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NUMERICAL STUDY OF THE HAZARDOUS FACTORS OF A FIRE IN A PASSENGER RAILWAY CAR

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This report presents the results of a numerical modelling of a fire in a typical Bulgarian State Railways passenger compartment railway car using the PyroSim software product. The created numerical model was previously verified through experiments conducted on different scales. This study examines two scenarios of fire development – with the compartment door closed and with the compartment door open, in which the fire occurred. The obtained dependencies of the change in time of two of the dangerous fire factors – loss of visibility and carbon monoxide concentration, which in this case are the most dangerous, were analysed. The obtained results show what is the maximum time for evacuation from the railway car. With the compartment door closed, passengers have about 80 seconds more to evacuate under favourable conditions from the corridor of the railway car.

Keywords: fire modelling, FDS, CFD field model, passenger railway car

ЧИСЛЕНО ИЗСЛЕДВАНЕ НА ОПАСНИТЕ ФАКТОРИ НА ПОЖАР В ПЪТНИЧЕСКИ ЖЕЛЕЗОПЪТЕН ВАГОН

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Настоящият доклад представя резултатите от проведено числено моделиране на пожар в типичен за Българските държавни железници пътнически купеен железопътен вагон чрез използване на програмния продукт PyroSim. Създаденият числов модел е предварително верифициран чрез проведени експерименти в различен мащаб. В настоящото изследване са разгледани два сценария на развитие на пожара – при затворена и при отворена врата на купето, в което е възникнал пожарът. Анализирани са получените зависимости на изменението на два от опасните фактори на пожар във времето – загуба на видимост и концентрация на въглероден оксид, които в конкретния случай са най-опасни. Получените резултати показват какво е максималното време за провеждане на евакуацията от обема на вагона. При затворена врата на купето пътниците имат около 80 секунди повече да се евакуират при благоприятни условия през коридора на вагона.

Ключови думи: моделиране на пожар, FDS, CFD полеви модел, пътнически купеен вагон

Introduction

Fires in passenger rolling stock are rare. They are 1.89% of all serious rail accidents in the European Union, less than 2.00% of all rail accidents in the Republic of Bulgaria and only 0.06% of all fires occurring on the territory of the Republic of Bulgaria. However, they can have serious consequences, raise public concern about the safe operation of the railway system and cause unexpected changes in it. A clear example of this is the fire that occurred on 28 February 2008 on the Sofia – Kardam train, in which nine people died and nine others were injured. After the fire, a sharp decline in passenger confidence in the fire safety of passenger rolling stock was reported, and all couchette cars were withdrawn from operation [2].

The presence of many passengers, limited evacuation options, and difficult access for fire safety and civil protection services to some parts of the railway infrastructure aggravate the situation in the event of a fire. This necessitates a detailed study of the development of fires.

A number of studies have been conducted worldwide in the field of fire safety of rolling stock. The common methods for studying the spread of fires and smoke are full-scale and reduced-scale experiments, numerical and analytical methods. Full-scale experiments of fires in passenger cars are rare, as they are expensive, time-consuming and complex to perform. Reduced-scale experiments can be considered as an alternative, but the results obtained in them cannot be fully converted to the results of real fires. This is due to the lack of complete similarity between the model and the real experiments. Theoretical methods are too limited and useful only in simple geometries. These limitations, together with the great revolution in computer processing capability, have convinced researchers to use numerical modelling as a powerful tool for studying fire phenomena in recent years [7].

The analysis found that over 75% of the experiments and studies conducted were in air-conditioned, open (saloon) railway cars. Studies with compartment passenger railway cars, which are typical of railway transport in the Republic of Bulgaria, are rare (passenger railway cars, type B84 are most commonly used in Bulgarian railways [2]).

Of all the hazardous factors in a fire, smoke toxicity and its spread pose the greatest risk to humans. The maximum permissible value for carbon monoxide is $1.16.10^{-3}$ kg/m^3, for oxygen – 0.226 kg/m^3, and for hydrogen cyanide – 23.10^{-6} kg/m^3. They are considered to be most critical when involved in a fire in a closed volume, such as a railway car, as there is a greater chance of oxygen deficiency, leading to incomplete combustion and a larger amount of these gases [9, 10]. It has been found that despite the toxicity of hydrogen cyanide, it is only a minor contributor to death in the presence of carbon monoxide [1]. It is carbon monoxide/dioxide and hydrogen cyanide that are the main products when burning polyurethane foam, which is the main material used for seats in railway transport.

