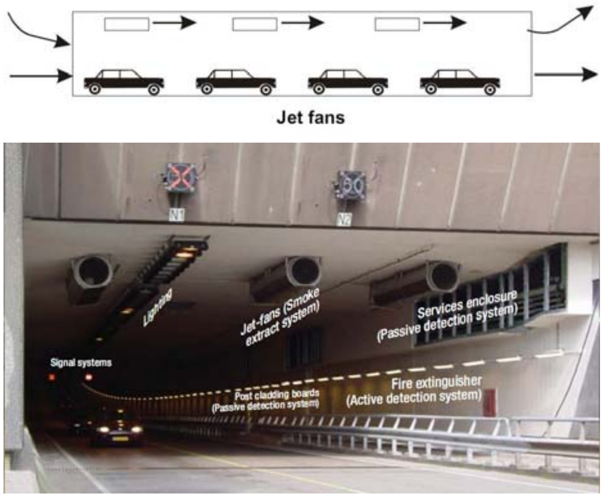

Figure 3. *Longitudinal ventilation system*

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The ventilation system would be operated to force the smoke and hot gases in the direction of the empty tunnel to provide a clear and safe environment behind the fire for evacuees and fire fighters. If the ventilation capacity is sufficient (Fig. 4b and Fig. 4c), all of the heated air and smoke will flow in the downstream direction. If the ventilation is weak (Fig. 4a), the upper layer of heated air and smoke may flow in the opposite direction causing backlayering, [1].

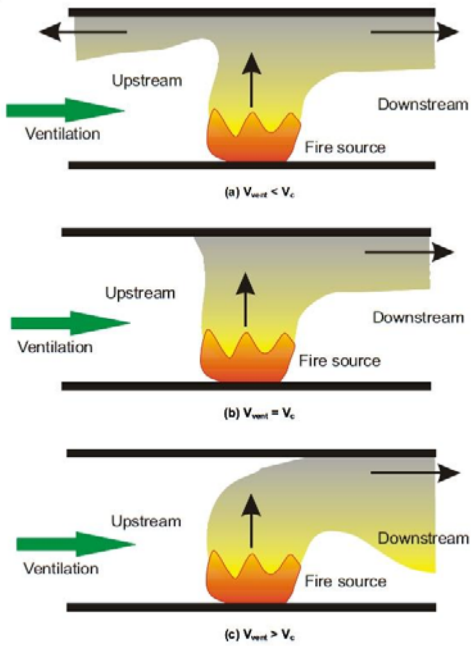


Figure 4. *Influence of longitudinal air velocity (*Vvent*) on smoke progress in the fire zone (*Vc= *critical velocity)*

The occurrence of backlayering depends on many factors including the intensity of fire, the grade and geometry of the tunnel, and the velocity of the ventilating air approaching the fire. The ability of the longitudinal ventilation system to prevent backlayering is the current industry standard to measure the adequacy of the system for smoke control (Fig. 5).

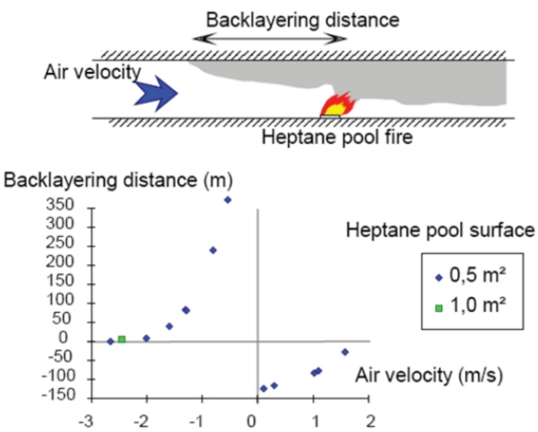


Figure 5. *Backlayering distance vs. longitudinal air velocity for two heptane pool surfaces*

The simultaneous solution of Eqn. (1) and Eqn. (2), by iteration, determines the critical velocity. The critical velocity, *Vc*, is the minimum steady-state velocity of the ventilation air moving toward a fire that is necessary to prevent backlayering, [5].

$$V_C = K_1 K_g \left(\frac{gHQ}{\rho C_p A T_f} \right)^{1/3} \qquad (1)$$

$$T_f = \left(\frac{Q}{\rho C_p A V_C} \right) + T \qquad (2)$$

Where:

A - Area perpendicular to the flow [(m^2)]

C_p - Specific heat of air [(kJ/kg K)]

g - Acceleration caused by gravity [(m/sec^2)]

H - Height of duct or tunnel at the fire site [(m)]

K_1 - 0.606

K_g - Grade factor (see Fig. 6)

