REAL FULL-SCALE EXPERIMENT AND NUMERICAL SIMULATION OF A FIRE IN A COMPARTMENT OF A PASSENGER RAILWAY CAR. A COMPARATIVE ANALYSIS

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Abstract. A comparative analysis of the results for the dynamics of fire development in the compartment of a passenger railway car of type B84 obtained in a full-scale real experiment and numerical modelling of fire using the software Fire Dynamic Simulation (FDS) implementing a Computational Fluid Dynamics (CFD) field model has been conducted. The obtained dependences of the change of the total volume temperature and the dangerous factors of fire over time have been analyzed. The results of the numerical modelling have been validated by comparison with the results of a real experiment.

Keywords: fire in a rail car, full-scale experiment, fire simulation model, FDS, CFD field model, railway car.

1. INTRODUCTION

The number of fires in passenger rolling stock is relatively small and unchanged over the years, but with large losses. On the other hand, the atypicality of the event arouses great media interest and every fire in the railway transport is covered by the media. This further has an extremely negative impact on public sentiment regarding the safety of this type of transport in the Republic of Bugaria. The presence of many passengers, the limited possibilities for evacuation and the difficult access of the fire safety and civil protection services to some places of the railway infrastructure further aggravate the situation in the event of a fire. A clear example of this is the fire that broke out in the Sofia-Kardam train on February 28, 2008, in which nine people died and nine others were imjured. After the fire, there was a sharp drop in passengers'

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confidence in the fire safety of passenger rolling stock, and all couchette cars in the Republic of Bulgaria were decommissioned.

Reducing losses and costs in fires requires carefully designed organizational, technical and preventive solutions. The correct decision-making by rescue operations managers depends on the availability of information about the development and spread of the fire, as well as how fire hazards affect people and equipment, as stated in [1]. To solve this problem, it is common around the world to analyze the dynamics of fire development and the spread of fire hazards, using both real full-scale experiments and modern computer modeling technologies. Although full-scale tests can provide reliable information, the high cost of conducting them limits their use in the investigation of fires in passenger rail transport.

Fire modelling can provide more detailed information about the development of fire and is much more cost-effective compared to real experiments. The numerical simulations can be preset for different fire development scenarios with changes both in the environmental conditions and with changes in the parameters related to the configurations of the compartments and the properties of the interior materials that affect the development of the fire.

A detailed analysis of a very large number of studies related to the development of a fire in a passenger railway car is made in [2]. The analysis shows that different train types and different materials used in them lead to large differences in the values of Heat Release Rate (HRR).

The mathematical models describing the formation and propagation of fire hazards are based on the classical knowledge of hydrogasdynamics. The Computational Fluid Dynamics (CFD) is a tool for numerical prediction of fluid, concentration and temperature fields in the studied objects.

Based on the field approach, the Fire Dynamic Simulation (FDS) model was developed by the National Institute for Standardization and Technology, USA. In 2000, the first software packages FDS and SmokeView were published, which today are becoming a major engineering tool for analyzing fires in confined spaces. The software has been successfully verified against various experimental studies and the data obtained from the FDS simulations are widely used in fire safety engineering practice [3].

The development of fire in passenger compartments is mainly determined by the pyrolysis of solid combustible materials in them, along with the characteristics of the ignition source. As a result, in order to perform a reliable simulation of a compartment fire scenario, it is necessary to model the pyrolysis process as accurately as possible. Despite its physical and chemical complexity, in FDS the pyrolysis process is modelled using the Arrhenius equation.

The cone calorimeter test is the most commonly used tool for determining the properties of pyrolysis, and such measurements are the typical experimental data available in industrial material databases.

It has been found that changes in the material properties of the seats in the passenger compartment have the greatest influence on the mechanism of occurrence and propagation of combustion in passenger railway cars.