The dynamics of fire and the change in temperature (as one of the dangerous factors of fire) in the compartment volume of a passenger railway car, type B84, are analysed in a comprehensive full-scale real experiment in [3]. The results are compared with a simulation model based on the theoretical approach, using FDS, version 6. The comparison of the results indicates that the created model is adequate.

In [3], the dynamics of a fire in the volume of a passenger railway car, type B84, with the door of the compartment in which the fire occurs open is analysed. Among leading fire safety specialists, there is a discussion about how the dynamics of a fire in the car would change if it developed with the door of the compartment closed and how this would affect the evacuation time of passengers. In light of the above discussions, the aim of the present study is to analyse and compare the toxicity of smoke during a fire and its spread within a conventional railway car, in order to understand the complex dynamics of smoke generation and accumulation in two development options: with the door of the compartment in which the fire occurs open and with the door of the compartment in which the fire occurs closed. For this purpose, numerical modelling techniques were used in the present study, the details of which are discussed in the next section.

Numerical modeling

Numerical modelling is performed using the PyroSim software product of Thunderheat engineering, for which an academic license was obtained. PyroSim is designed to complement the Fire Dynamics Simulator (FDS). FDS is a powerful fire simulator that was developed at the National Institute of Standards and Technology (NIST) in the USA. FDS models can predict smoke, temperature, carbon monoxide and other substances during fires. The software has been successfully verified against various experimental studies, and the data obtained from FDS simulations have been widely applied in fire safety engineering practice [2]. FDS simulates fire scenarios using computational fluid dynamics (CFD) optimized for low-velocity, thermally driven flow.

Mathematical model for predicting fire dynamics

FDS solves the Navier–Stokes equations numerically, where 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 grid. The three-dimensional Navier–Stokes equations, together with the mass conservation equation, are solved iteratively for the turbulent and transient flow in the railway car. Equation (1) controls the time step throughout the simulation, according to the Courant, Friedrichs and Lewy (CFL) conditions [8]:

$$(1) \qquad \Delta t = \frac{5.\sqrt[3]{\delta x \delta y \delta z}}{\sqrt{g.H}}.$$

The combustion models are calculated at each time step. The flow turbulence is modelled using the Large Eddy Simulation (LES) model. In this study, a field fire model implemented using the PyroSim program was used. The field fire model is based on the following equations [5, 8]:

- Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}.(\rho u_j) = 0,$$

where: ρ – density, kg/m^3; t – time, s; u – projection of the velocity vector along the x-axis in Cartesian coordinates, m/s.

- Momentum conservation equation:

$$\frac{\partial}{\partial t}(\rho u_j) + \frac{\partial}{\partial x_j}(\rho u_j u_i) = -\frac{\partial p}{\partial h_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i,$$

where: p – dynamic pressure, Pa; g – gravitational acceleration, m/s^2.

For Newtonian fluids, the viscous stress tensor is defined as follows:

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\mu\frac{\partial u_k}{\partial x_k}\delta_{ij},$$

where: μ – laminar dynamic viscosity, Pa.

- Energy conservation equation:

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_j}(\rho u_j h) = \frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j}\left(\frac{\lambda}{c_p}.\frac{\partial h}{\partial x_j}\right) - -\frac{\partial \dot{q}_j^R}{\partial x_j},$$

$$h = h_0 + \int_{T_0}^{T} c_p dT + \sum_k Y_k H_k,$$

$$c_p = \sum_k Y_k c_{p,k},$$

where: Y_k – static enthalpy of the mixture; H_k – heat of formation of the k-th component; Cp – heat capacity of the mixture at constant pressure; $\dot{q}_j^R$ – flux of radiation energy in the direction x_j; λ – coefficient of thermal conductivity, W/m.K.

