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Computer Modelling of Automobile Fires

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1. Introduction

The use of the *CFD* (*Computer Fluid Dynamics*) theory and its practical knowledge has become widespread in such academic disciplines as aerodynamics, fluid dynamics, combustion engineering and other fields. However, in the disciplines, which examine the ongoing processes in larger sizes, CFD was applied during the last decades only. One of such discipline is a spread of fire. Fire processes are a very complicated and complex phenomenon consisting of combustion, radiation, turbulence, fluid dynamics and other physical and chemical processes. A good knowledge about complex phenomena and processes occurring during fire in different environments is a significant component of fire safety. As fire itself is very complicated phenomenon, interdisciplinary approach to the problem is required.

This is also one of the reasons of a gradual development of programs in this area. In addition, large dynamics of burning processes requires high spatial resolution for sufficiently accurate calculation and also very small time step of calculation (thousandths of second) resulting in high demands on computer memory and high performance processors.

Knowledge of and experience with the combustion processes were achieved mostly by experiments in the past. This form of investigation is quite difficult not only with regard to financial aspects but also from the point of view of variability of the input data related to burning.

In recent years, computer simulation of fire is used as an economically least expensive method to obtain the knowledge about ongoing fire processes and their visualization. This approach is especially valid in the case of fires in tunnels, car parks and buildings because full-scale fire experiments in such structures could cause serious damages of material and technical equipment. Nowadays, monitoring the development of processes in fire environment allows to achieve relatively good knowledge about the dynamics of liquids and gases. Existing software tools provided by CFD simulation also enable to visualize their development.

In the literature, computer simulation of fire was firstly formulated in the seventies as *zone models* and later as *multi-zone models* [1, 2, 3, 4]. In these models, the fire area is divided into separate fire areas (zones) so that each of these ongoing processes has been settled. The theoretical basis of these methods comprises the laws of conservation of mass and energy. The whole space is divided into two spatially homogeneous zones: warmer upper volume containing heat and smoke, and lower part significantly less affected by heat and smoke. For each zone, mass and energy balances are enforced with additional models describing other physical processes such as fire plumes, flows through doors, windows and other vents, radiative and convective heat transfer and solid fuel pyrolysis. Relative physical and computational simplicity of the zone models has led to their widespread use in the analysis of compartment fires scenarios. However, for certain fire scenarios, more detailed spatial distributions of physical properties are required.

Computational fluid dynamics (CFD) models were introduced in the nineties and have reached significant development and relatively widespread use in various fields of human activity. The rapid growth of computing power and advances in CFD have led to the development of CFD based field models based on solving the Reynolds-averaged form of the Navier-Stokes equations. The use of CFD models has allowed the description of fires in complex geometries incorporating a wide variety of physical phenomena related to fire.

The simplified equations developed by Rehm and Baum [5], referred to in the combustion research community as low Mach number combustion equations, describe low speed motion of a gas driven by chemical heat release and buoyancy forces [6]. These equations are solved numerically by dividing the physical space where the fire is to be simulated into a large number of rectangular cells. Within each cell, gas velocity, temperature, etc., are assumed to be uniform changing only with time. The accuracy with which the fire dynamics can be simulated depends on the number of cells that can be incorporated into the simulation. This number is ultimately limited by the computing power available. Nowadays, single processor computers limit the number of such cells to at most a few millions. Parallel processing can be used to extend this range to some extent, but the range of length scales that need to be accounted for if all relevant fire processes are to be simulated is roughly 10^4 to 10^5 because combustion processes take place at length scales of 1 mm or less, while the length scales associated with building or automobile fires are of the order of tens of meters/centimeters.

Several advanced systems intended for simulation of combustion processes have been developed. CFX, SMARTFIRE and FDS [7, 8, 9] and others provide alternative models which may offer a good performance. We use the Fire Dynamics Simulator (FDS) system [9], whose first version was developed in 2000 by the NIST (National Institute of Standards and Technology, USA). At present, significantly better FDS version 5.5 is available already. The development of both CFD software systems and their program modules will certainly continue. It is obvious that a careful verification and validation of these systems will continue in the future to enhance their quality and reliability.

2. Basic equations of the FDS model

FDS solves a form of conservation equations for low speed, thermally driven flow. Smoke and heat transfer from fires is the main concern of this system, which also includes the thermal radiation, pyrolysis, combustion of pyrolysis products, flame spread and fire suppression by sprinklers. The basic set of the conservation mass, species, momentum and energy equations are as follows [9]:

$$\begin{aligned}\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} &= \dot{m}_b''' \\ \frac{\partial}{\partial t}(\rho Y_\alpha) + \nabla \cdot \rho Y_\alpha \mathbf{u} &= \nabla \cdot \rho D_\alpha \nabla Y_\alpha + \dot{m}_\alpha''' + \dot{m}_{b,\alpha}''' \\ \frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \rho \mathbf{u} \mathbf{u} + \nabla p &= \rho \mathbf{g} + \mathbf{f}_b + \nabla \tau_{ij} \\ \frac{\partial}{\partial t}(\rho h_s) + \nabla \cdot \rho h_s \mathbf{u} &= \frac{Dp}{Dt} + \dot{q}''' - \dot{q}_b''' - \nabla \cdot \dot{\mathbf{q}}'' + \varepsilon,\end{aligned}$$

where $\dot{m}_b''' = \sum_\alpha \dot{m}_{b,\alpha}'''$ is the production rate of species by evaporating droplets or particles; ρ is the density; $\mathbf{u}=(u,v,w)$ is the velocity vector; Y_α , D_α , and $\dot{m}_{b,\alpha}'''$ are the mass fraction, the diffusion coefficient, and the mass production rate of α -th species per unit volume, respectively; p is the pressure; \mathbf{f}_b is the external force vector; τ_{ij} is the viscous stress tensor; h_s is the sensible enthalpy; the term \dot{q}''' is the heat release rate per unit volume from a chemical reaction and \dot{q}_b''' is the energy transferred to the evaporating droplets; and the term $\dot{\mathbf{q}}''$ represents the conductive and radiative heat fluxes. Note that the use of the material derivative $D()/Dt = \partial()/\partial t + \mathbf{u} \cdot \text{grad}()$ holds in the last equation.

Other two equations, the pressure equation and the equation of state,

$$\nabla^2 H = -\frac{\partial}{\partial t}(\nabla \cdot \mathbf{u}) - \nabla \cdot \mathbf{F} \quad \text{and} \quad p = \frac{\rho R T}{W}$$

are added to the previous four equations. The pressure equation is obtained applying the divergence on the momentum equation. In this equation, the value H represents the total pressure divided by the density. R is the universal gas constant, T is the temperature and W is the molecular weight of the gas mixture.

Thus, we have the set of six equations for six unknowns, which are functions of three spatial dimensions and time: the density ρ , three components of $\mathbf{u} = (u, v, w)$, the temperature T and the pressure p . These equations must be simplified in order to filter out sound waves, which are much faster than typical flow speed. The final numerical scheme is an explicit predictor-corrector finite difference scheme, which is second order accurate in space and time. The flow variables are updated in time using an explicit second-order Runge-Kutta scheme.

Boundary conditions are prescribed on walls and vents. All input data for simulation are required in the form of a text file in prescribed format, which describes the coordinate

system, geometry of domain and its location in given coordinates, mesh resolution obstacles, boundary conditions, material properties and other different simulation parameters. An important limitation of the system is that the domain should be rectilinear, conforming with the underlying grid. The domain is filled with rectangular obstructions representing real objects, which can burn, heat up, conduct heat, etc. Simulation outputs include quantities for gas phase (temperature, velocity, species concentration, visibility, pressure, heat release rate per unit volume, etc.), for solid surfaces (temperature, heat flux, burning rate, etc.), as well as global quantities (total heat release rate, mass and energy fluxes through openings, etc.). These outputs are saved during simulation with the desired format for visualization and can be visualized by the Smokeview program.

As it is mentioned in [9], the overall computation can either be treated as Direct Numerical Simulation (DNS), in which the dissipative terms are computed directly, or as Large Eddy Simulation (LES), in which large-scale eddies are computed directly and subgrid-scale dissipative processes are modelled. The numerical algorithm is designed so that LES becomes DNS as grid is refined. The numerical schemes used for the solution of all equations is completely described in [9].

All FDS calculations must be performed within a domain consisting of rectilinear meshes divided into rectangular cells. These cells can be either uniform in size or stretched, fulfilling the requirements of finite difference numerical scheme used in FDS. Their number depends on the desired resolution of fire scenario. As the FDS numerical scheme uses Fast Fourier Transforms (FFTs) in the y and z directions, the second and third mesh dimensions should each be of the form $2^l \times 3^m \times 5^n$ where l , m and n are integers.

In this chapter, we focus on computer simulation of:

- automobile engine compartment fire
- automobile passenger and/or luggage compartment fire
- fire spread from burning automobile onto a near standing automobile.

3. Automobile fire experiments

Automobile fires, causing enormous losses of property and lives as well as large environmental damages, have become a significant phenomenon, highly injurious to public. They occur in different surroundings, both in open air (on roads, on open parking areas, in vicinity to forest) and in closed or semi-closed structures (in underground car parks, in garages, in tunnels). Such different types of fire show own specific behaviour and the way of spread. Therefore, fire investigation has to take into account various conditions affecting the fire development and serious research is of great importance.

Numerous papers dealing with different aspects of automobile fire safety have appeared and several advanced computer fire simulation systems have been developed. Such systems are capable to model, simulate and visualize the spread of flames and smoke and the fire behaviour, and even to estimate environmental damages caused by fire in various conditions.

Full-scale automobile fire experiments belong to the important means which are necessary for improvement of automobile safety. They provide information about overall automobile fire behaviour which may be difficult to extrapolate from laboratory testing of the automobile components. They are usually expensive to carry out, leading to short experimental series consisting of a few or even only one experiment. Typically they are extensively instrumented in order to obtain as much information as possible from one experiment. They require special experimental facilities because of great size of automobile fires leading to damage of real structures. Several experiments on automobile fires had been carried out under different conditions (open, closed, or semi-closed car parks) and reported in the literature.