As there are no data about the heat dissipation rate, density and ignition temperature of the seats used in the type B84 wagons that are the subject of this study, they were tested on a cone calorimeter in the "Fire Research Laboratory" of the Faculty of Occupational Safety at the University of Nis, Republic of Serbia. It is known from previous studies of the authors that the ignition temperature is lower and the rate of combustion is higher on the surface of seats lined with fabric operated for more than 3 years [4–5]. The obtained data are used in the following simulation of a fire in a passenger railway car compartment.

The aim of the present study is to analyze the dynamics of fire development and the change in temperature in the volume of a compartment in a passenger railway car of type B84, as one of the dangerous factors of fire, in an overall full-scale real experiment, and to compare the results with a simulation model based on the theoretical approach using FDS version 6.

2. STATEMENT OF THE PROBLEM

The passenger railway car B84 is most often used in the Bulgarian State Railways. The car is Bulgarian development and production. Its main characteristics are as follows: length of body 24,200 mm; height of empty body from the main rail 4050 mm; width of the basket with the cladding in the lower window sill 2960 mm; width of the windows 14,000 mm; window height 950 mm; doors width 700 mm and height 1900 mm.

When equipped as a second class compartment car with a side corridor, it has the following parameters: width of the side corridor 726 mm; number of compartments in the car 9; length of the body 2100 mm; body width 2100 mm; height of the body 2500 mm; number of seats in the compartment 8, Fig. 1.

The internal equipment of the wagon is as follows: Seats – single covered with special fabric lining and filling of soft polyurethane foam with a volume weight of 52–68 kg/m^3; Internal partition walls – made of veneered panels of wood particles with a thickness of 16–18 mm; Flooring – vinyl flooring with a thickness of 4 mm, laid along the entire floor of the car except for the

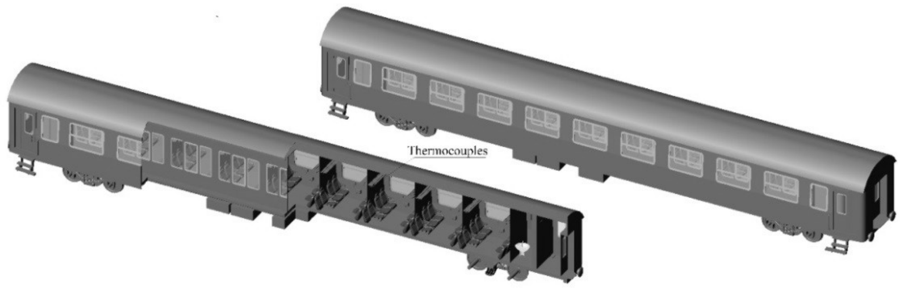

Fig. 1. General view of a compartment second-class chair railway car (type B84)

bathrooms; Internal partition ceiling of the compartments – ordinary plywood with a thickness of 6 mm; Thermal insulation of expanded (rigid) polyurethane foam on the metal structure of the basket, with a thickness of 5–6 mm. Expanded polystyrene foam with a thickness of 30 mm is placed above the inner partition ceiling.

The experiment was conducted at Iliyantsi station, Sofia. The air temperature is 11 °C and the relative humidity is 90%. The wind is light with a speed of 1 m/s from the east. The car is oriented in the northeast-southwest direction.

The ignition is carried out in compartment No 2, with source of ignition – a paper cushion, defined in UIC 564-2 – Code of the International Union

