UDC: 614.841:519.711
DOI: 10.5937/SE2101015C
Research article
www.safety.ni.ac.rs

VALENTIN CHOCHEV[1]
SVILENA ARABADZHIEVA[2]
MILAN PROTIĆ[3]

[1,2]Academy of the Ministry of Interior,
Faculty of Fire Safety and Civil Protection, Sofia,
Republic of Bulgaria
[3]University of Niš,
Faculty of Occupational Safety, Niš

[1]*vchochev@abv.bg*
[2]*ssarab@mail.com*
[3]*milan.protic@znrfak.ni.ac.rs*

FIRE MODELING IN A COMPARTMENT RAILWAY PASSENGER CAR

Abstract: *In this paper numerical modeling of fire development in a single compartment of a railway passenger car has been performed using the FDS software. The simulation was focused on the dynamic calculation of temperature field and heat release rate. Obtained simulation results were compared with experimental results and satisfactory agreement was detected. It can be concluded that FDS can be used for simulating different fire scenarios in railway passenger cars.*

Key words: fire modeling, FDS, CFD field model.

INTRODUCTION

The mathematical models describing the ignition and fire spread in open and confined spaces heavily rely on knowledge of fluid dynamics. Computational fluid dynamics (CFD) is a branch of fluid dynamics where physical processes of fluid flow are mathematically modeled and consequently solved using numerical methods [1]. A number of software tools, such as ANSYS, FLUENT, STAR-CD, have been developed for solving fire modeling problems in complex geometries. For example, in [2] ANSYS software was used for determining the fluctuations in temperature field in steel columns.

The mathematical modeling of combustion problems in fires is challenging and requires inputs from diverse disciplines. Models are often quite complex containing several equations: Navier–Stokes equations; equation of state; law of conservation of energy; equation of scalar quantities describing the concentration of a combustible substance, oxidant, combustion products, inert gas and nitrogen oxides, etc.

Fire modeling is further complicated due to the presence of turbulent convective and radiant heat transfer between combustible gases and constructive elements of the room. All this significantly contributes to heterogeneity of temperature, momentum and concentration fields in analyzed spaces [3].

In order to describe thermal and gas-dynamic parameters of fire, three main approaches of mathematical modeling of fire are applied: integral, zonal and differential (field).

The FDS software (Fire Dynamic Simulation) is developed by the National Institute of Standards and Technology (NIST), USA and is based on a field approach. In 2000 the first version of software package FDS and SmokeView were published. Nowadays FDS is a mature, proven and reliable tool for modeling and analysis of fires in confined spaces. The software has been successfully verified for different fire scenarios and the data resulting from FDS simulations have wide application in fire protection engineering. Simulations and verification of obtained results are very well documented in the literature [4].

FDS uses the Smagorinsky model, as a basic turbulence model for the Large Eddy Simulation LES method. The model is designed so that when the grid is compressed to the Kolmogorov scale, calculations transfer directly from LES to Direct Numerical Simulation DNS. The computational problem is simplified by restricting the validity of equations to low-speed, convective flows with an emphasis on smoke and heat transfer in case of fire. FDS solves numerically the Navier–Stokes equations, whereby their partial derivatives for mass conservation, momentum and energy are approximated as final results and the method of solving is updated in time and space based on a three-dimensional rectangular structured grid [5].

Law of conservation of mass [6]:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = \dot{m}_b''' \quad (1)$$

Law of conservation of momentum:

$$\frac{\partial}{\partial t}(\rho u) + \nabla.\rho u u + \nabla p = \rho g + f_b + \nabla.\tau_{ij} \quad (2)$$

where stress tensor is

$$\tau_{ij} = \mu\left(2S_{ij} - \frac{2}{3}\delta_{ij}(\nabla.u)\right);\ \delta_{ij} = \begin{cases}1\ i=j\\0\ i\neq j\end{cases};\quad S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\ i,j = 1,2,3 \quad (3)$$