Q - Heat fire is adding directly to air at the fire site [(MW)]

T - Temperature of the approach air [(K)]

T_f - Average temperature of the fire site gases [(K)]

V_c - Critical velocity [(m/sec)]

ρ - Average density of the upstream air [(kg/m^3)]

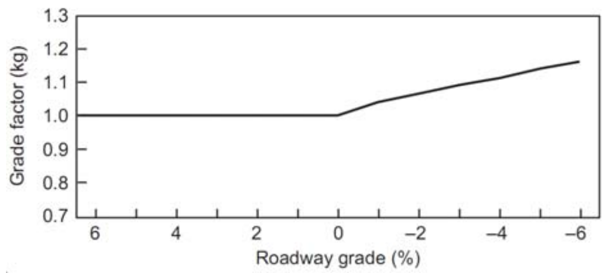


Figure 6. *Grade factor for determining critical velocity*

For large tunnel fires critical velocity can be taken as dependent of the HRR (Fig. 7).

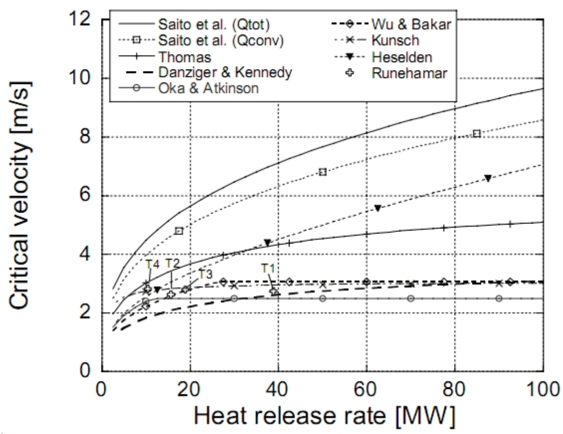


Figure 7. *Critical velocities as function of total HRR according to four different relations*

Fire Data for Typical Vehicles, according NFPA 502 Standard for Road Tunnels, Bridges and Other Limited-Access Highways are shown in the Table 1, [5].

Table 1. *Fire Data for Typical Vehicles*

Type of vehicle	HRR (MW)
Car	5-10
Multiple passenger cars (2-4 vehicles)	10-20
Bus	20-30
Heavy goods truck	70-200
Tanker	200-300

In Figure 8 the five fire temperature curves are presented graphically (the first two hours), [2].

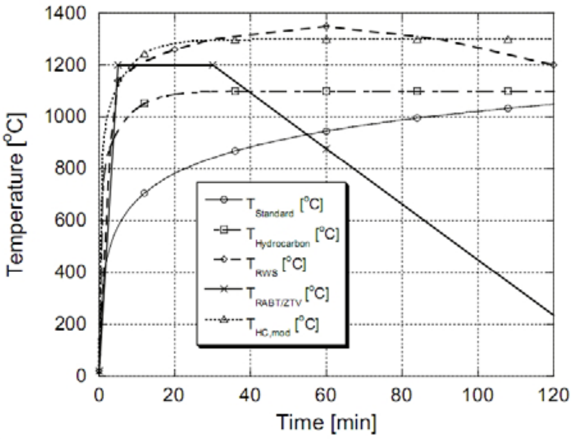


Figure 8. *Specific temperature curves of hydrocarbon fires in tunnels*

In Japan and Australia water extinguishment systems are widely used in tunnels. In Europe, however, there has been a reluctance to use sprinkler in tunnels. According NFPA 502 Standard the major concerns expressed by tunnel authorities regarding fire sprinkler use and effectiveness include the following, [5]:

(a) Typical fires usually occur under vehicles or inside passenger or engine compartments that are designed to be waterproof from above; therefore, overhead sprinklers have no extinguishing effect.

(b) With any delay between ignition and sprinkler activation, a thin water spray on a very hot fire produces large quantities of superheated steam without suppressing the fire. Such steam has the potential to be more damaging than smoke.

(c) Tunnels are long and narrow, often sloped laterally and longitudinally, usually ventilated, and never subdivided, so heat normally is not localized over a fire.

(d) Because of stratification of the hot gases plume along the tunnel ceiling, a number of activated sprinklers are unlikely to be located over the fire. A large number ofactivated sprinklers are likely to be located at a distance from the fire scene, producing a cooling effect that tends to draw the stratified layer of smoke down toward the roadway level.

(e) Even a light spray from sprinklers can catch motorists unaware and can exceed that which windshield wipers could clear. Sprinkler discharge can also cause the roadway to become dangerously slippery.