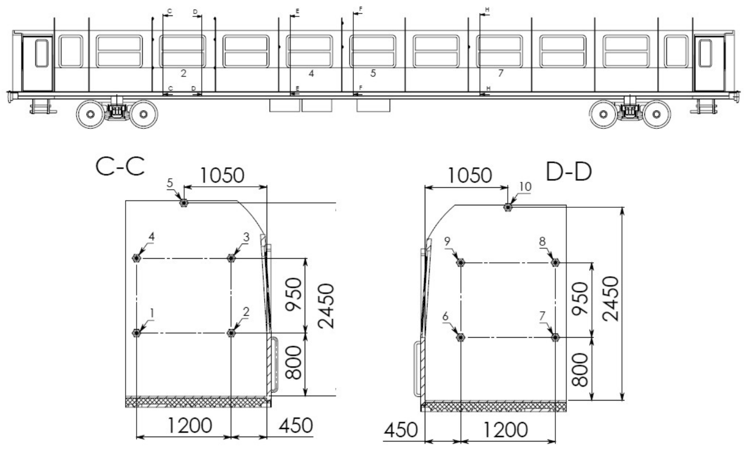

Fig. 2. Location of the thermocouples

of Railways [6], weighing 100 g, dried for 3 hours at a temperature of 70 °C. The compartment is standardly equipped with two rows opposite 4 pcs. seats, each measuring 900 × 450 mm.

The temperature in the compartment is measured by means of 10 thermocouples of type "K", with copper plates mounted on the warm end of the thermocouple. The thermocouples have dimensions: diameter 12 mm and thickness 1.5 mm. The location of the thermocouples is shown in Fig. 2.

The critical duration of the fire is considered to be the time to reach dangerous to human values of the temperature of 70 °C at a height of 1.7 m from the floor of the compartment.

2.1. Initial and boundary conditions of the fire modelling task

The guidelines of the manuals were followed during the development of the model [3, 7]. The following scenario is accepted in the modelling of a fire in a compartment: the fire is in a separate compartment; it is developed in a closed volume, limited by the calculation area; the passenger door is open; the window of the compartment is closed; the combustible load consists of standard seats and bulkheads used in a type B84 railway car.

The following initial conditions were accepted in the modelling: initial temperature of the medium is 11 °C; the ignition source is activated at time $t = 0$ s; combustion source is a source of typical ignition due to arson or vandalism, for example, a newspaper that has a flame for 3 minutes and an average power of 7 kW, creating a flow from 25 kW/m^2 to 30 kW/m^2 in accordance with Annex A of BSS EN 45545-1 [8]. The ignition model is a paper cushion, defined in UIC 564-2 – Code of the International Union of Railways [6], with dimensions 0.39×0.17 m; the duration of the impact of the ignition source on the seats is 180 s; the doors of the compartment are open; the glazing of the compartment window and doors at the start of the fire is strong.

The following conditions are limiting: the compartment has dimensions of 2.1×2.1×2.5 m; material of the outer wall of the compartment – metal; a standard window is provided on the outer partition wall parallel to the longitudinal axis of the passenger compartment; the seats are filled with polyurethane foam, lined with fabric; the glazing of the compartment window and doors is destroyed when the ambient temperature in the glazing zone exceeds 300 °C.

2.2. Characteristics of the model

The geometry of the model in FDS-version 6 includes the studied coupe with dimensions of 2.1 × 2.1 × 2.5 m and a computational network consisting of 332,667 cells with dimensions of 0.09 × 0.09 × 0.09 m, Fig. 3. The quality of the network is always crucial to the success of any CFD fire simulation. In these simulations, the computational range was expanded by 2 m and included a volume outside the passenger compartment in order to be correctly modelled the flue gas flow through the open door [9].

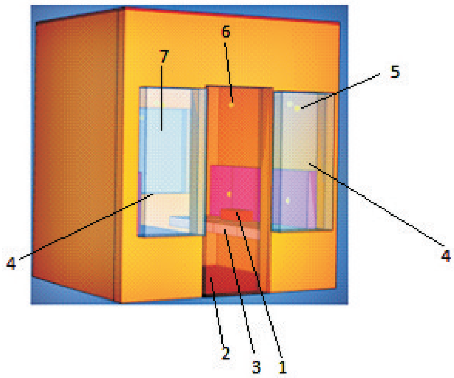

Fig. 3. Common view of the model: 1 – ignition source; 2 – door; 3 – seats; 4 – windows to the corridor; 5 – temperature sensor in the glazing area; 6 – temperature, O_2, CO, CO_2 and visibility sensors; 7 – window