Law of conservation of energy:

$$\frac{\partial}{\partial t}(\rho h_s) + \nabla.\rho h_s u = \frac{Dp}{Dt} + \dot{q}''' - \dot{q}_b''' - \nabla.\dot{q}'' + \varepsilon \quad (4)$$

where heat transfer is

$$\dot{q}'' = -k\nabla T - \sum_\alpha h_{s},\alpha\rho D_\alpha \nabla Y_\alpha + \dot{q}_r'' \quad (5)$$

and energy of dissipation

$$\varepsilon \equiv \tau_{ij}.\nabla u = \mu\left(2S_{ij}.S_{ij} - \frac{2}{3}(\nabla.u)^2\right) \quad (6)$$

Equation of state of a hypothetical ideal gas:

$$p = \frac{\rho RT}{\bar{W}} \quad (7)$$

These six equations have six independent variable quantities: three components of rate, density, temperature and pressure.
LES is used for modeling dissipative processes (viscosity, thermal conductivity, diffusion), whose scales are less than the dimensions of a clearly defined numerical grid. This means that the μ, k, D parameters in the equations above cannot be directly used and therefore they are substituted for expressions modeling their effects

$$\mu_{LES} = \rho(C_s\Delta)^2\left(2\bar{S}_{ij}.\bar{S}_{ij} - \frac{2}{3}(\nabla.\overline{u})^2\right)^{\frac{1}{2}} \quad (8)$$

$$k_{LES} = \frac{\mu_{LES}c_p}{Pr_t} \;;\; (\rho D)_{i,LES} = \frac{\mu_{LES}}{Sc_t} \quad (9)$$

AIMS AND PURPOSES

The numerical modeling conducted aims at determining the parameters of fire in a compartment of a railway passenger coach type B84, that is most commonly used in the Bulgarian State Railways Company, by using the data for characteristics of materials used for the construction of that type of coaches, as well as validation of results by comparing them to a conducted experiment with a model of a railway passenger coach type B84.

INITIAL AND BOUNDARY CONDITIONS OF THE TASK

In order to assess the dynamics of the development of fire in the compartment, the following scenario has been assumed:

- fire in a separate compartment, developed in a closed room restricted in space is studied;
- the doors and windows of the compartment are closed, and the not tight closing is simulated through openings in the zone of the wall on the door and the door itself with a total size 0,08 m;
- the fire load consists of standard seats and partition walls used in railroad coach type B84.;

The following initial conditions have been assumed when modeling:

- primary ambient temperature 30°C;
- ignition source activates at a certain moment: t = 0 s;
- ignition model represents a source of typical ignition due to arson or vandalism, for instance using a newspaper. The ignition model is a combustion source with a flame with a 3 min duration and average power of 7 kW, creating a flow from 25 kW/m^2 to 30 kW/m^2 in accordance with Annex A of BDS EN 45545-1. The ignition model is a paper cushion specified in UIC 564-2 – Code of International Union of Railways with dimensions 0,39 x 0,17 m.
- duration of action of the ignition source on seats is 180 s;
- the doors of the compartment are closed;
- the glazing material of the windows and doors of the compartment is undamaged at the primary moment of fire.

The following conditions appear to be boundary:

- the compartment is with dimensions 2,1x2,1x2,5 m;
- material of the external wall of the compartment - metal;
- a standard window is intended to be on the external partition wall, parallel to the longitudinal axis of the compartment;
- material of the interior partition walls, floor and ceiling - particle boards 0,018 m thick;
- seat padding is of polyurethane foam and seats have fabric covers;
- the glazing material of the windows and doors of the compartment destroys when the temperature in the middle of the glazed zone reaches above 300°C.

SPECIFICATIONS OF THE MODEL

Geometry of the model in FDS-version 6 includes the tested compartment with dimensions 2,1 x 2,1 x 2,5 m (fig. 1) and computational grid consisting of 332 667 cells with dimensions 0,09 x 0,09 x 0,09 m.