(f)Water that sprays from the ceiling of a subaqueous tunnel suggests tunnel failure and can induce panic in motorists.

(g) The use of sprinklers can cause the delamination of the smoke layer and induce turbulence and mixing of the air and smoke, thus threatening the safety of motorists in the tunnel.

(h) Periodic testing of a fire sprinkler system to determine its state of readiness is impractical and costly.

NUMERICAL MODEL

For the calculation of temperature fields and smoke concentration fields formed in case of fire within the tunnel space, the CFD software package NIST Fire Dynamics Simulator version 5 (FDS5) was used. For the calculation of flow and temperature fields of the air formed within the tunnel, *k-ε* turbulent model was used. Because of certain identical segments of the tunnel and the high length of the entire tunnel (Fig 9), in simulation used segment he was dimension: 600m(segment 60m) x 11.7m x 7.1m (lenght, wide, high, respectivelly). The FDS5 domain was divided into cells of dimension 0.15 m × 0.15 m × 0.15 m. The tunnel is built at grade in concrete. The fire source in the simulation was represented by burning of a flammable liquid in a pool with dimensions 5 x 5 m. The maximum heat release rate per unit area (HRRPUA) of the fire was 4000 kW and the total heat release rate (HRR) was 100 MW. The initial air temperature in the whole tunnel was set to 20 °C. This calculation determined that the ventilation of each tunnel segment is to be carried out by 2×2 pairs of regularly arranged jet fans and three parallel lines of sprinklers K-11 type. Distance between sprinklers is 3.05 m, according NFPA 13 Standard, [6]. The maximum volumetric flow of fresh air through these jet fans should be 17.1 m^3/s and 34.2 m^3/s.

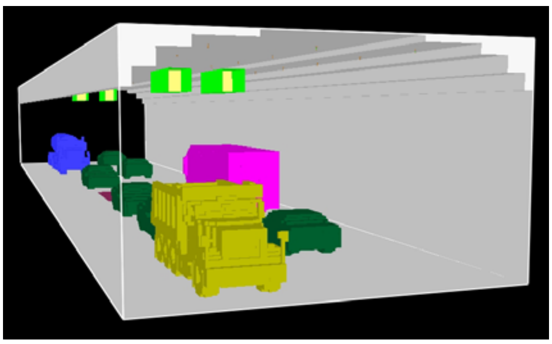


Figure 9. *The computational domain for the tunnel fire simulations*

RESULTS OF CALCULATIONS

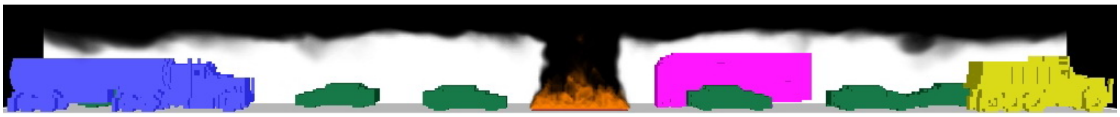
Spread of smoke in a tunnel

a) Natural ventilation

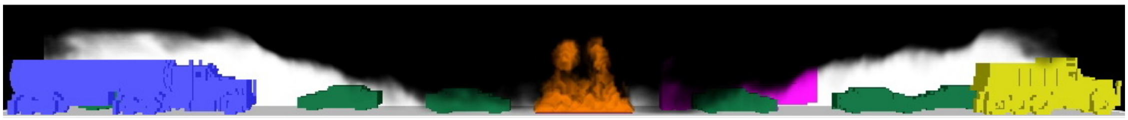
b) Forced ventilation (jet fan 17.1 m^3/s)- backlayering

c) Forced ventilation (jet fan 34.2 m^3/s)