2.3. Choice of turbulence model

As the main turbulent model, FDS offers the Smagorinski form for the Large Eddy Simulation (LES). The model is designed so that when the network is compressed to the Kolmogorov scale, the calculations move directly from LES to Direct Numerical Simulations [10]. The computational problem is simplified by limiting the validity of the equations to low-velocity, convective flows with an emphasis on smoke and heat transfer in a fire. FDS numerically solves the Navier-Stokes equations, in which their partial derivatives for conservation of mass, momentum and energy are approximated as finite differences and the solution is updated in time and space, based on a three-dimensional rectangular structured network [11]. In this simulation, LES was adopted as a numerical simulation of a fire in the passenger compartment. LES is used to model dissipative processes (viscosity, thermal conductivity, diffusion), the scale of which is smaller than the size of a clearly defined numerical network.

2.4. Choice of reaction

The main fire load in the compartment are the seats, containing soft polyurethane foam filling. For this reason, the reaction of the gas phase is defined as the combustion of polyurethane foam, with characteristics specified in [12].

2.5. Duration of the simulation

The duration of the fire is 800 s and simulations with a time step of 1 s are performed.

3. RESULTS

The visualization of the development of fire in the volume of the compartment at 200 s, 300 s, 307.4 s, and 368 s in the FDS model is shown in Fig.4.

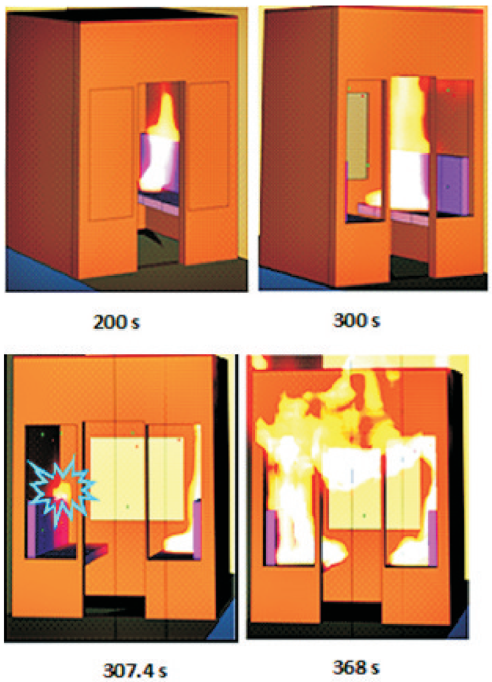

Fig. 4. Development of fire according to the FDS model

Observing the requirements of BSS EN 45545-1, the ignition source ceases to operate after 180 s, but under its influence after 200 s the seat on which it is placed is ignited. At 218.9 s the temperature in the area of the outer window reaches 300 °C and the glazing is destroyed. At 252.7 s the glazing of the window located on the left of the door is destroyed, and at 266.3 s – on the right of it. The heated combustion products generated by the burning seats on the right are concentrated near the roof of the passenger compartment and, moving to the left, they heat the seat backs located on the left side of