The measurements in older experiments [10, 11, 12] were restricted to gas and structure surface temperatures in the vicinity of burning car. During three full-scale experiments reported in [13], the heat release rate, mass loss and mass loss rate, heat flux, carbon monoxide, carbon dioxide and smoke production rate and gas temperatures above the automobile, and temperatures inside the automobile were determined as a function of time. Two full-scale fire experiments in a tunnel shuttle wagon [14] were carried out. A series of 10 experiments (5 with one and 5 with two automobiles) with a ceiling above the automobile and spread of fire from one automobile to another [15] were performed, collecting the combustion products and oxygen consumption where rate of heat release was measured using oxygen consumption calorimetry. A series of 10 experiments (3 experiments with a single automobile, 6 with two automobiles and 1 with three automobiles parked next to each other) were carried out [16, 17, 18], where heat release rate was measured using oxygen consumption calorimetry. Two experiments with three latest generation automobiles parked in an open car park were carried out [19], where gas and steel temperatures and vertical displacements of steel beams were reported. One experiment in car park (3 automobiles in 0.5 and 0.7 m distances) was performed [20]. An experiment with automobile fire in a four-storey car park was performed [21], measuring temperatures, displacement and strain of car park structures. Four full-scale automobile fire experiments were carried out [22], igniting in different parts of automobile and measuring mass loss, mass loss rate and temperature curves.

In 2009, a series of three full-scale automobile fire experiments with 4 cars in open air in the testing facilities of Fire Protection College of the Ministry of Interior of Slovak Republic in Povazsky Chlmec (Slovakia) and one full-scale automobile fire experiment with 2 cars in 0.5 m distance in the experimental tunnel of Scientific Research Coal Institute in Stramberk (Czech Republic) were carried out [23, 24, 25]. The primary objective of these experiments was to measure gas and surface temperatures (on the surface, above and inside the automobile and engine compartment) to gather data for validation of computer simulations of tested automobile fire scenarios. The main aim of the experiments was to obtain better knowledge about burning of a single automobile, to determine most combustible materials contributing to fire and to study the spread of fire from one vehicle to another. On the basis of these experiments we have consequently made computer simulations.

4. Automobile engine compartment fire experiment and simulations

This type of automobile fire has specific fire behaviour and nowadays it belongs to the most frequent vehicle fires [25, 26, 27, 28]. According to our knowledge, the spread of fire inside the engine compartment has not been analysed by computer fire simulator and published yet. We believe that such type of fire analysis and consequent computer simulation is very important. It provides more realistic fire spread in vicinity of the automobile and therefore more realistic input data for computer fire simulations in car parks, garages, or tunnels. We conjecture that ignition process for car fire simulations in such places simulated by a pool with burning gasoline (for example) is less realistic because it produces constant heat release rate.

The reported automobile fire experiments were carried out on automobiles of the same category. In the sequel, we focus on the first fire experiments from the reported series of full-scale automobile fire experiments. The first one was carried out on Audi 80 Quattro with just slightly distorted bodywork and missing front lights parked in open air on a concrete surface (Fig. 1). All doors and windows of the automobile were closed during the experiment. Gas temperatures inside the engine compartment (on the upper part of the engine block), inside the passenger compartment (in front part on the dashboard) and above the automobile (at 1.5 m height) were measured by thermocouples with 10 s recording interval. Temperature on the engine compartment lid surface was recorded by infra-red camera placed in front of the automobile at 3.5 m height and at 6 m distance from the automobile. The fire behaviour observations were recorded by digital cameras. Basic meteorological data (exterior temperature, wind speed, atmospheric pressure and others) were also collected.



Figure 1. Automobile with thermocouples prepared for the experiment

The fire was ignited by burning of a small amount of gasoline (about 5 ml) poured onto a small cloth, which was placed in the engine compartment under the rubber tube (Figures 2 and 3) imitating a frequent failure in the engine compartment. Immediately after the fire ignition, the engine compartment lid was closed. Sparse smoke above the lid appeared very soon and became denser gradually. During the first three minutes, smoke from the interstices at right edges of the lid and on the lid below the front window was prevailing. At the 4th minute, the smoke leaking out from the holes at the place of missing front lights became more intensive. At the 7th minute, weak flames appeared in the hole at the place of the missing left front light. Between the 7th and 8th minute of fire, flames appeared on the surface on the left side of the lid (varnish ignition). After 12 minutes, the fire was extinguished and inspection started to determine the components degraded most by the fire, and to detect the most flammable materials in the engine compartment.

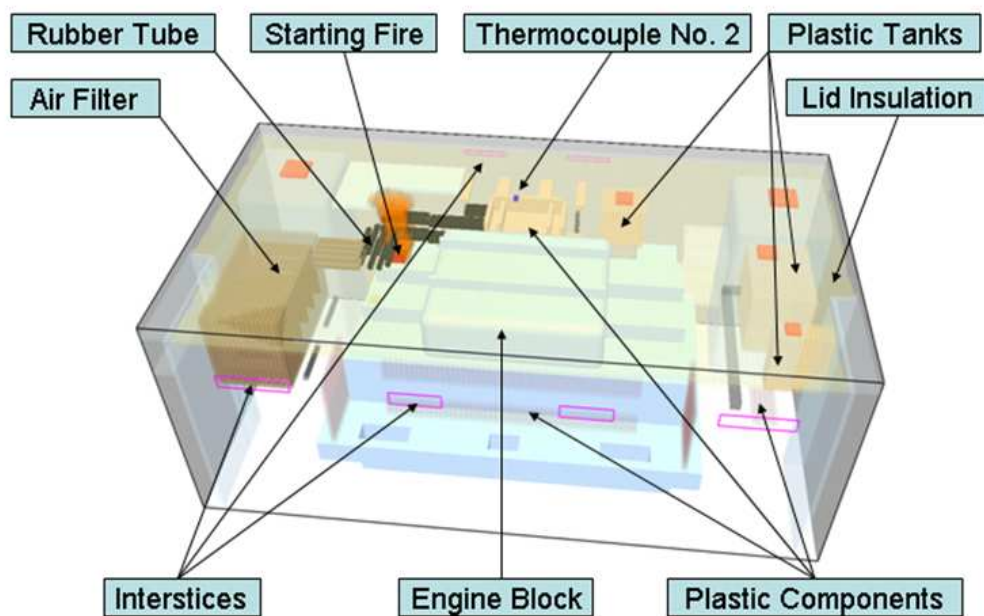


Figure 2. Scheme of automobile engine compartment



Figure 3. Engine compartment before (left) and after (right) the fire experiment

The most flammable objects in the engine compartment, completely or almost completely burnt during the first 12 minutes of burning, were: the rubber tube (above the fire ignition source), 3 plastic tanks (in the right back part of the engine compartment), air filter box with its paper content (on the left side of the engine compartment), and several other plastic components (Figures 2 and 3). It was confirmed that these components contribute most to fire in engine compartment. The inspection also showed significant degradation of several electric cables and other hoses, partially auto battery and partially molten parts of engine block, and other components afflicted by fire. However, the contribution of these components to fire seems to be small. Fig. 4 shows that the temperature recorded by the thermocouple in the automobile engine compartment reached as many as 900 °C.

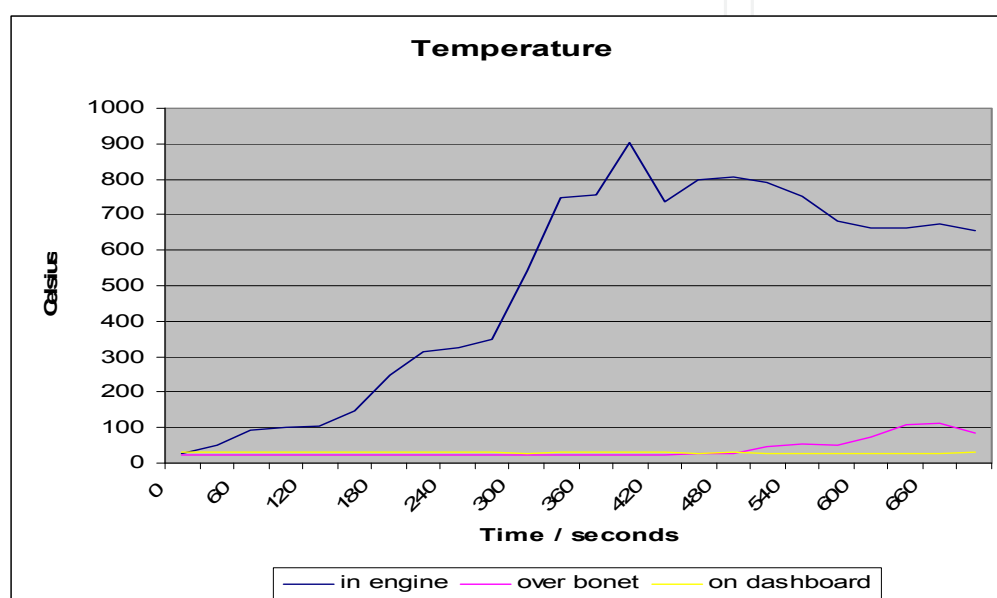


Figure 4. Temperature in the engine compartment, over the bonnet and on the dashboard

The next automobile fire experiment modelled a possible real situation of fire occurred during car driving. The driver observed fuming, stopped the car after some hesitation, and decided to extinguish the fire in engine compartment through slightly ajar lid by portable car fire extinguisher. During this experiment, a technical failure was confirmed.

Fire fighters, who should have fought the fire, could not open the engine compartment due to the melting of the lock control mechanism of the engine compartment lid. It was even not possible to open the engine compartment by heaver and plate shears had to be used (see Fig. 5). For this reason, the fire fighting could start with a substantial delay only. Thus, it can be concluded that cars with such plastic control lock mechanism of engine compartment lid may not be extinguished by portable car fire extinguisher due to inaccessibility of the space where the combustion takes place.

