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NUMERICAL MODELLING OF FIRE AND SMOKE DEVELOPMENT IN RAILWAY TUNNEL

K. Cábová*, M. Bernas, F. Wald*****

Abstract: *Simulation of fire spread and development of toxic gases during a fire accident in a rail tunnel allows prepare and validate models of safe evacuation of people. Highly complex problem of fire dynamics in a tunnel can be solved by the aid of CFD method. It can simulate the temperature resolution and toxic gases development in a tunnel, which can be together with visibility considered as the most important parameters affecting the safety of persons involved in tunnels accidents. In order to check the degree of qualitative agreement of model prediction, verification and validation process is applied. Prediction method of fire and smoke development by the aid of numerical model in FDS is applied to a real construction of tunnel Špičák.*

Keywords: Railway tunnel, Fire and smoke development, Fire safety, CFD method, FDS code.

1. Introduction

According to international statistics, fire accidents in tunnels are less frequent than on the open space. However, consequences of a fire in a tunnel may be more serious comparing to fire on the open road (Carvel & Marlair, 2005). During the fire in a tunnel higher amount of heat released thanks to ventilation and geometry of a structure is generated. Extreme radiation inducing high temperatures may destroy structure of a tunnel. It leads to several days of infrastructure lay-by and financially demanding repairs. Considering railway tunnels potential for a large number of casualties and lost of transported material in the event of a fire is even higher comparing to road tunnels.

In the design phase fire safety is evaluated from the length of a tunnel of 350 m, which is considered as the length with higher risk for human safety. Temperature resolution and development of toxic gases in a tunnel are together with visibility considered as the most important parameters affecting the safety of people involved in tunnel accidents. In order to provide models of safe evacuation of people, numerical simulation of highly complex problem of fire dynamics in tunnels by the aid of CFD method provides safe and economically optimized solution.

2. Numerical modelling

Nowadays, mathematical modelling of fire dynamics plays a key role in fire engineering. Together with the development of computer technology, a number of sophisticated software tools, which implement the so-called Computational Fluid Dynamics method (CFD) dramatically increases. Computational Fluid Dynamics modelling is a numerical approach to representing fluids that divides a fluid domain into number of smaller subdomains, resulting in the generation of a mesh of cells (control volumes). Three-dimensional, time-dependant partial differential equations of conservation of mass, momentum and energy transfer and conservation of species are written for each control volume based on fundamental equations of fluid dynamics, thermodynamics, chemical reactions and mechanics. Appropriate initial boundary conditions are then applied to find numerical solutions to these equations. Currently available

* Ing. Kamila Cábová, PhD.: Department of Steel and Timber Structures, Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7; 166 29, Prague; CZ, kamila.cabova@fsv.cvut.cz

** Ing. Martin Bernas: Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7; 166 29, Prague; CZ, martin.bernas@fsv.cvut.cz

*** prof. Ing. František Wald, CSc.: Department of Steel and Timber Structures, Faculty of Civil Engineering, Czech Technical University in Prague, Thákurova 7; 166 29, Prague; CZ, wald@fsv.cvut.cz

CFD models include sub-models for solution of burning and heat transfer, so they provide a framework for including all phenomena which are present during fire in a tunnel into a calculation.

One of the freely available numerical code, Fire Dynamics Simulator (FDS), developed by National Institute of Standards and Technology (NIST), is frequently used for simulation of fires. It is a numerical solver to simulate a flow and movement of fluids, also caused by burning. FDS solves numerically a form of the Navier-Stokes equation appropriate for low-speed, thermally-driven flow with an emphasis of the transport of heat and smoke from fires (McGrattan, et al., 2010). The code consists of several independent models, for example model of burning. To interpret data obtained from FDS postprocessor Smokeview is used. The computer program Fire Dynamics Simulator (McGrattan et al., 2007) is used in this study.

2.1. Verification and validation

Despite the rapid software development there are many contradictory opinions about the reliability of computer predictions. Therefore, verification and validation is always recommended to evaluate reliability and accuracy of numerical predictions.

In order to verify the accuracy of the model of fire and smoke development in a railway tunnel in FDS v6, a model of a single-track railway tunnel of simple geometry (length of 50 m and a rectangular cross section with dimensions of 5.0 x 5.0 m) was subjected to calculation in software Smartfire v4.3 (Ewer et al., 2013). Results of statistical relationships introduced in (Cabová & Wald, 2016) demonstrate that the verification of the numerical model undertaken in both software has reached a good agreement (Paerson´s correlation coefficient is equal to 0.97). Details of the verification study including sensitivity analysis of influence of mesh density on attained results may be found in (Cabová & Wald, 2016) and (Horová et al., 2015).