- Chemical component conservation equation k:

$$\frac{\partial}{\partial T}(\rho Y_k) + \frac{\partial}{\partial x_i}(\rho u_j Y_k) = \frac{\partial}{\partial x_j}\left(\rho D\frac{\partial Y_k}{\partial x_j}\right) + S_k.$$

- Equation of state of an ideal gas:

$$p = \rho R_0 T \sum_k \frac{Y_k}{M_k},$$

where: R_0 – universal gas constant; T – absolute temperature, $^\circ K$; M_k – molar mass of the kth component.

Using the above equations, a local equilibrium is obtained. These equations fully describe laminar flows.

As mentioned above, polyurethane foam is the most widely used material for seats in railway transport. The numerical model incorporates data on the properties of polyurethane foam used for seats in type B84 passenger railway car from [4] as well as from [6], the main ones of which are: density – 106 kg/m^3; specific heat capacity – 1,7 kJ/kg.K; thermal conductivity – 0,05 W/m.K; heat of combustion – 2,54E+4 kJ/kg; soot yield– 0,113 g/g; carbon monoxide yield – 0,024 g/g.

To confirm the gas species after the multiphase reaction, the components of each element were calculated using the stoichiometric balance equation. Due to limitations in the use of FDS, nitrogen was balanced against N_2. This is shown in equation (2).

$$C_xH_yO_zN_v + v_{O_2}CO_2 \to v_{CO_2}CO_2 + v_{H_2O}H_2O + v_{CO}CO + v_S Soot + v_{N_2}N_2 \tag{2}$$

The molar mass of the fuel is calculated using equation (3) as shown below. Since FDS assumes that carbon black is composed of carbon and hydrogen [11], the molecular mass of carbon black reduces to equation (4).

$$m_F = x.m_C + y.m_H + z.m_O + v.m_N \tag{3}$$

$$m_S = X_H.m_H + (1 - X_H)\,.m_c \tag{4}$$

The stoichiometric coefficients for carbon monoxide and soot are calculated using equation (5).

(5)

$$v_{CO} = \frac{m_F}{m_{CO}}.Y_{CO} : v_S = \frac{m_F}{m_S}.Y_s \tag{5}$$

To calculate the unknown coefficients, the known atomic balances are arranged in matrix form as shown in equation (6).

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 2 & 0 & 0 \\ 2 & 1 & 0 & -2 \\ 0 & 0 & 2 & 0 \end{bmatrix} \begin{Bmatrix} v_{CO_2} \\ v_{H_2O} \\ v_{N_2} \\ v_{O_2} \end{Bmatrix} = \begin{Bmatrix} x - v_{CO} - v_S\,(1 - X_H) \\ v_{H_2O} \\ v_{N_2} \\ v_{O_2} \end{Bmatrix} \tag{6}$$

The stochiometric coefficients are as follows: $v_{CO_2} = 1,9791$; $v_{H_2O} = 0,3845$; $v_{CO} = 0,0441$; $v_s = 0,3099$; $v_{N_2} = 0,1000$; $v_{O_2} = 2,7234$.

Digital model of a passenger railway car and boundary conditions

A passenger railway car type B84 was adopted as the basis for developing the numerical model (Fig. 1), with which a real full-scale experiment was carried out, described in [3].

Main characteristics of the model: length of the car – 24,200 mm; height of an empty car from the main rail – 4,050 mm; width of the car with the lining in the lower window section – 2,960 mm; width of the windows – 14,000 mm; height of the windows 950 mm; width of the doors - 700 mm; height of the doors 1,900 mm.