The temperature peak over the bonnet comes earlier than that in engine compartment. Probable reason of that is insufficient oxygen supply in engine compartment, which suppressed the fire spread inside the engine compartment and caused that the thermocouple in the engine compartment was not exposed to direct plume. Instead, the sealing compound burnt down and gaseous fuel was created in the engine compartment.

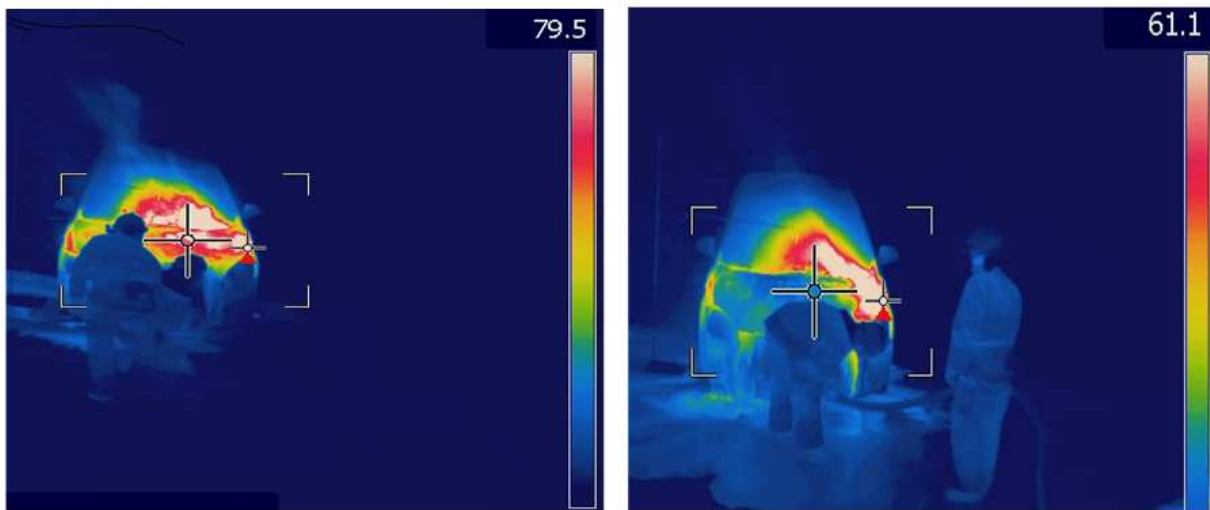


Figure 5. Destruction of the plastic control lock mechanism of engine compartment lid

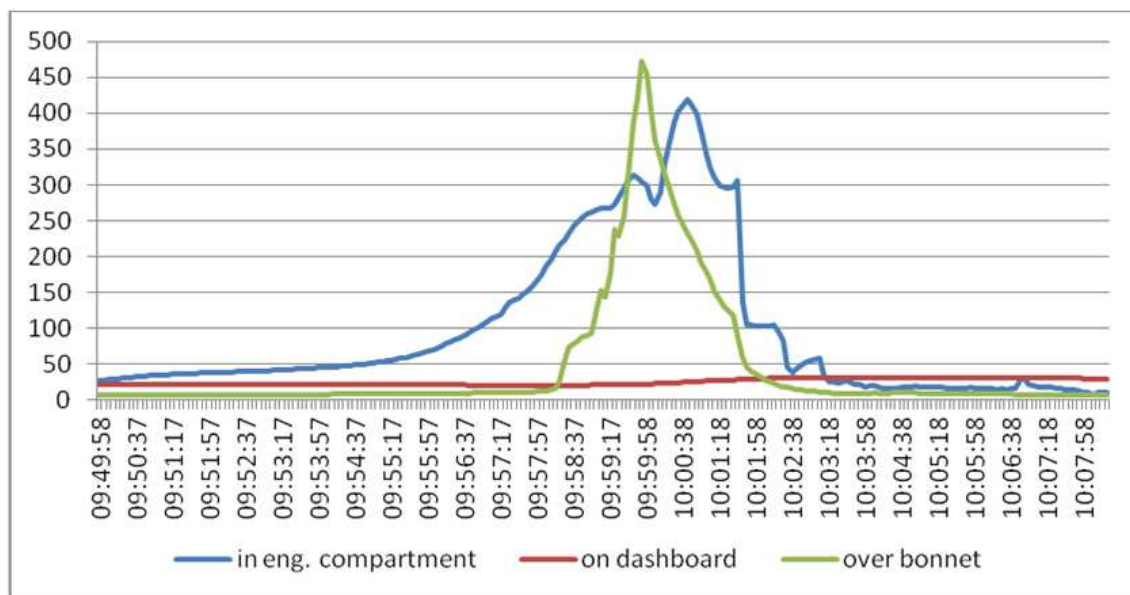


Figure 6. Temperature in the engine compartment, over the bonnet and on the dashboard

4.1. Computer simulation of engine compartment fire

Simulation of automobile engine compartment fire belongs to the most complex FDS simulation problems. Due to the extremely complex geometry of the burning space and objects inside the engine compartment, which affect the fire development and then have to be accurately captured, such a simulation requires very fine mesh resolution and therefore significant computational power for calculation. That is why the design of engine compartment geometry and of the components in the input FDS file is of great importance. In order to properly model the engine compartment as well as all relevant flammable components in its interior, corresponding input geometry of simulated space was elaborated using available 3D scans, as well as direct measurements of distances and proportions of detected flammable components (done before the start of experiment). The

simulation domain includes all flammable components mentioned above and other plastic and metallic components which influence the direction of fire and smoke spread in time (see Fig. 2).

Engine compartment fire simulation is just the situation in which certain geometric features of engine compartment components do not conform to rectangular mesh, and have to be represented in a different way (electrical cables, tubes, hoses, etc.). The shape of plastic tanks and air filter can be captured almost realistically. However, the rubber tube (small thickness and cylindrical shape) has to be represented by a cluster of thin stripes where the total mass of stripes is equal to the mass of the tube itself. Moreover, the surface to volume ratio of the stripes is the same as that of the tube. Both these parameters, which are crucial for heating up and burning of material, were maintained. By this way some other components, such as paper interior of the air filter box, were modelled. Several other components, which did not appear to be critical for heat transfer and burning (e.g. small plastic caps of tanks too small to be properly captured), were represented by plastic or metallic slabs placed at appropriate places in the simulation space.

Proper determination of material properties (physical parameters describing burning properties of materials) in the engine compartment was another essential task to be solved. There were four prevailing types of materials identified: aluminium alloy (metallic components), rubber (rubber tube), paper (air filter interior) and mixture of polyethylene (plastic components). Some material parameters for automobile varnish were estimated (e.g. the heat release rate per unit area) and some of them were derived from observations (e.g. the ignition temperature was determined from recorded infra-red camera observations) during the experiment. Most material parameters were determined by specialists from University in Zilina (Slovakia).

In the simulation, the fire ignition source (the small burning cloth placed on the engine block under the rubber tube) is represented by a burning surface with the dimensions of 4 x 4 cm and total heat release rate set to 2.1 kW for the period of 60 s.

Several measurement devices were defined in the simulation to provide proper output parameters describing the fire behaviour in time, such as gas temperature and velocity, surface temperature, oxygen concentration, etc.

4.2. FDS simulation results

For the simulation of the fire scenarios described above, we used a PC with 4-core processor Intel Q9550 with the frequency of 2.83 GHz, 8 GB of RAM and 1TB hard disk.

Two types of the engine compartment fire simulation are briefly presented in this section. They differ from each other:

- in the manner in which the computational domain was chosen
- by their computational requirements, the range of consideration of the automobile environment in fire scenario

- by the number and precision of output quantities provided.

For each case, dozens of simulations were performed in order to test and find proper values of significant parameters and appropriate location of interstices affecting the oxygen supply.

4.2.1. Simulation A

In this simulation, the computational domain includes the interior of engine compartment and 3 cm space above the engine compartment lid to show also the temperature distribution on the upper surface of the lid. The domain boundary conditions defining the heat transfer are given by the material properties of the bodywork (aluminium alloy) and are set 'OPEN' for the upper boundary of the 3 cm space above the engine compartment. The interstices in the bodywork (Figures 2, 3 and 7) are represented by narrow vents with boundary conditions 'OPEN', which allow convective gas transfer between the engine compartment and the automobile environment, not explicitly included in this simulation. They represent the holes at the place of missing front lights and the corresponding interstices at the front and back sides of the engine compartment and on the lid edges.

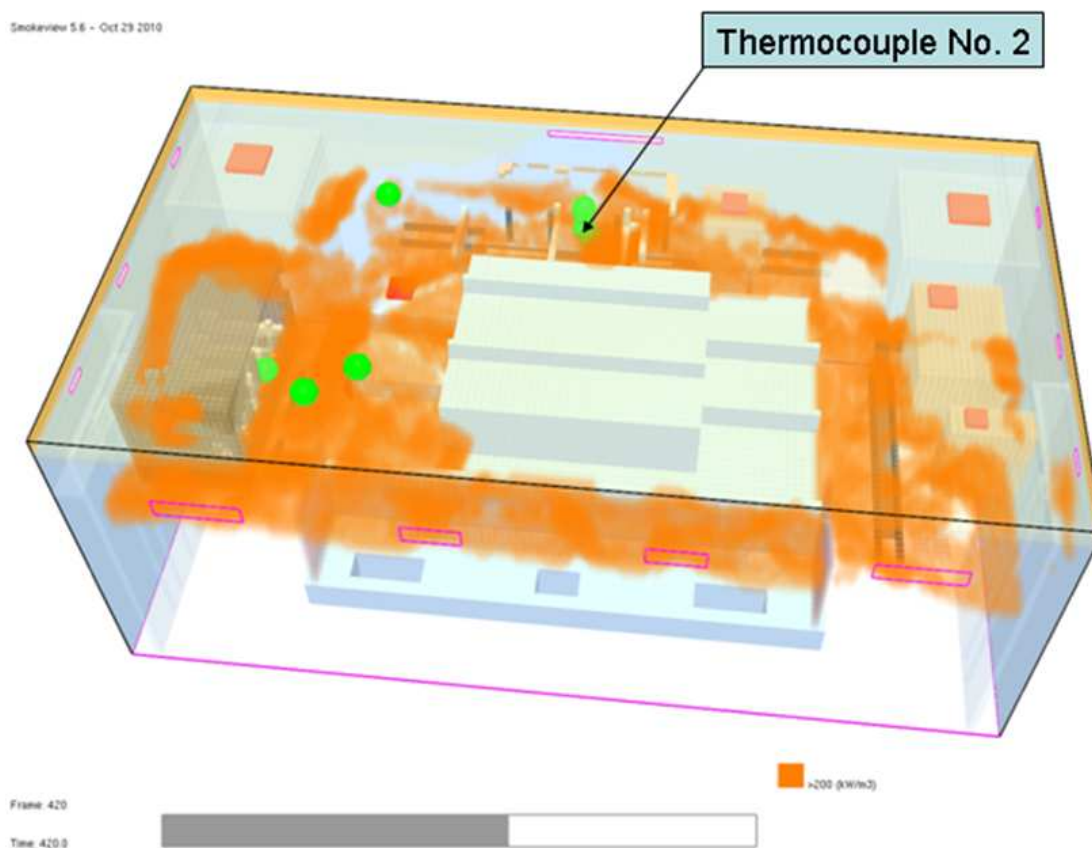


Figure 7. Simulation A in the 7th minute of burning. The orange colour volumes represent the volumes with HRR per unit volume values higher than 200 kW.m⁻³