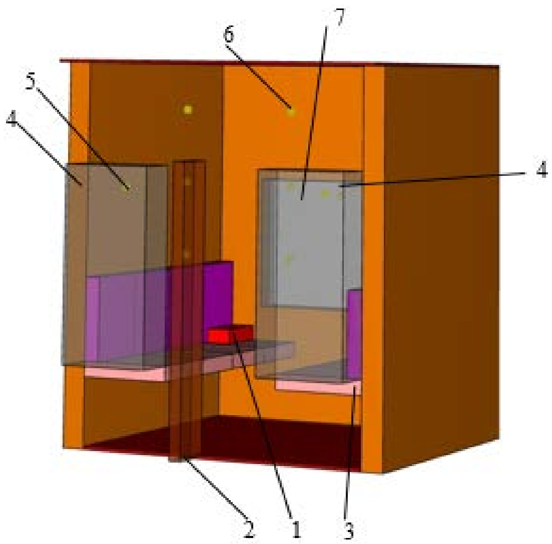

Figure 1. *Overall appearance of the model*

1-ignition source; 2- door; 3-seats; 4- windows near the door; 5-temperature sensor in the glazed area; 6-sensors for temperature measuring, O_2, CO, CO_2 concentration and visibility; 7-window on external wall

The LES model with simulation time 600 s has been used as a basic turbulence model. When applying LES simulation the size of the grid is the main parameter that has to be examined very carefully in order to obtain reliable results of the simulation. The size of the grid is determined by the expression D*/δx, where D* is the characteristic diameter of flame, and δx is the nominal size of the grid cell. The characteristic diameter of flame is defined in [7].

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty C_p T_\infty \sqrt{g}}\right)^{2/5} \tag{10}$$

Where: Q* - heat release rate; cp – specific heat capacity of smoke; T∞ – ambient temperature

Using the tests of McGrattan and others [8] and [9] the size of the grid for the simulation presented must be 0,5D* in order to obtain correct results from the simulation forHRR Q=150 кW. Therefore, the dimensions of the grid were determined to be 0,09 m in the three-dimensional directions (x, y and z). The number of grid cells is 332 667 (fig.2).

45 sensors for measuring temperature, the concentration of oxygen, carbon oxide, carbon dioxide and visibility are located in the capacity of the compartment at height respectively 1,2 m, 1,7 m and 2,2 m, as well as 3 sensors measuring temperature in the zone of glazing of the compartment.

To validate the results of the simulation, the temperature sensors are arranged in a similar way to the sensors used in the real-size coupe experiment described in [10] and shown in Figures 10-11.

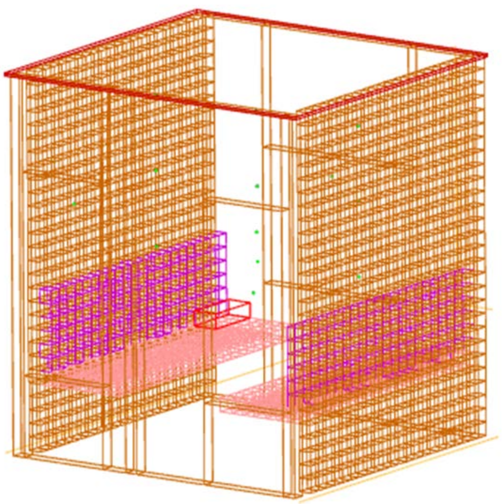

Figure 2. *Kind of grid of the tested object*

For the properties of the partition walls such as density, ignition temperature, heat release temperature, ignition temperature the data from [11,12] have been used.

Since data about heat release rate, density and ignition temperature of seats used in passenger cars type B84 were not present, they were tested in the Fire Testing Laboratory, Faculty of Occupational Safety with the University of Nis, Republic of Serbia. Tests have been conducted on the cone calorimeter. The cone calorimeter meets the requirements of EN ISO 13927. The basic working element in it is a source of heat with a conical shape, that provides permanent heat flow within the range from 0 to 150 KW/m2. Testing at different levels of radiation is needed for a detailed analysis. According to ISO 5660-1: 2013, three samples of the tested material must be tested per flow: 25, 35, 50 and 75 KW/m².

The test is conducted by placing the sample on a scale that measures the mass loss of the sample during combustion. The source of ignition is an electric spark. After the ignition, the fire effluents are lead through a conical heater and chimney into the ventilation system. During the experiment number of parameters are closely measured and archived. These measurements allow the calculation of heat release rate.

The test model has an area of 88,4 cm², a thickness of 17 mm and a mass 27,1 g. The test is performed in accordance with the requirements of EN ISO 13927.