For the process of validation which enables to evaluate a level of agreement between a computer prediction and a physical model, meaning experimentally reached results, data measured during the fire test in road tunnel Valík (Pokorný & Hora, 2007) were used. Numerical model was validated with experimental results by the aid of gas temperature which is calculated in three height levels (4.0 m, 6.5 m and 7.9 m) and several vertical sections from the source of fire (0 m, 5 m, 10 m and 15 m). Results of the small-scale model and the model of real dimensions, presented in (Cabová & Wald, 2016) were in agreement with measured values during the fire test. For more information about validation see (Cabová & Wald, 2016).

2.2. Practical application to Špičák tunnel

After the evaluation of acceptable level of accuracy of mathematical model, the prediction of fire and smoke development by the aid of FDS code is applied to a real tunnel construction. The tunnel Špičák which represents one of the longest old tunnel in the Czech Republic is chosen. The tunnel is 1747 m long. Along the tunnel length cross-section of the tube changes. In total there are twenty different cross-section areas. Material of the tunnel linings is also variable. High difference of both portals is negligible.

2.2.1. Model description

In numerical model the cross-section of 6.97 m width and 5.33 m high, which covers the longest part of the tunnel and which has the minimum high, is used. Arc shape of the tube is replaced by staircase shape of the cross-section in the model, as illustrated on Fig. 1a. The tunnel lining is formed by 0.4 m thick layer of concrete with density of 2200 kg/m^3, conductivity of 1.3 W/mK and specific heat of 1.02 kJ/kgK. Tunnel portals opened throughout the cross-sectional area provide natural gas flow (in FDS code plane surface type VENT is OPEN).

Fire scenario of burning inside a passenger train wagon is simulated by uniform heat release rate of 20 MW (input data corresponds to results of fire test of passenger train wagon described in (White, 2010)). The heat flux is released through four window openings, each of area of 1,44 m^2, situated 2 m above the ground level. The fire (areas releasing the heat flux) is located in the third wagon from the total of five wagons. The train stopped after 935 m after entering its portal (stands between 810 m and 935 m of the tunnel length). In FDS burning is simulated by mixed-fraction ratio of polyurethane (defined by fractions of carbon, hydrogen, oxygen, nitrogen and soot yield particles). Development of rate of heat release is based on t-quadratic curve for ultra-fast fire (Bernas, 2016).

Computational domain of dimensions 1747 m x 6.97 m x 5.33 m consists of five meshes. Size of mesh is determined according to rules given in (McGrattan et al., 2007). Cell size in axis (x, y, z) equals to (0.345 m, 0.348 m and 0.355 m). In the region of fire source the grid is refined to half size, in axis (x, y, z) cell size equals to (0.182 m, 0.174 m, 0.178 m). The total number of cells is 1 530 600.

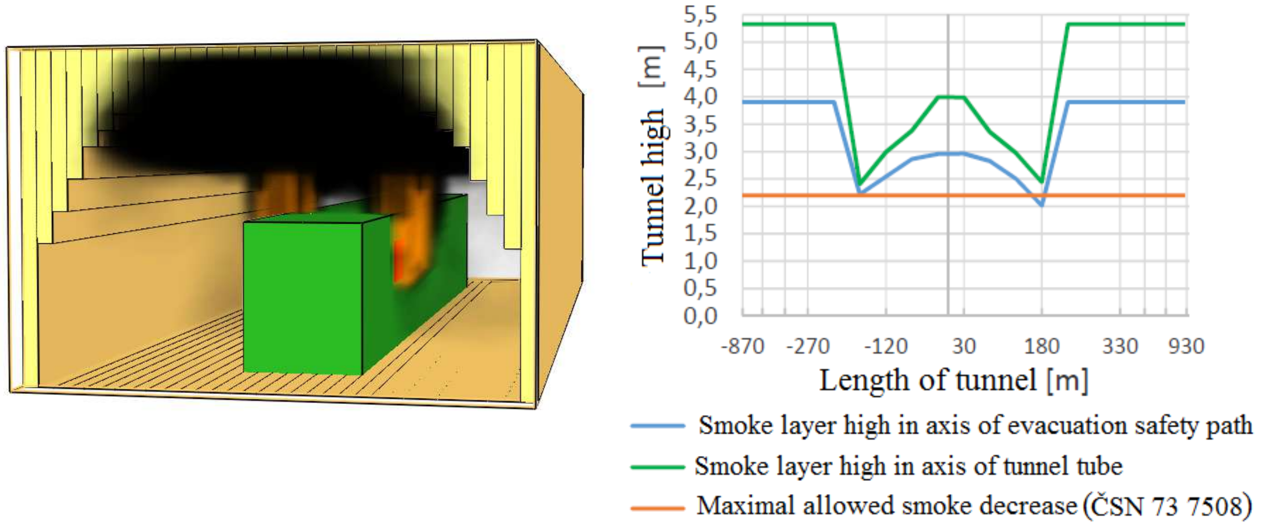
In the tunnel there is negligible natural gas flow as the high difference of both portals is very small. Initial gas flow velocity is therefore set to 0 m/s. Gas temperature before fire ignition is considered as 10°C. In FDS turbulence model is applied by Smagorinski formulas of large eddy simulation (LES) with coefficient Cs equals to 0.2. Heat transfer by radiation is applied by 100 discrete angles.