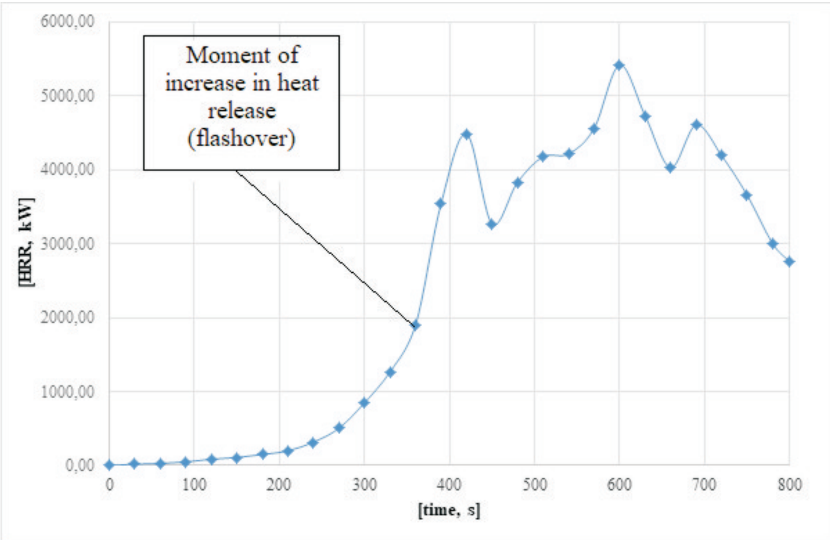

Fig. 5. Change in HRR in a compartment fire measured in a model in FDS

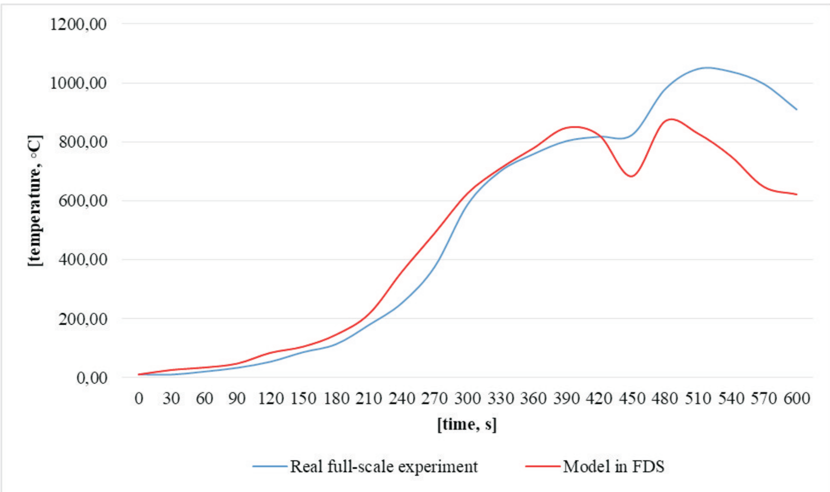

Fig. 6. Change in volume average temperatures in a compartment fire measured in a real experiment and model in FDS

the passenger compartment. After reaching the ignition temperature of 307.4 s, combustion initially occurs in the upper part of the left seats. After 368 s, the temperature in the passenger compartment volume exceeds the ignition temperature of the seats and the combustion spreads throughout the passenger compartment. The rate of heat dissipation at this point increases sharply and the power of the fire increases from 1900 kW at 360 s to 4483 kW at 420 s, Fig. 5.

A similar development of the fire was observed in the full-scale real experiment.

The change in the volume average temperatures in the passenger compartment, measured in the real experiment and modelling, is shown in Fig. 6.

The spread of combustion and the ignition sequence of the seats were initially faster in the FDS model than in the actual experiment, which explains the higher temperature after ignition. In general, the temperatures in the FDS model follow the temperatures from the actual test relatively well.

4. CONCLUSION

From the comparative analysis of the results for the dynamics of fire development in the compartment of a passenger railway car of type B84, obtained in a full-scale real experiment and modelling with FDS, the following conclusions can be made:

- About 100 s after the occurrence of fire in a passenger railway car compartment, the temperature at a height of 1.7 m from the floor reaches the critical human values of 70 °C. In the model it was reached at 90 s, while in the real experiment at 102.8 s;
- When the passenger compartment door is open, after 300 s from the occurrence of combustion, the power of the fire increases sharply to 4483 kW, due to reaching the ignition temperature of the seats and ignition of the pyrolysis gases (flashfover);
- The comparative analysis of the simulation of fire propagation in a compartment of a passenger railway car of type B84 with mathematical model (software FDS-6) and the data from a real experiment allowed good validation of the model;
- In order to achieve reasonable results, the setting of the parameters of the materials for the pyrolysis model must be correct, comparing them with validation tests.

CFD modelling allows the use of FDS to predict the spread of fire in a passenger railway car compartment, but working with the model requires expert knowledge and competence of the user for the limitations of the model, as well as for the behaviour of materials in fire and the dynamics of fire development. There is a risk that the model will be misused by users without sufficient levels of competence, who may be tempted to misuse the data from the model result and then rely on it without complying with the limitations.

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