The moment of flame spreading is at 21 s, and the time of combustion end at 342 s.

Variation of average heat release rate and effective heat of combustion of the models of seats tested are displayed in fig. 3 and fig. 4.

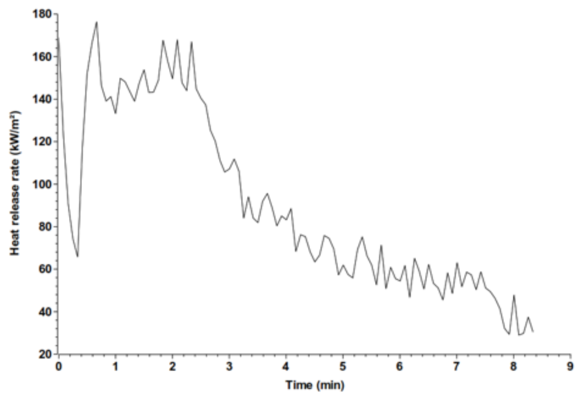

Figure 3. *Variation of average heat release rate*

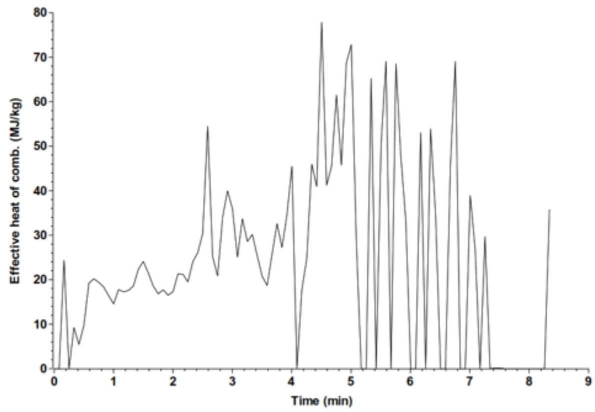

Figure 4. *Variation of effective heat of combustion*

RESULTS

At initial moments fire develops with fixed power of 97,71 KW/200 s. In the time range from 288 s to 296 s the glazing of windows in the zone of the door destroys, and at 375 s the glazing of the window of the compartment destroys. From that moment on the heat release rate sharply increases to values from 1694,3 кW/400 s to 4387,6 KW/600 s (fig. 5.). The sharp increase in fire intensity can be explained by oxygen entering the compartment, as well as by the moment of the beginning of explosive combustion of the seats heated to their temperature of ignition. The obtained results correspond well enough to the data from other publications[11,13].

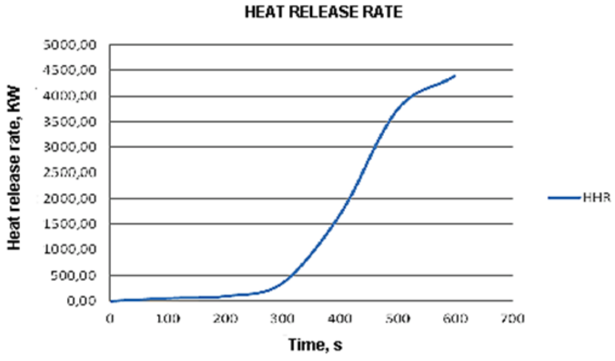

Figure 5. *Dependence of fire intensity on time*

Stages of fire development at 296 s, 375 s, 400 s and 600 s are shown in fig. 6 – 9.