The whole computational domain is represented by one computational mesh of 1 cm resolution with 503,712 cells which was assigned to one CPU core. Most of the dynamic processes of burning occurred in the left part of the mesh. The simulation of 720 s of fire required 207 hours of CPU time at Intel Q9550, 2.83 GHz CPU.

The main fire spread tendencies are similar to observations during the fire experiment. The simulated fire behaviour was as follows. At the 22nd second of fire, the rubber tube and the lid insulation layer above the burning cloth started to burn. At the 50th second of burning, flames were spread in the whole engine compartment. At that time, the total heat release rate (HRR) of about 15 - 20 kW was achieved. In rear part of the engine compartment, significant ascending air flow was created by the interstices located under the front window, which made the fire spread along the rubber tube to the rear part of the engine compartment.

This fire behaviour is in accordance with the observation of intensive smoke from the interstices below the front window in this phase of fire and with increase of the lid temperature detected by IR camera, as well as with increase of thermocouple No. 2 during the fire experiment (see Figures 4 and 8).

Meanwhile, the air filter was heated up and its paper content ignited, although its HRR was very low because of insufficient oxygen supply. Between the 200th and 300th second of simulation, the plastic components in the rear part of the engine compartment burnt away, which led to significant increase in air supply and caused temporary temperature increase at sensor No. 2 and to more intensive burning of the air filter. This behaviour is in accordance with the fire experiment, which showed strong increase of temperature of a part of the lid above the air filter in that phase of fire (see the surface temperature distribution on the lid shown in Fig. 8 as well as the peak in Fig. 4), as well as intensive smoke produced in the front part of the automobile. Although the range of colour schemes for surface temperatures in simulation and IR camera outputs in Fig. 8 are not the same, the temperatures show similar behaviour.

Heat and flames spread mainly along the air filter in the direction towards the hole at the place of missing left front light. At the 428th second of simulation (440th second in the fire experiment), the outer lid surface reached the temperature of 300 °C and the varnish ignited. After the air filter burnt away, the plastic components in the front part of the engine compartment started to burn more intensively (flames in the holes at the place of missing front lights were observed during the experiment too). The maximal value of total HRR achieved was about 40-50 kW.

The maximal surface temperature on the lid achieved by simulation is well comparable to the values recorded by the IR camera. It can be seen in Fig. 8 that the lid surface temperature distribution in time is in good spatial and temporal accordance with IR camera records (see also Fig. 9). The time of varnish ignition on the lid surface corresponds with observations during the experiment.

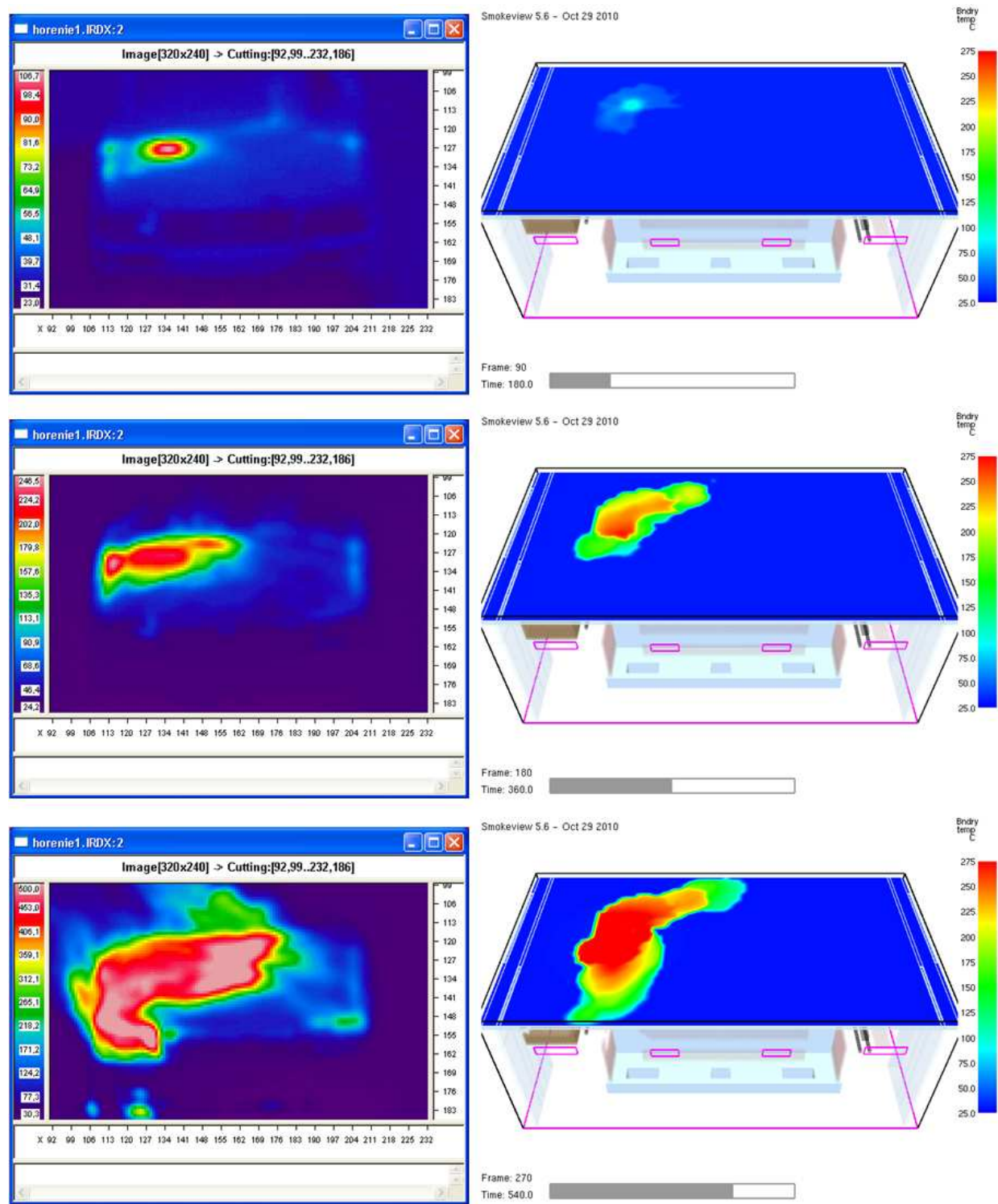


Figure 8. Surface temperature distribution on the engine lid: in IR camera output (left) and in simulation A (right) in the 3rd, 6th and 9th minute of burning

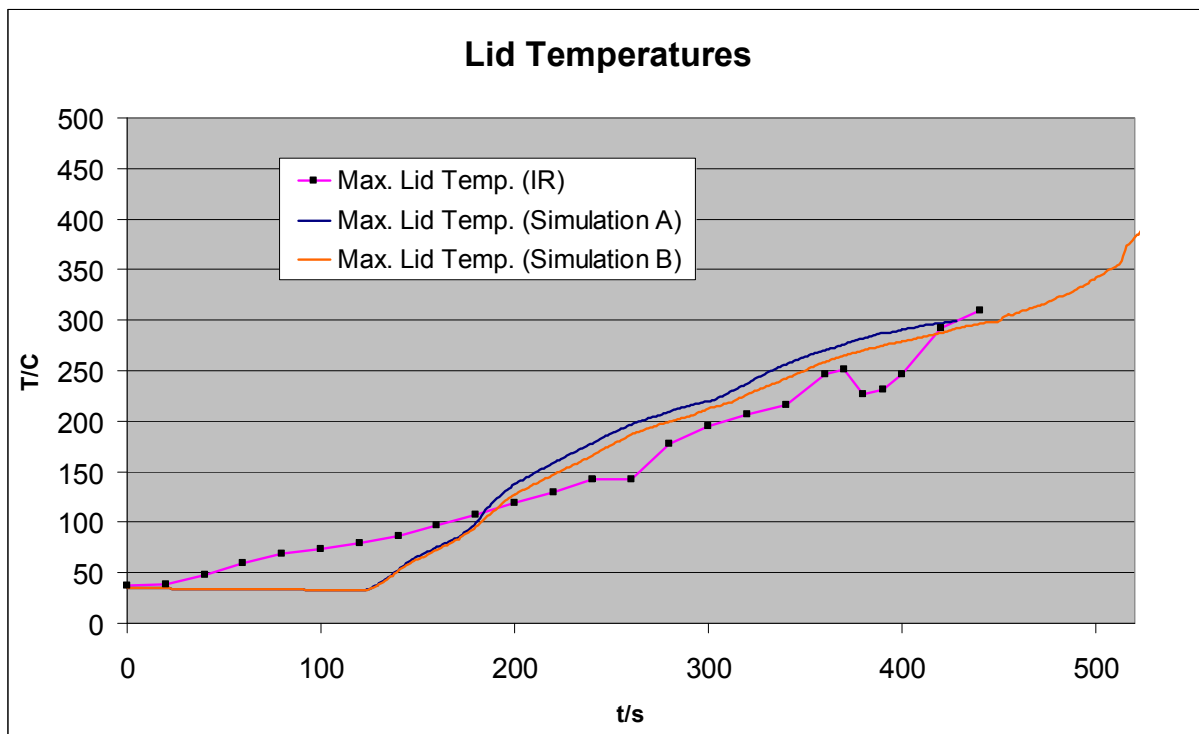


Figure 9. Maximal temperature of the lid surface in simulation and in the IR camera output

4.2.2. Simulation B

In this case, the computational domain includes the engine compartment interior as well as additional space above the engine compartment lid providing information about the fire spread above the engine compartment (see Fig. 10). The domain boundary conditions defining the heat transfer are again given by the material properties of the bodywork (aluminium alloy) and 'OPEN' for the space above the engine compartment. The interstices in the bodywork are represented as before by vents with boundary conditions 'OPEN'.