Figure 10. *Spread of smoke in a tunnel*



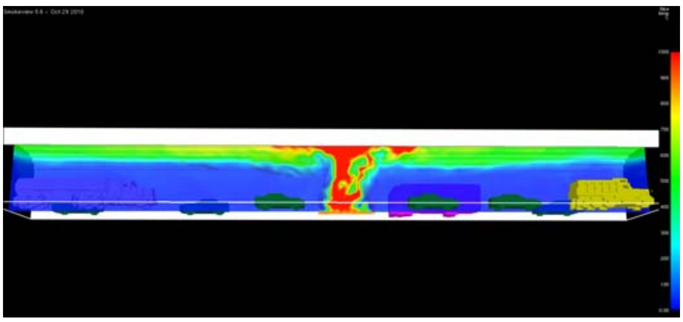
a) Without sprinklers activation



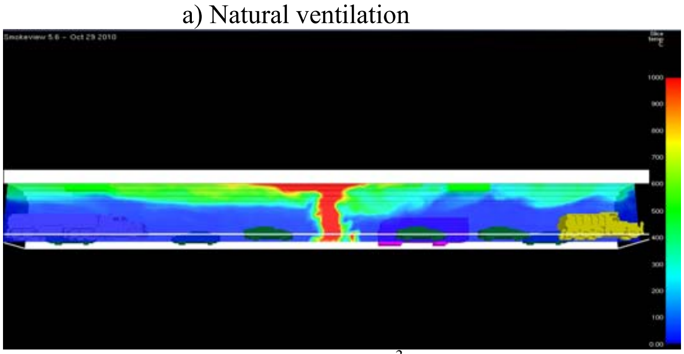
b) Sprinklers activated

Figure 11. *Spread of smoke in a tunnel without and with activated sprinklers*

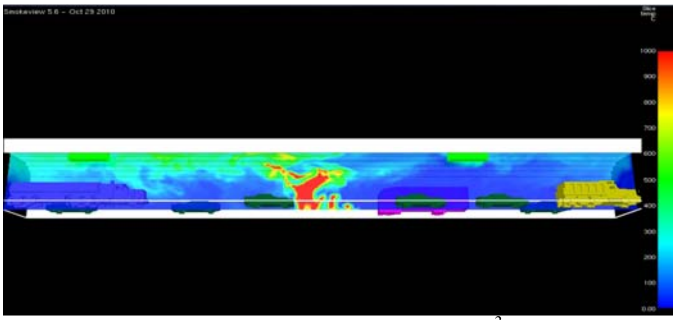
Temperature schedule



a) Natural ventilation



b) Forced ventilation (jet fan 17.1 m^3/s)- backlayering



c) Forced ventilation (jet fan 34.2 m^3/s)

Figure 12. *Temperature schedule along the centreline vertical plane*

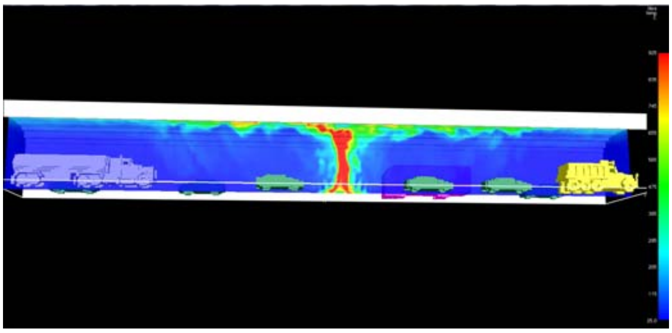
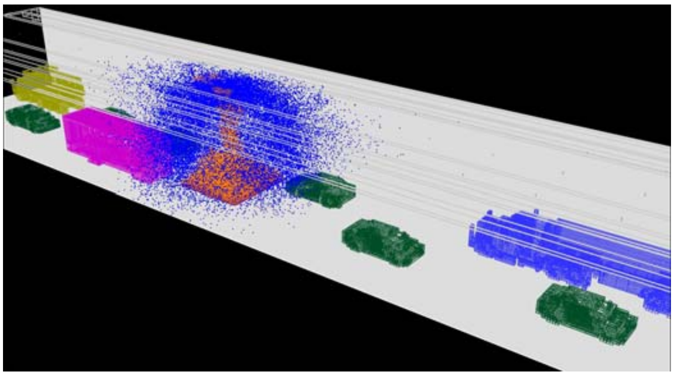
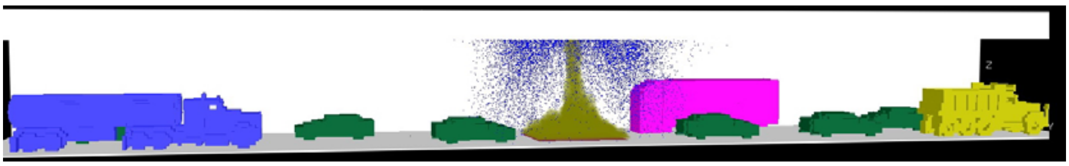


Figure 13. *Temperature schedule along the centreline vertical plane with activated sprinklers*