[2pt]

Interior equipment: seats – textile upholstery and polyurethane foam filling with

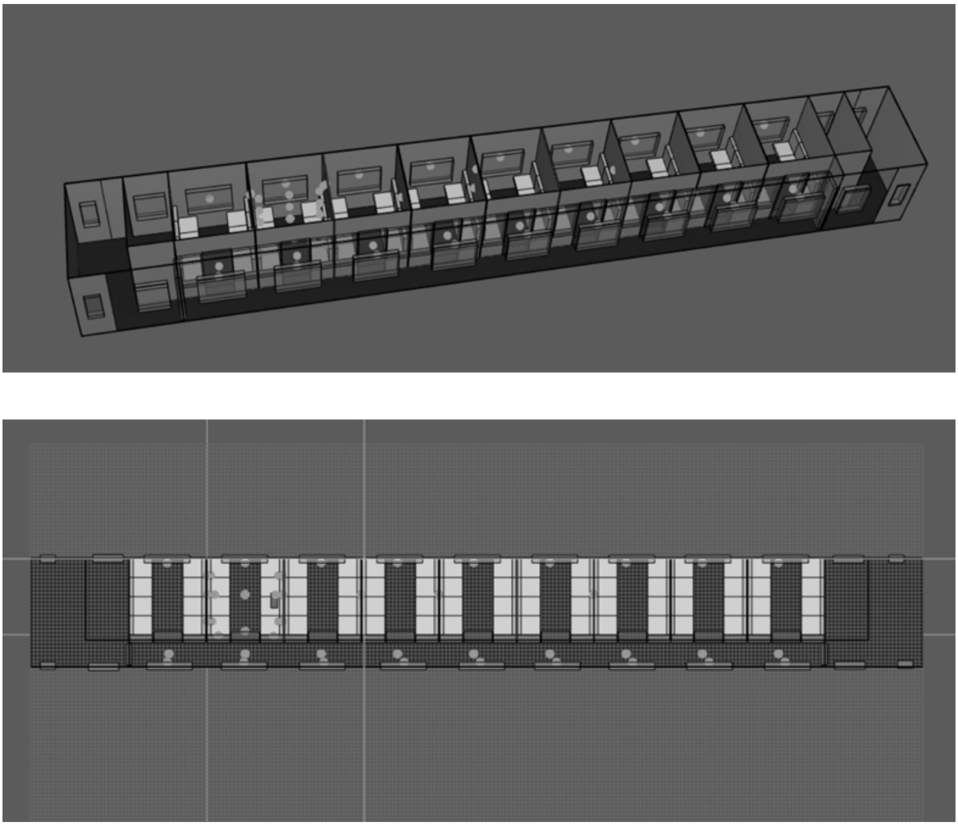


Fig. 1 Digital model of a second-class compartment railway car, type B84
(the grey dots are sensors for measuring T, CO, CO_2, O_2 and visibility)

a density of 106 kg/m^3; interior partitions – made of veneered particle boards with a thickness of 18 mm.

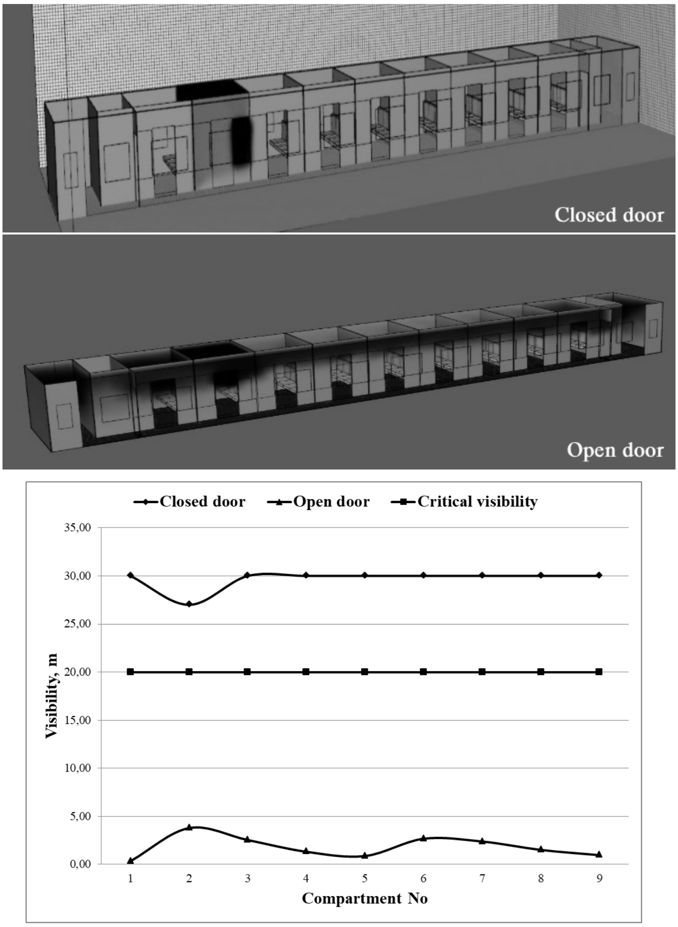
When modelling the fire, the following scenario was adopted: a fire in compartment No. 2 is considered, developing in a closed volume, limited by the calculation area; the compartment door is open/closed; the compartment windows are closed; the combustible load consists of standard seats and partitions used in a railway car, type B84.