The additional mesh placed above the lid includes the space, in which potential varnish fire occurs during the simulation. Its resolution decreased to 2 cm having 192,640 additional cells. The engine compartment itself was assigned to one computational mesh. Most dynamic processes of burning occurred inside the engine compartment, therefore, the impact of such division on the accuracy of computation was small. The additional space above the engine compartment lid did not influence the simulation of fire in the engine compartment interior much (see Fig. 9). However, the simulation provides more realistic visualization of fire above the lid (see Fig. 10). The advantage of case B in comparison with case A is that it provides further additional output quantities of fire outside the engine compartment (e.g. the HRR of varnish fire, temperature above the lid, etc.) at the cost of growth of computational requirements. The simulation of 700 s of fire required 200 hours of CPU time at Intel Q9550, 2.83 GHz CPU.

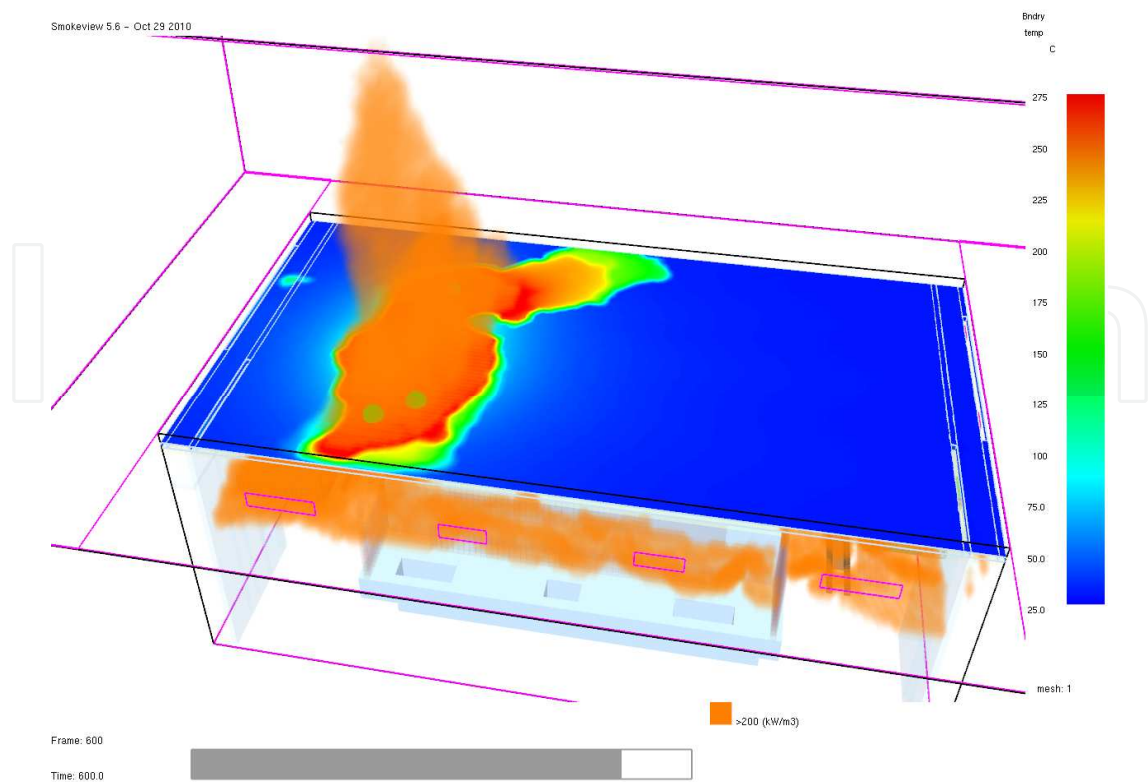


Figure 10. Simulation B in the 10th minute of burning. The orange volumes represent the ones with HRR per unit volume values higher than 200 kW.m⁻³

The main tendencies of the fire spread in this simulation are similar to the fire behaviour in simulation A and to observations during the fire experiment. The results of HRR of both simulation A and B are shown in Fig. 11.

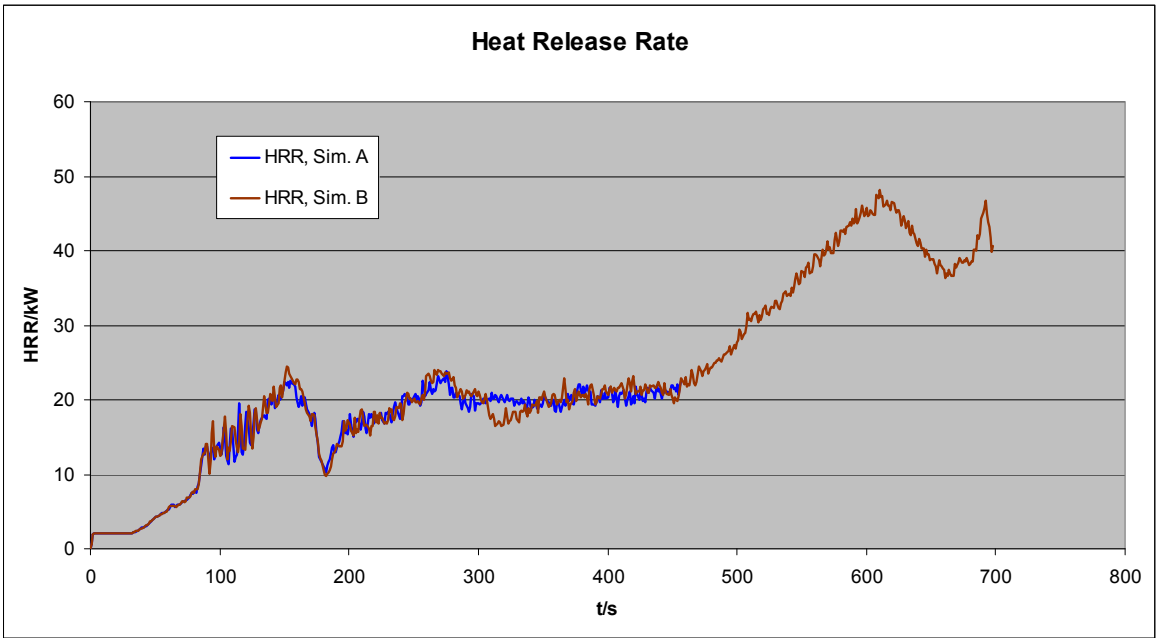


Figure 11. Heat release rate of fire in the simulations A and B

5. Automobile fires in passenger and luggage compartments

Fires of automobile passenger and/or luggage compartment are not very frequent. However, if they occur, they can be very dangerous particularly in urban conglomeration. They often accelerate fast especially in sooner manufactured automobiles with more flammable car seat upholstery materials and/or flammable vehicle load. Such fires can cause large damages especially in the case, when the interior of automobile is sufficiently supplied with oxygen during fire (for example, if it flows through a broken window or ajar door).

In this section, we will describe the FDS simulations of automobile fires in passenger and luggage compartment related to one of three full-scale fire tests conducted during the third fire experiment carried out in Slovakia in 2009 (see Fig. 12).



Figure 12. Full-scale fire experiment: passenger compartment fire

The fire was initiated on the back seat behind the driver seat. The left back window was open. The aim of the experiment was to monitor the course of passenger compartment fire and subsequent spread of fire from burning automobile onto a near-standing vehicle. Temperatures were measured by thermocouples on the engine block, over the engine compartment and in the middle of dashboard. Lateral air flow was imitated by a fan. The experiment showed a strong relation between the passenger compartment fire and the air supply via the open window. Substantial fire acceleration was observed in the moment of the windscreen destruction. High plumes and dense smoke appeared in the passenger compartment very soon in the same minute as the fire was ignited. The temperature in the passenger compartment reached the value of 750 °C in the second minute of fire. In the 3rd minute of burning, the windscreen destruction and airbags explosion occurred followed by strong plumes. At the 4th minute of fire, a driving mirror burning was observed caused by over-jumping a burning piece of flammable material from burning automobile in consequence of the airbag explosion. We performed a simulation of the fire scenario described above. The geometry of the used automobile was constructed and flammable components in the passenger compartment were modelled by the upholstery and plastic volumes (see Fig. 13).

The real material properties were estimated, or gathered from tables. Boundary conditions 'OPEN' were used for the domain boundaries. For the simulation, one computational mesh

of 3 cm mesh resolution consisting of 1,049,760 cells was used. The simulation of 600 s of fire required 130 hours of CPU time at Intel i7-990X CPU, 3.46 GHz CPU. Some typical phases of the simulated passenger compartment fire are demonstrated in Figures 14 and 15.