In the model there are sensor to measure high of smoke layer, temperature of hot gas layer and temperature of gas layer below the smoke level. These sensors are situated in 50 m span sections in the axis of the tunnel tube and in the position of 0.6 m from the side lining, which should control the area of safety evacuation path.

2.2.2. Results

After fire ignition layer of hot smoke gases accumulated below the tube arch. The tunnel linings cooled hot gases down and smoke sank to lower level of the tunnel. Visualisation of fire and smoke development originated form the fire of passenger train wagon in 600 s is given in Fig. 1a. Fig. 1b shows decrease of smoke layer high along the tunnel length in 5 min. In the diagram three curves are introduced – curve of smoke layer high calculated by numerical model in the axis of evacuation path (0.6 m from the tunnel linings), curve of smoke layer high calculated in the axis of the tunnel cross-section and a curve indicating the level of maximal smoke layer decrease according to ČSN 73 7508. In the figure it is visible that the calculated high of smoke layer in the axis of evacuation path is lower than the level of 2.2 m. This level is considered as the maximal limit for safe evacuation.

Gas temperature calculated in the axis of fire source in the same time is illustrated in Fig. 2a. The maximal value calculated in 600 s is 800°C which is denoted to temperature of flames. From the view of safe evacuation temperature of 80°C is usually controlled in the high of 2 m above the evacuation path. Temperature of tunnel linings calculated in 600 s of fire reaches about 150°C directly above the fire source.



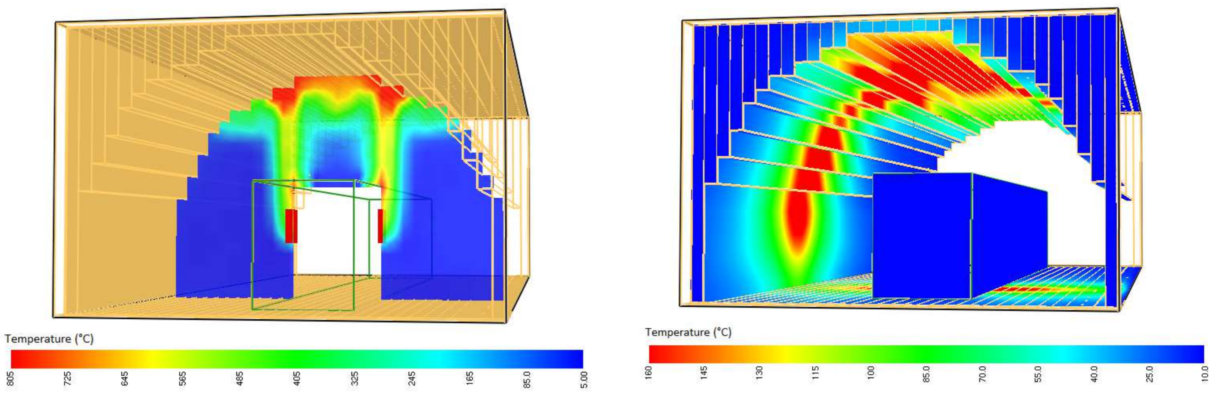
a) *b)*

Fig. 1: Model of passenger train fire in railway tunnel – a) smoke development in 600 s; b) smoke layer high along the tunnel length in 5 min.

3. Conclusions

Findings from the numerical simulations of fire and smoke development in railway tunnels enables to improve models of human evacuation during fires in tunnels. Similarly to shown study of model of passenger wagon fire in Špičák tunnel, gas temperature resolution, development of smoke layer together with visibility, toxicity of smoke and other parameters which are beyond the capabilities of CFD codes may be evaluated. Except optimization of fire safety equipment and evacuation scenarios, by the aid of numerical models it is possible to improve emergency procedures of IRS, provide accurate gas temperature resolution for the design phase, evaluate material behavior of tunnel linings and rail bed at elevated temperatures and during rapid cooling caused by firefighters.

Correctly applied CFD models may reproduce the qualitative behaviour of fire in each tunnel. The degree, to which qualitative agreement is achieved, is necessary to find out by the aid of verification and validation process. Accurate prediction of fire and smoke spread in tunnels on the bases of physical properties is a promising approach how to stress the human safety and fire design economy.



a) *b)*

Fig. 2: Model of passenger train fire in railway tunnel – a) gas temperature in 600 s; b) temperature of tunnel linings in 600 s.

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