The following initial conditions were assumed in the modelling: initial temperature of the environment is 11°C; the ignition source is activated at time t = 0 s; the combustion source is a source of typical ignition due to deliberate arson or vandalism, (e.g., a newspaper ignited for 3 minutes), with an average power of 7 kW, producing a heat flux of 25 to 30 kW/m^2 in accordance with Annex A of BDS EN 45545-1. The ignition model is a paper cushion, defined in UIC 564-2 – Code of the International Union of Railways, with dimensions of 0.39 × 0.17 m; the duration of the impact of the ignition source on the seats is 180 seconds; the glazing of the compartment window and doors at the initial moment of the fire is solid.

The domain is a space with a length of 23 m, a width of 10 m and a height of 10 m.

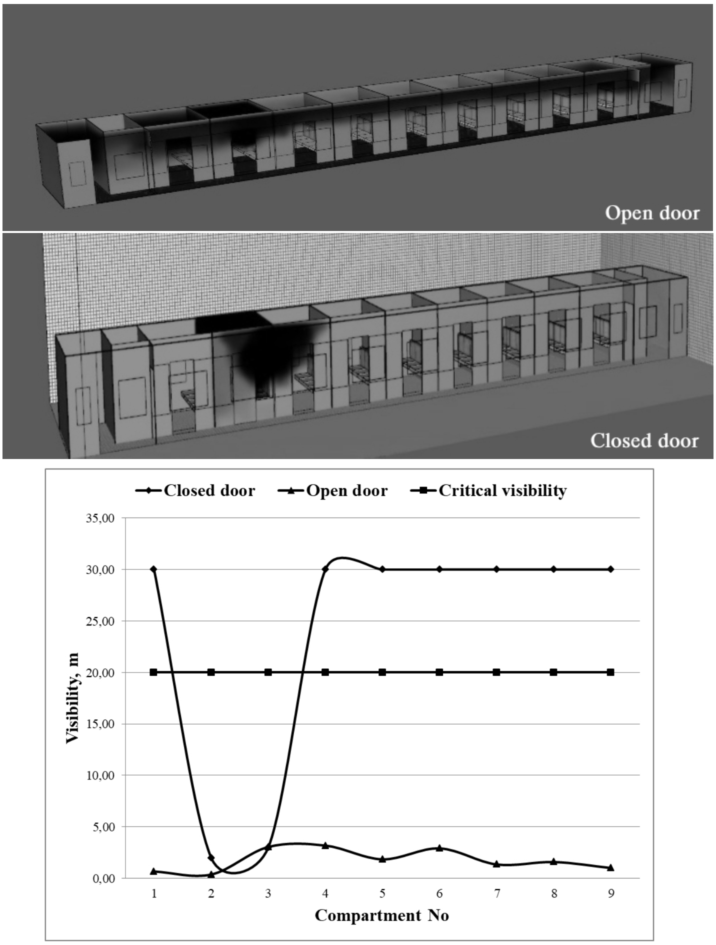
The computational grid consists of 2,340,000 with dimensions of 0.1x0.1x0.1 m. In order to record the data on temperature, concentration of carbon monoxide, carbon dioxide, oxygen and visibility in compartment No. 2, 45 pcs. sensors are placed. 45 pcs of sensors are placed also in the corridor of the car, in front of the door of each compartment, at a height of 1.70 m (average height of a person). The duration of the simulation is 600 s. The glazing of the windows of the compartment, corridor and doors is destroyed when the temperature of the environment in the glazing zone reaches 300°C.