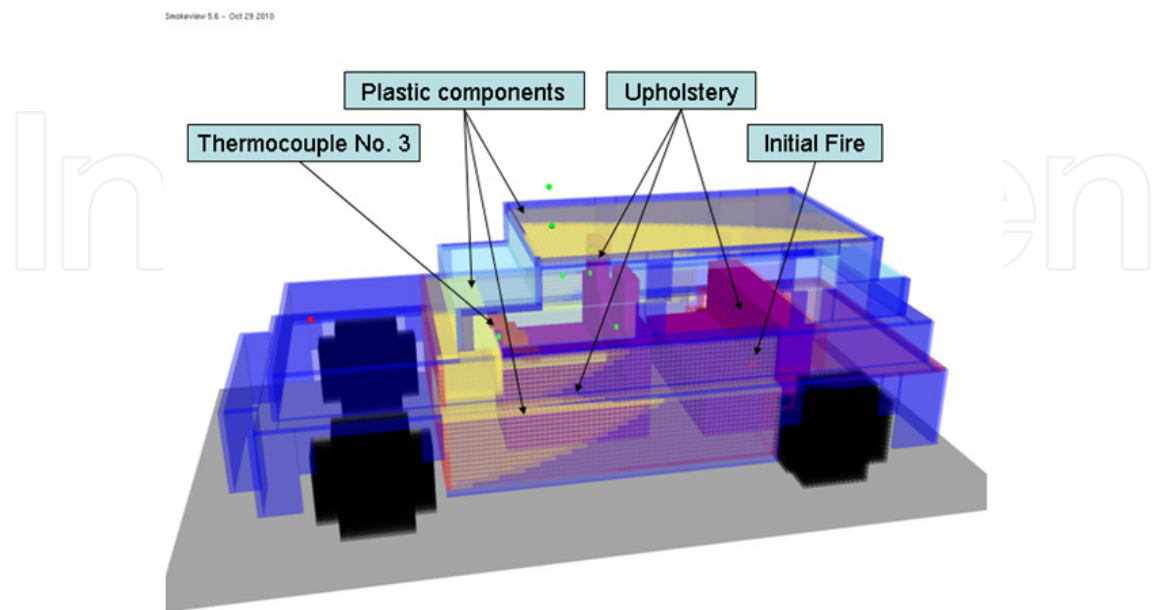


Figure 13. Scheme of automobile passenger compartment and used materials

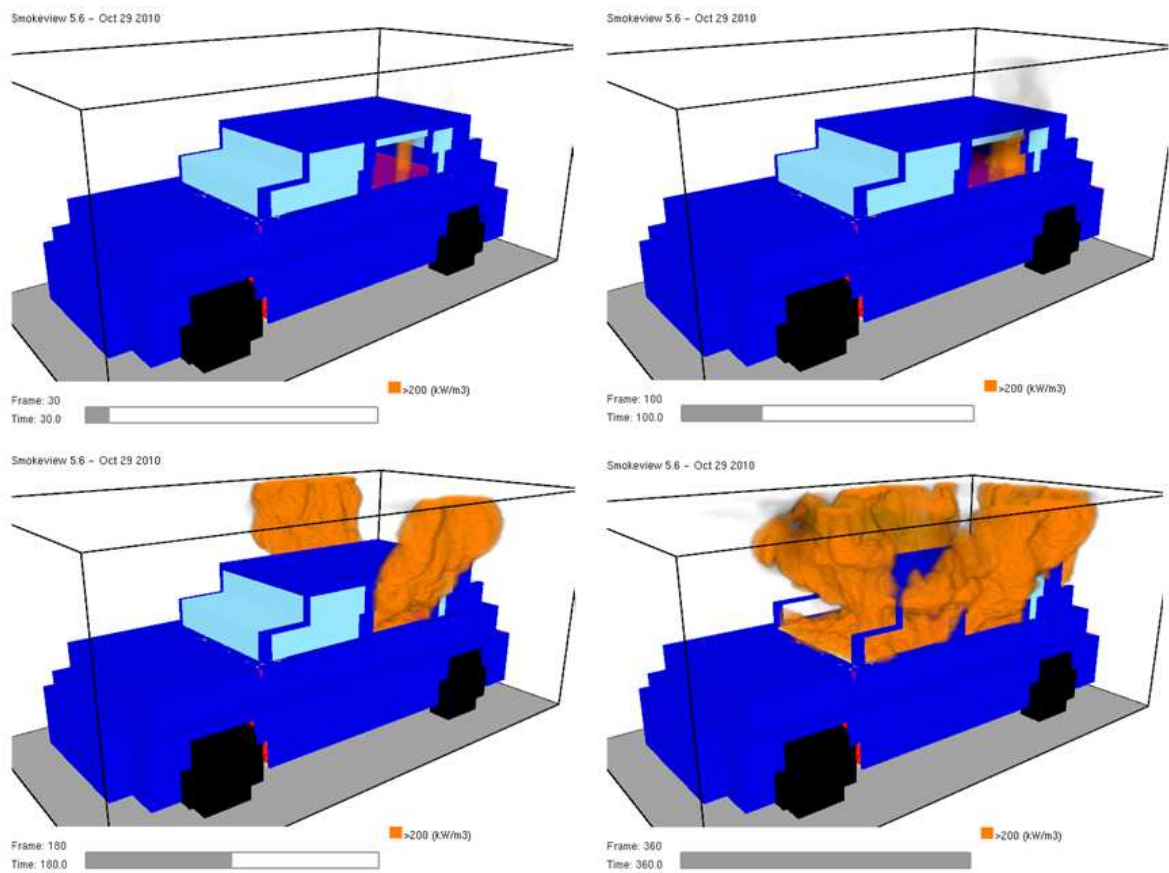


Figure 14. Simulation of passenger compartment fire in the 30th, 100th, 180th and 360th s of fire

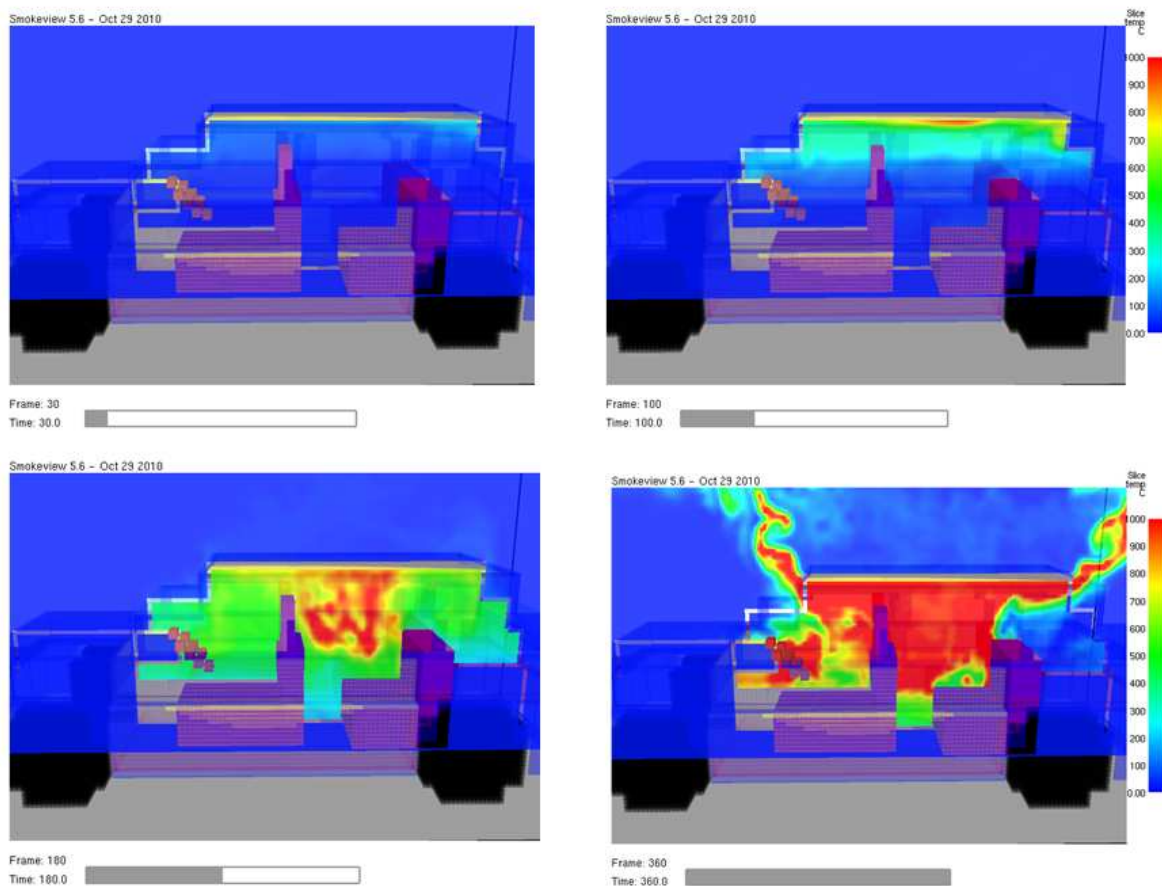


Figure 15. Simulation of passenger compartment fire: temperature cuts in the 30th, 100th, 180th and 360th second of fire

The fire behaviour was as follows. The fire was ignited in the same place as in the fire experiment, on the back seat behind the driver seat. Significant air supply through open left back window enabled rapid spread of fire throughout the whole back seat and significant increase of HRR. Other windows were removed in the simulation, step by step by observations from the fire experiment. Thus, the air supply increased even more in the next phases of burning. After 115 s of simulation, the whole back part of the passenger compartment was ignited and the right back window was removed. After 240 s, all remaining windows were removed and the HRR reached the maximal value of about 4 MW.

Fig. 16 shows the HRR behaviour during the fire, while temperature in passenger compartment and its comparison with the experimental values (thermocouple No. 3) are shown in Fig. 17.

The simulation results are in good agreement with experimental observations, although the value of the maximum temperature in simulation is higher by about 200 °C. In order to make this simulation more accurate, some additional research of real upholstery and plastic components material properties is required. The “step” behaviour of the temperature curve in the simulation, which can be seen in Fig. 17, was caused by the sudden removal of windows. In the real fire, this removal was more gradual. Therefore, no such sudden

increase occurred. Thorough examination of material properties of glass and its incorporation into the simulation can solve this problem.