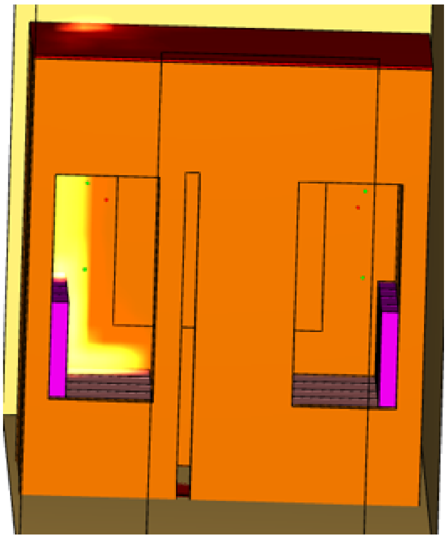

Figure 6. *Fire development at 296 s*

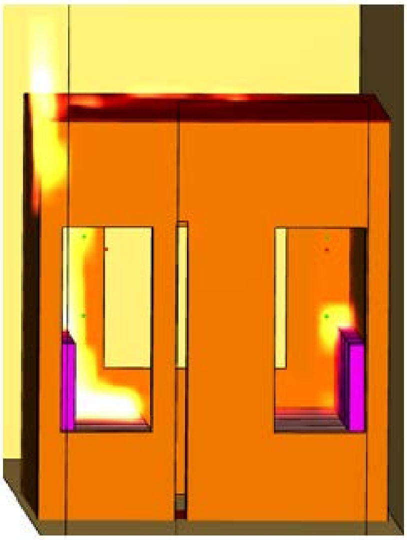

Figure 7. *Fire development at 375 s*

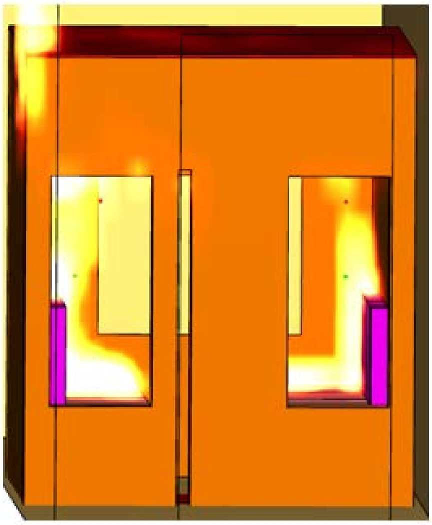

Figure 8. *Fire development at 400 s*

Figure 9. *Fire development at 600 s*

A similar development of the fire was observed in a real experiment described in [10].

To study the dangerous factors of the fire, a model of a second-class coupe, designed for the transport of passengers, in real size was built (Fig. 10-11).

Figure 10. *Model of a coupe on a railway car type B84*

Figure 11. *Model of a coupe on a railway car type B84*

To study the temperature change in the volume of the cabin, 24 thermocouples were installed, nine were placed in the volume of the cabin, eight on the walls above the seats, two on the inside of the window of the cabin, two on the wall above the window, three in height of the inside cabin door. The report analyzes data from eight thermocouples mounted at a height of 1.7 m, the height that is assumed to be the average respiratory level of a person in an upright position. The temperature is measured every 30 s. Values in the range of 70°C, with an exposure time of a few seconds to a minute, are considered to be critical closed temperature values.

The comparison of the change in temperatures in the volume of the cabin (Fig. 12) clearly shows the very good correlation between the data obtained from the real experiment and the simulation.

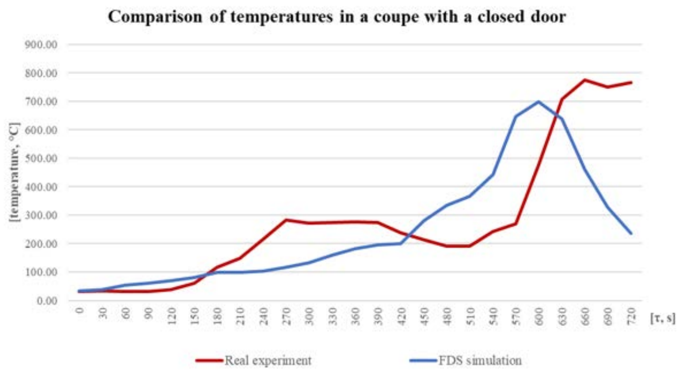

Figure 12. *Change in mean volume temperature*

The obtained results correspond well enough to the data from other publications [11, 13].

CONCLUSION

In this work, numerical simulation of fire onset and development in a railway passenger car has been performed using the FDS software. Additionally, the experiment was performed where temperature, heat release rate, and fire effluents were closely monitored. Moreover, samples of passenger seats were tasted in a cone calorimeter according to EN ISO 13927.