Main results



(a) 87 s

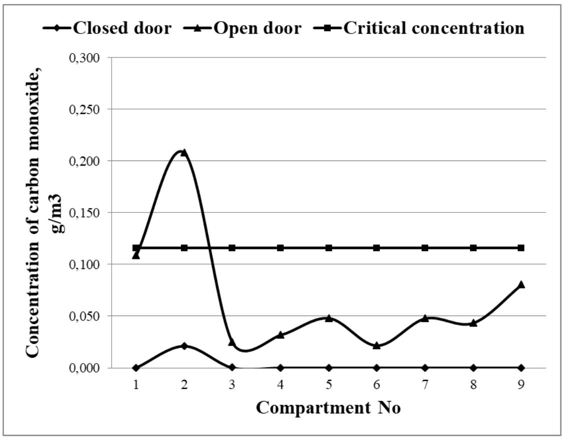
When analysing the spread of smoke gases and the change in visibility in the corridor of the railway car, it can be seen that 87 seconds after the occurrence of combustion in compartment No. 2 (Fig. 2a) the visibility with the closed door of compartment No. 2 is above the critical 20 m, while as the fire develops with the door open it is already below the critical for normal movement of people. At 89 seconds, (Fig. 2b), at the moment of destruction of the glazing of the door of compartment No. 2, the visibility in the area of compartments No. 2 and 3 sharply drops below the critical one, due to the release of combustion products into the corridor, while in the rest of the car it is above the critical one.



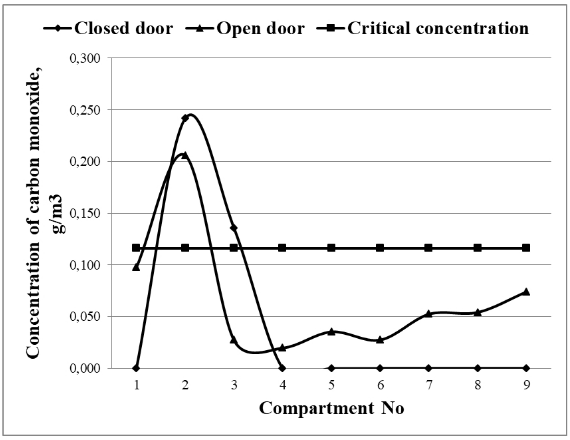
(b) 89 s

Fig. 2. Spread of smoke products of fire and change in visibility in the carriage corridor at (a) 87 s and (b) 89 s

Tracking the change in the concentration of carbon monoxide, it is evident that at 87 seconds (Fig. 3a) its concentration with the open door of compartment No. 2 is 0.208 g/m^3, which is above the critical value for people of 0.116 g/m^3, while with the closed door it is below the critical one. At 89 seconds (Fig. 3b) the concentration of carbon monoxide in the area of compartment No. 2 in both variants of fire development is above the critical one, with the one with the initially closed door having a value of 0.242 g/m^3 and being higher than that with the open door. These results may be due to the fact that with the closed door of the compartment, combustion proceeds in a lack of oxygen as incomplete combustion with the release of a larger amount of carbon monoxide.



(a) 87 s



(b) 89 s

Fig. 3 Carbon monoxide concentration at (a) 87 s and (b) 89 s

Conclusions

Due to the increasing number of fires in railway transport, a better understanding of fire dynamics and the spread of toxic combustion products is needed to reduce life-threatening effects on people. The danger of smoke in the event of a fire in a railway carriage compartment is fundamental for passengers.

The present study, conducted through numerical studies and the results obtained, show that the condition of the doors of the compartment in which the fire occurred affects the visibility and concentration of carbon monoxide in the corridor of the railway car.

With the door of the compartment in which the fire occurred closed, passengers have about 80 s more time to evacuate under favorable conditions in the corridor of the carriage, without reduced visibility and dangerous concentrations of carbon monoxide.

The results of this study can be used in the development of practical guidelines and standard operating procedures for the actions of service personnel during the evacuation of passengers in cases of fire in compartment railway carriages.

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