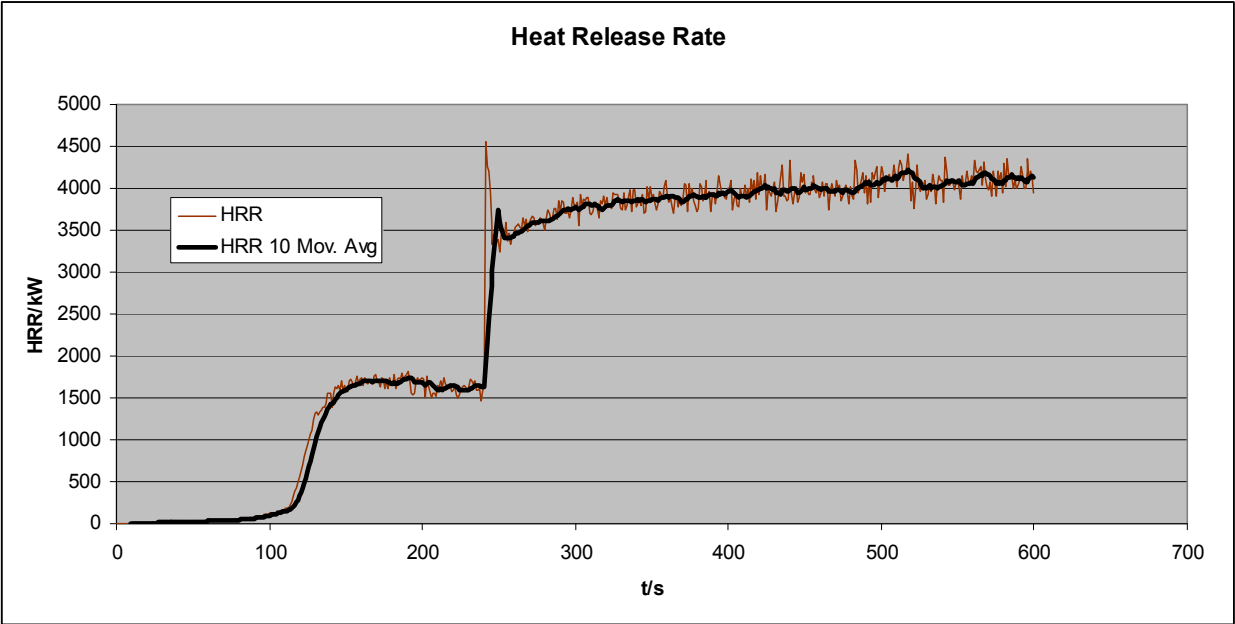


Figure 16. HRR of passenger compartment fire

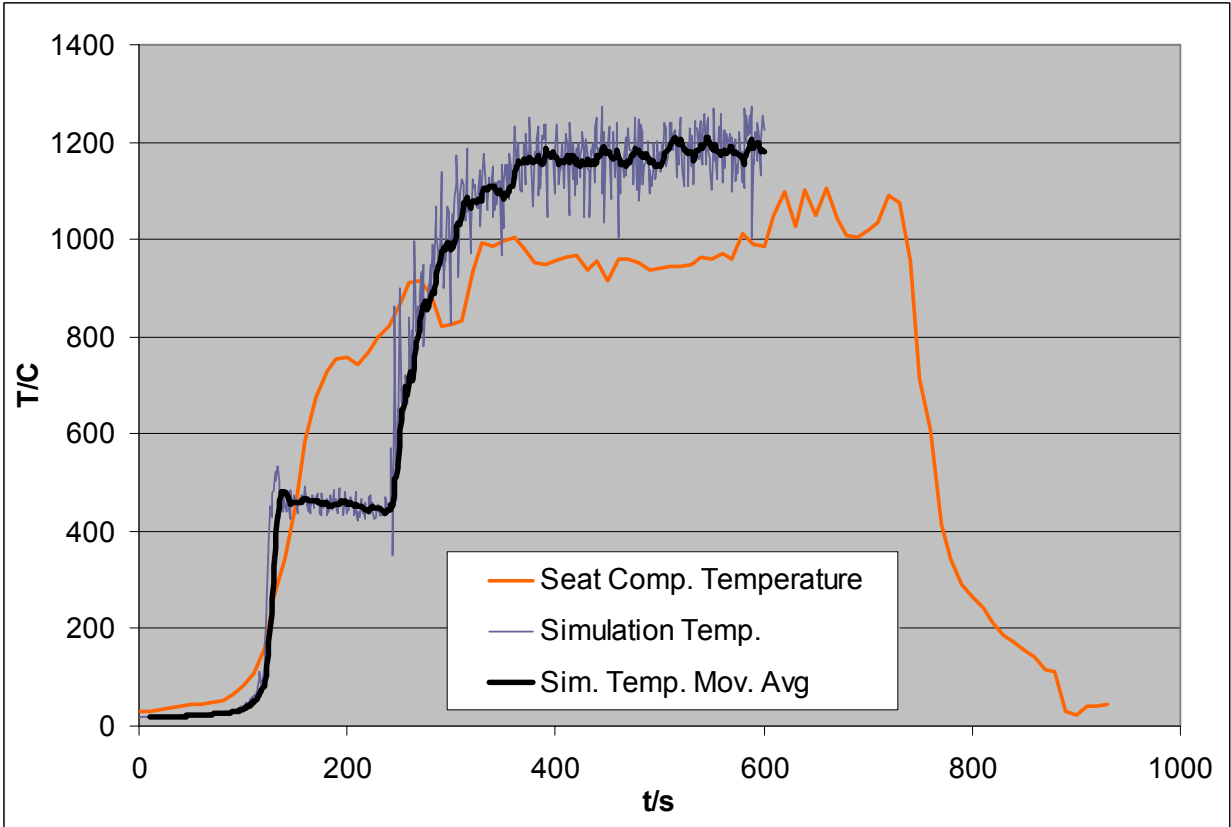


Figure 17. Temperature curves in the passenger compartment interior during the fire: simulation and experiment

6. FDS simulation of fire spread from burning automobile onto a near-standing vehicle

In this section, the FDS simulations of automobile fire spread onto a near-standing automobile will be described which are related to one of three full-scale fire tests conducted during the fourth fire experiment carried out in Slovakia in 2009 (see Fig. 18).



Figure 18. Full-scale fire experiment: spread of fire onto near-standing automobile

A simple case of the simulation of near-standing automobile ignition from burning vehicle is shown in Fig. 19. The aim of the simulation was to investigate the influence of wind speed and distance between the automobiles upon automobile ignition. Three automobiles were used in the simulation, two of them are of the same type as in the previous simulation. The first automobile (left) modified the air flow profile only. The second (central) automobile with slightly different bodywork geometry represented a source of fire. The third automobile was exposed to the central vehicle fire. The air flow direction was chosen to accelerate the spread of flames from the second to the third automobile. The distance between the second and the third automobiles and air flow velocity varied from 15 cm to 75 cm and from 0 m.s⁻¹ to 3 m.s⁻¹, respectively. The total HRR of burning engine compartment was 787.5 kW (HRR per unit area was 500 kW.m⁻²). In order to evaluate the impact of fire on the third automobile, a thermocouple was placed on the right side of its bodywork (Fig. 19).

The computational domain size was 810 x 540 x 225 cm with 5 cm computational mesh resolution. The total number of cells was equal to 787,320. Boundary conditions for the left and right domain boundaries (see the green surfaces in Fig. 19) are defined by the air flow velocities considered in the fire scenarios. Boundary conditions 'OPEN' are set for other domain boundaries. Intel i7-990X CPU, 3.46 GHz CPU was used for a series of simulations with different distance and velocity parameters. Duration of 100 s fire simulation was approximately 12 hours. Maximal simulation time was 600 s. By this way, it is possible to simulate and analyze the ignition time of near-standing automobile depending on different parameters in different conditions in open, semi-closed and closed areas for miscellaneous car categories.

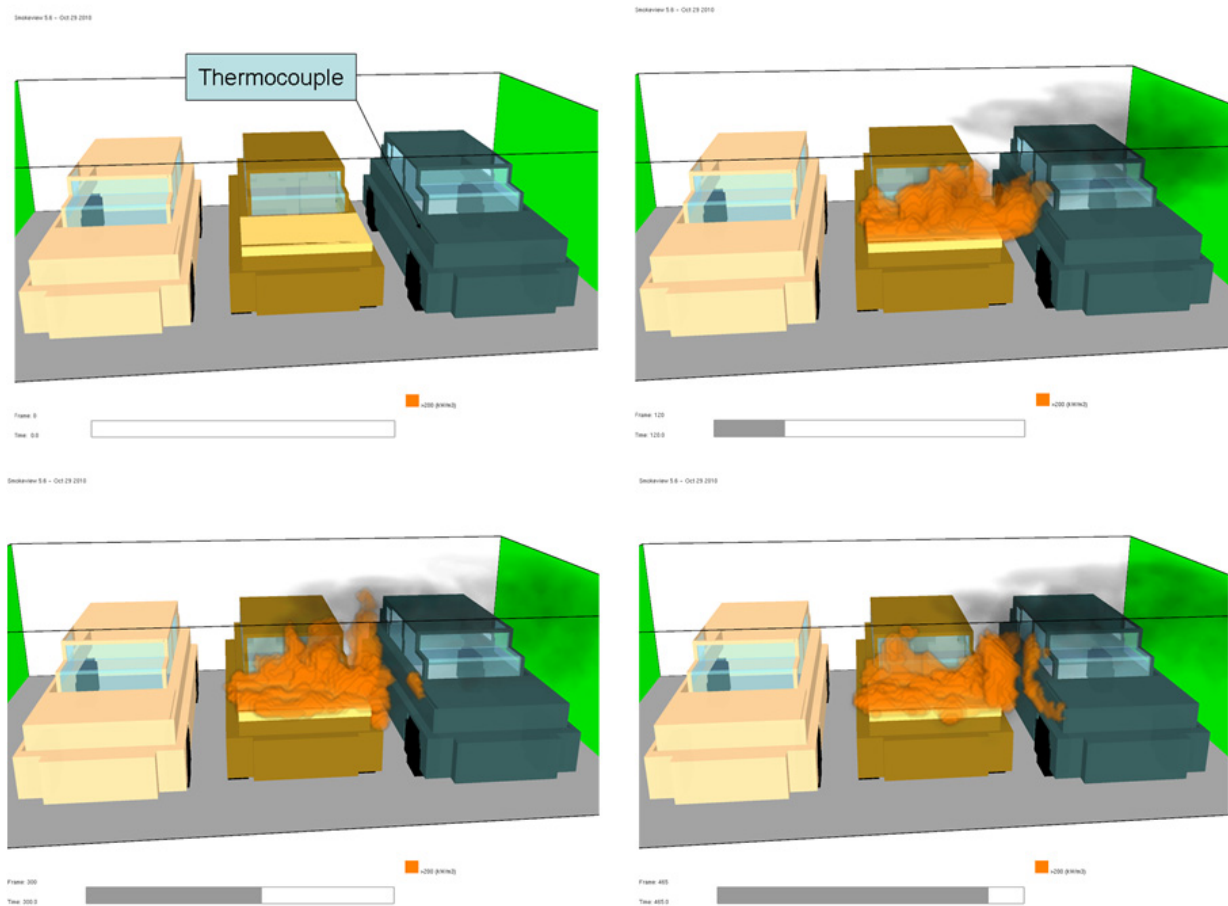


Figure 19. Simulation of near-standing automobile ignition: the case of 45 cm distance between automobiles and 2 m.s^{-1} air flow velocity in the 0th, 120th, 300th and 465th s of fire