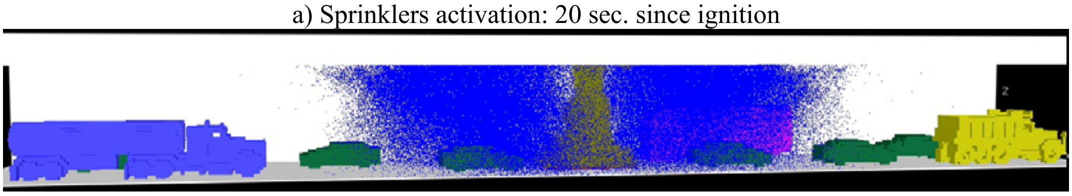
Sprinklers activation



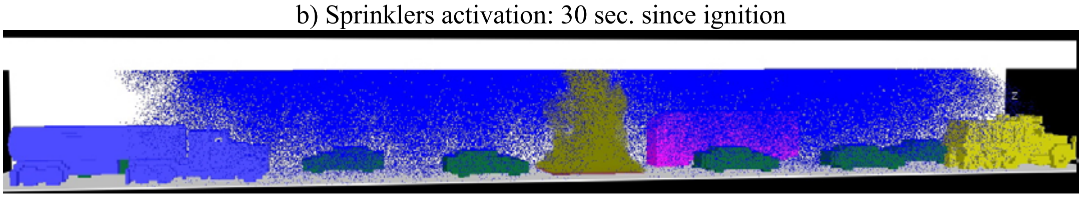
Sprinklers position



a) Sprinklers activation: 20 sec. since ignition



b) Sprinklers activation: 30 sec. since ignition



c) Sprinklers activation: 40 sec. since ignition

Figure 14. *Splinklers position and activation*

CONCLUSION

In the event of a fire in an tunnel with natural ventilation (Fig. 10a), due to difference in densities, hot combustion products rise above the fire and entrain the surrounding cold air forming a plume. The rising plume reaches the ceiling and forms two smoke streams flowing in opposite directions along the ceiling. In tunnels with longitudinal ventilation systems (Fig. 10b and Fig. 10c), the symmetry of the rising plume and the ceiling smoke streams is broken. The rising plume bends and the length of the ceiling layer flowing against the ventilation current is reduced. The reversal of the flow of the plume is referred to as backlayering (Fig. 10b). If ventilation system operates only half at the maximum flow rate designed for the ventilation of the tunnel (17.1 m^3/s) come to a backlayering effect. If ventilation system operates only at the maximum flow rate designed for the ventilation of the tunnel (Fig .10c), no wil be backlayering effect. In fire simulation with sprinklers, sprinklers activation come to destroying the smoke stratification (Fig. 11b) and there by decreasing the visibility, spreading liquid fuel over a larger area and there by spreading the fire, the risk for explosion, the production of steam affecting the people inside the tunnel. The maximum predicted gas temperature near the ceiling was just below 1000 °C (Fig. 12), in simulations with activated sprinklers 925 °C (Fig. 13). Also, the sprinkler system was not able to reduce temperature directly above the fire in the unshielded simulation. Apparently, sprinkler droplets are too light to penetrate the fire plume and are simply swept away. Simulation results suggested that the longitudinal ventilation system was very effective for blowing all smoke and hot gases in the downstream direction, which could be generally deemed empty, so immediately creating upstream the fire a safe route for evacuation and rescue.

REFERENCES

[1] A. Kashef, N. Bénichou, G. Lougheed: "Numerical modelling and behaviour of smoke produced from fires in the Ville-Marie and L.-H.-La ontaine Tunnels", literature review, NRCC Report IRC-RR-141, 2003.

[2] D. Lacroix, A. Haack: "PIARC Design Criteria for Resistance to Fire for Road Tunnel Structures", In Joint Issue ITA/PIARC of Route-Roads on Fire Safety in Tunnels, 2004.

[3] K. McGrattan, S.Hostikka, J. Floyd, H. Baum, R. Rhem: "Fire Dynamics Simulator (Version 5) Technical reference guide", National Institute of Standards and Technology, 2007, Washington.

[4] M. Banjac, B.Nikolić: "Simulation of a tunnel fire and optimization of the ventilation system with the use of numerical fluid dynamics", 11th International conference on fire and explosion protection, Novi Sad, 2008, pp. 44-50.

[5] NFPA 502: "Standard for Road Tunnels, Bridges, and other Limited Access Highways", 2004 ed., National Fire Protection Association, 2004.

[6] NFPA 13: "Standard for The Installation of Sprinkler Systems", 1999 ed., National Fire Protection Association, 1999.

BIOGRAPHY

Darko Zigar was born on April 16, 1973. in Pancevo, Serbia. He received B.Sc. degree in Environmental Protection and M.Sc. degree in Occupational Safety in 2002 and 2007 respectively, from University of Niš, Serbia.
He has been with the Faculty of Occupational Safety, University of Niš, since 2008., where he is working as a researcher / assistant lecturer. His areas of expertise include numerical fire simulations, as well as investigations of possible adverse effects of electromagnetic field irradiation from mobile phones and wireless systems.