Conducting real experiments under these conditions is difficult; therefore, the results of the test presented show that the computational fluid dynamics (CFD) can be successfully used for simulation of the spread of fire in a compartment of a railway passenger coach. A clear definition of parameters of the object tested (geometry, kind and amount of the source of fire, initial and boundary conditions) is a necessary condition for performing successful tests.

REFERENCES

[1] V. Iliev, S. Deliev, M. Hristova, Modelling the spread of smoke in a public building, VIII scientific conference with international participation Civil Safety 2017, Sofia, 2017;

[2] I. Todorov, Hr. Prodanov, Evaluation of the temperature development in insulated steel elements using ANSYS, Bulletin No 26, FSCP Faculty, AMoI, pp. 121-130, ISSN 1318-6687, 2020;

[3] D.Zigar, D.Jovanović, M.Zdravković, CFD Study of Fire Protection Systems in Tunnel Fires, Safety Engineering, vol.1 (1), pp. 11-16, 2011.

[4] BDS EN 45545-1. Railway applications - Fire protection on railway vehicles - Part 1: General;

[5] S. Mijorski, Modeling of non-isothermal air currents in case of fire occurrence and spread, Abstract of the dissertation, Technical University of Sofia, 2012, Sofia;

[6] K. McGrattan, S. Hostikka, R. McDermott, J. Floyd, C. Weinschenk, K. Overholt, *Fire dynamics simulator technical reference guide volume 1: mathematical model*, National Institute of Standards and Technology, 2013, Washington;

[7] K. McGrattan, S. Hostikka, J. Floyd, H. Baum, R. R. W. Mell, R. McDermott, Fire Dynamics Simulator (Version 5.4) Technical reference guide, National Institute of Standards and Technology, Washington, 2009;

[8] K. B. McGrattan, H. R. Baum, R. G. Rehm, Large-eddy simulations of smoke movement, Fire Safety Journal, vol. 30, pp.161–178, 1998;

[9] N. Cai, W. K. Chow, Numerical studies on heat release rate in-room fire on liquid fuel under different ventilation factors, International Journal of Chemical Engineering, 2012;

[10] S. Arabadzhieva, T. Toshev, Experimental study on hazardous fire factors in a passenger train coupe, 58th Science Conference of Ruse University - SSS, Bulgaria, 2019;

[11] M. Hjohlman, M. Försth, J. Axelsson, Design fire for a train compartment, Brandforsk project 401-051, SP Technical Research Institute of Sweden, SP Report 2009, Borås 2009;

[12] A. Andreini., R. Da Soghe, A. Giusti, L. Caruso, Pyrolysis modeling and numerical simulation of rail carriage fire scenarios for the safe design of a passenger train, Chia Laguna, Cagliari, Sardinia, Italy, 2011;

[13] S. Mo, Z. Li, D. Liang, J. Li, N. Zhou, Analysis of smoke hazard in train compartment fire accidents base on FDS, Procedia Engineering, vol. 52, pp. 284 – 289, 2013;

[14] UIC 546-2: Regulations relating to fire protection and fire-fighting measures in passenger-carrying railway vehicles or assimilated vehicles used on international services, 1994.

BIOGRAPHY of the first author

Valentin Chochev was born in Plovdiv, Republic of Bulgaria, in 1959. His main areas of research include fire-modeling, operational tactics of firefighting and management of firefighting forces. He is currently working as an Associate Professor at Academy of the Ministry of Interior, Faculty of Fire Safety and Civil Protection, Sofia, Republic of Bulgaria.

MODELIRANJE POŽARA U KUPEU PUTNIČKOG VAGONA

Valentin Chochev, Svilena Arabadzhieva, Milan Protić

Rezime: *U ovom radu izvršeno je numeričko modeliranje požara u kupeu železničkog putničkog vagona korišćenjem softverskog paketa FDS. Simulacija je bila fokusirana na dinamičko sračunavanje temperaturskog polja i toplotne snage. Rezultati simulacije upoređeni su sa ekperimentalno dobijenim vrednostima pri čemu je dobijena zadovoljavajuća podudarnost. Može se zaključiti da se softverski paket FDS može koristiti za simuliranje različitih požarnih scenarija kod putničkih vagona.*

Ključne reči: modeliranje požara, FDS, CFD model polja.