Some typical phases of the simulation with 45 cm distance between automobiles and 2 m.s^{-1} air flow velocity are shown in Fig. 19. In the simulation, the ignition occurred at the 288th second of burning. In Table 1, the simulation results for different combinations of the chosen parameters are shown.

	0 m.s^{-1}	0.5 m.s^{-1}	1 m.s^{-1}	2 m.s^{-1}	3 m.s^{-1}
15 cm	304 s	251 s	185 s	137 s	107 s
30 cm	384 s	327 s	254 s	193 s	167 s
45 cm	494 s	441 s	348 s	288 s	268 s
60 cm	-	-	474 s	407 s	389 s
75 cm	-	-	-	575 s	-

Table 1. Time of the third automobile ignition for different distance and air flow velocity values

Fig. 20 shows the temperature behaviour at the thermocouple placed on the third automobile (see Fig. 19) for 2 m.s^{-1} air flow velocity and different distance values.

The simulation results confirmed the observations during the fire experiments conducted, that 60 cm distance between automobiles can be considered to be a reasonable safe distance

between automobiles in car parks. For this value of the distance, ignition occurred only if the air flow velocity was above 1 m.s^{-1} and a relatively intensive fire lasted for almost 10 minutes. Such conditions are relatively rare in semi-closed or closed compartments.

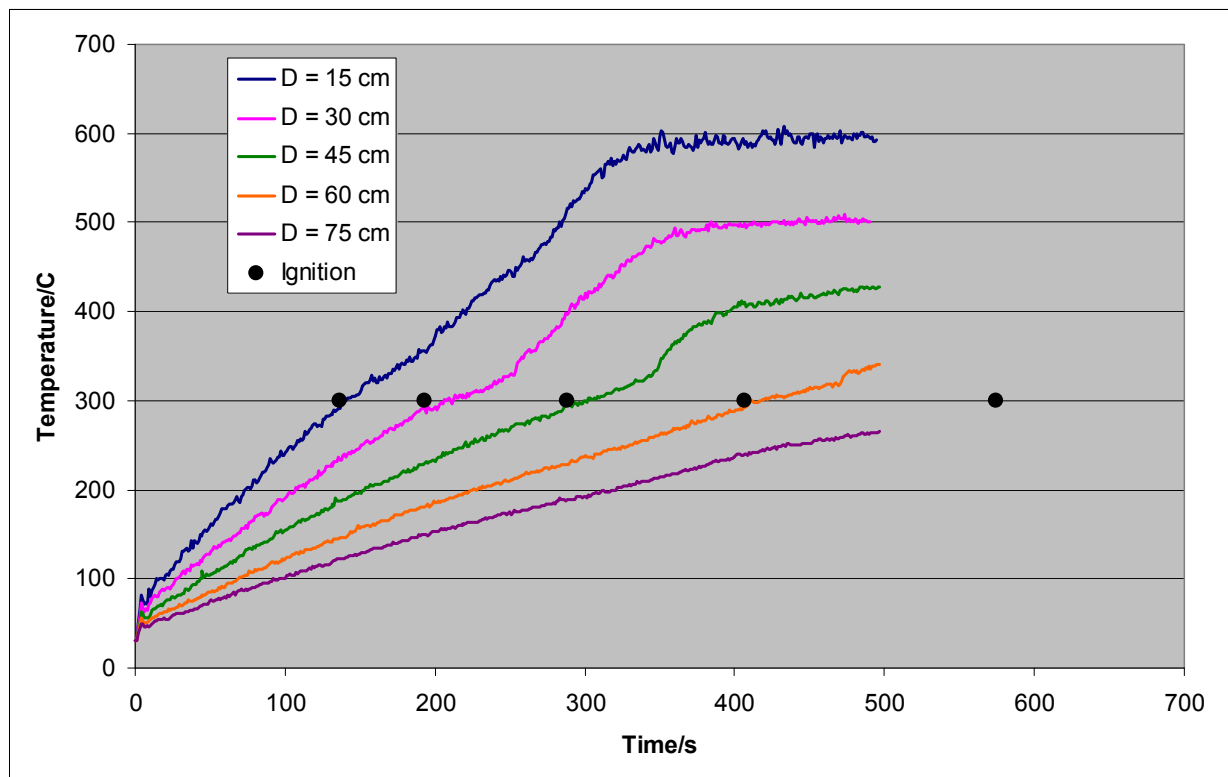


Figure 20. Temperature behaviour for 2 m.s^{-1} air flow velocity and different distance values. Black points represent the time of ignition of the third automobile observed in simulation. This time is not inevitably the same as the time when the temperature in control thermocouple reached the ignition temperature. The place of ignition was different in every simulation.

Another important observation is that a higher air flow velocity does not necessarily mean a higher probability of the ignition. For 75 cm distance and 3 m.s^{-1} air flow velocity, the ignition did not occur, although for 3 m.s^{-1} velocity the third automobile was ignited. In this case, a cooling effect of strong air flow and its influence on flame distraction probably prevailed and heating effect of burning vehicle was suppressed.

Simulations of this kind can be used for specific automobile fire scenarios expected in practice to evaluate the impact of fire, as scenarios parameters can be easily modified according to user requirements.

7. Conclusion

In this chapter, three simple cases of typical automobile fire safety problems arising in real traffic situations and their computer simulation are briefly described:

- automobile engine compartment fire
- automobile passenger and/or luggage compartment fire

- fire spread from burning automobile onto a near-standing automobile.

These simple fire scenarios were simulated by using advanced fire simulator FDS (Fire Dynamics Simulator) and validated by results of the full-scale fire experiments in the testing facilities of Fire Protection College of the Ministry of Interior of Slovak Republic performed in 2009 in Povazsky Chlmec (Slovakia). These fire types correspond to most frequent automobile fires associated with real situations on roads, parking areas, underground car parks, garages and road tunnels. During these experiments, several automobile fires have been performed to better understand the burning process itself and to collect proper fire parameters describing the fire behaviour for the purposes of verification of the computer FDS simulations of these fires.

The developed simulations indicate the ability of the used fire simulation system to model, simulate and visualize various practical fire scenarios and can help test the fire behaviour and various critical parameters which are important for automobile fire safety (such as e.g. critical distance between burning vehicle and near-standing automobile and/or other objects, ignition time of near-standing objects afflicted by automobile fire or vice-versa, tunnel ventilation parameters in the fire regime, etc.). Computer simulation allows also to test the influence of flammable material properties on the fire behaviour for certain fire scenario. The simulation can provide us with information about the main fire spread tendencies, as well as about its quantitative characteristics like fire heat release rate, temporal temperature curves, etc. It allows to evaluate fire risk for the automobile environment and to test possible fire scenarios for concrete situations, which can help evaluate fire suppression options in further fire phases.

General agreement between the simulations presented and the fire experiment observations have been confirmed. However, several specific features can be seen when analyzing the suggested simulations:

- Size of flames from engine compartment interstices in initial phase of the simulation. They seem to be longer than observed. A possible reason of that phenomenon can be the visualization of hot gases coming out from interstices (HRR per unit volume of which exceeds 1199 kW.m^{-3}), which are visualized as “flames” but are still not recognized as “flames” by human eye. Moreover, the real interstices were a bit narrower and longer than the simulated ones, maintaining the realistic total leakage area for the air flow, and they have more intricate form (of cavity under the lid). This imperfect “geometry” of interstices following from the mesh limitations could not entirely capture more complicated burning in these small, but intricate spaces. Hot gas could interact with metal surface of the lid in more complicated way than the simple open vent in the simulation. Although this phenomenon was manifested in the simulation B by a bit longer “flames” coming out from the interstices, the simulation of burning inside the engine compartment was reliable.
- Limitations of models implemented in FDS concerning heat conduction modelling in solids probably affect the surface temperature distribution in the lid. Since the FDS does not simulate 3D heat transfer in the lid, the shape of isotherms on the lid is slightly

different than in the IR pictures recorded during the fire experiment. However, this influence was of minor importance for the simulation reliability.

Despite the fact that the automobile engine compartment fire is a complex FDS simulation problem, the FDS simulator proved its applicability for modelling such complex fires. Although the exact geometry of objects in the simulated space is important, if the mesh resolution limitations prevent to capture them precisely, at least their surface to volume ratio and the total mass should be maintained. Air supply and proper size and position of interstices is crucial for the fire development; however, this information is usually not available and user should experiment with several simulations in order to find the proper solution. Next important problem is the determination of material properties where small differences in some values can change the fire behaviour qualitatively. Moreover, efficient realization and validation of fire simulations of large places (for example in a road tunnel) for fire safety purposes in parallel using parallel computers and distributed environments is also a challenging problem.

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