PERFORMANCE OF FDS VERSIONS 5 AND 6 IN PASSENGER CAR FIRE COMPUTER SIMULATION

Weisenpacher, P. [(a)], Glasa, J. [(b)], Sipkova, V. [(c)]

[(a),(b),(c)]Institute of Informatics, Slovak Academy of Sciences, Dubravska cesta 9, 84507 Bratislava, Slovakia

[(a)] upsyweis@savba.sk, [(b)] utrrglas@savba.sk, [(c)] upsyvsip@savba.sk

ABSTRACT

In this paper, the performance of FDS versions 5 and 6 and their accuracy in high performance parallel simulations of passenger car fire is evaluated. The results of measurements obtained during a full-scale fire experiment conducted in Povazsky Chlmec (Slovakia) in 2009 have been used to test the geometrical representation and material properties of two passenger cars and their passenger compartments used in the model. The tested simulation scenario includes a fire in passenger compartment of one car and its spread to an adjacent car. A series of simulations is executed on a cluster of computers using the NIST FDS system, versions 5.5.3 and 6.1.2. The differences between the simulation results obtained by both FDS versions are described and discussed.

Keywords: passenger car fire, fire simulation, parallel simulation, high performance computing

1. INTRODUCTION

Advances in Computational Fluid Dynamics (CFD) as well as increasing performance of computers and clusters of computers have recently enabled to simulate the course of fire for safety purposes in unprecedented detail. CFD simulations dealing with smoke propagation in car parks and road tunnels have achieved significant level of reliability and practical applicability. Knowledge on car fire behaviour is an important factor contributing to efficiency of fire safety measures and to CFD simulations applicability. Extensive experimental research has been conducted in order to investigate the course of single car fire course as well as the spread of fire to adjacent vehicles (Mangs and Keski-Rahkonen 1994; Shipp and Spearpoint 1995; Okamoto et al. 2009; Zhao and Kruppa 2004). These experimental results determined the heat release rate (HRR), the mass loss rate, the heat flux, temperatures and other quantities inside and outside the car inevitable for fire description. CFD simulations of car fires focus mainly on smoke propagation (for example Deckers et al. 2013) as the smoke pose the main threat for people's safety.

Prevailing approach in the literature is to model the source of fire (usually burning cars) as a pool fire, i.e., with a constant or prescribed HRR. This approach is well justified by the need for a well-defined fire source in order to compare the performance of different ventilation systems. However, in some cases a mutual interaction between the fire and the ventilation (or sprinklers) must be taken into account and the assumption of prescribed HRR not depending on air flows is of limited use. In (Weisenpacher, Glasa, and Halada 2016) we elaborated the model of passenger car with its interior modelled in detail and with specified parameters of corresponding materials for the purposes of computer simulation of passenger car fire by Fire Dynamics Simulator (FDS). The reliability of such car representation is based on comparison with the results of full-scale experiments carried out in open air in Povazsky Chlmec (Slovakia) in 2009. The experiments included a fire in car interior and its spread to an adjacent vehicle (Polednak 2010; Svetlik 2010). During this experiment, temperatures inside and outside passenger compartment were measured to be used for the calibration of computer simulation. Subsequent simulations confirmed credibility of this model.

The model enables to simulate the fire of passenger car located in a car park or a tunnel and to capture the response of the fire on ventilation performance. Similar approach was used in (Partanen and Heinisuo 2013) to investigate the effect of sprinklers on fire of three cars in a car park. Due to significant computational requirements caused by the combination of fine mesh resolution and large dimensions of compartments in which fire occurs, parallel computation is inevitable for practical purposes. However, the process of parallelization in FDS leads to a loss of accuracy. The performance and accuracy of FDS simulations, version 5.5.3 is evaluated in (Weisenpacher, Glasa, and Halada 2016). For practical applicability and validation of simulations performed by new versions of the simulation software it is also necessary the ability to evaluate and compare the results of simulations executed by different versions of simulation software, especially if new models of particular phenomena or improved computational algorithms are included in the new version. Such comparison may lead to an important adjustment of the used geometrical representation of burning objects or their material properties and to enable significant improvement of the simulation accuracy. In this paper, we compare the performance and accuracy of parallel computation performed by the

FDS versions 5 and 6 and discuss specific features of the simulated fire behaviour.

2. MANAGEMENT OF SIMULATION RUNS

Fire Dynamics Simulator is CFD simulation system capable to simulate fire-driven fluid flow, developed at National Institute of Standards and Technology (NIST), USA (McGratten et al. 2010; McGrattan et al. 2013).

FDS is a Fortran program solving conservation equations that describe the evolution of fire. It reads input parameters from a text file, computes a numerical solution to the governing equations, and writes user-specified output data to files.

FDS has been developed to run on a variety of hardware platforms under operating systems MS Windows, Mac OS X and Linux. The employed computer ought to have fast processors (CPUs) – this will determine how long the computation will take to finish, and at least 4 GB RAM per processor – this determines how many mesh cells can be held in memory. To save the output of the calculation a large hard disk is required, since the results can consume more than 1 GB of storage space. FDS supports the configuration of various programming models – a serial model, designed for running on a single computer, and several parallel models, designed for running on multiple computers. There are three ways to execute FDS in parallel:

- OpenMP (Open Multi-Processing), model exploits multiple cores on a single computer or a compute cluster node (OpenMP, Internet source).
- MPI (Message Passing Interface) model exploits multiple processors distributed over the computers on a network or cores embodied in a compute cluster. In this case the computational domain must be divided into multiple meshes and typically, each mesh is assigned its own MPI process (Open MPI, Internet source).
- Combined MPI and OpenMP model, where each MPI process can be supported by OpenMP threads. This approach enables a two-level parallelization: at first, the computational domain is break up into multiple meshes (MPI), and then within each mesh the multi-threading (OpenMP) on some selected code regions is applied.

Most of the speedup is achieved by the MPI which is the better choice for multiple mesh simulations. OpenMP works best when exploiting multiple cores associated with a single (physical) processor or a node socket. It can speed the calculation by an extra factor up to about 2.

Simulations were performed using the FDS package versions 5.5.3 and 6.1.2. Both have been installed on the HP compute cluster (SIVVP, Internet source) located at the Institute of Informatics, Slovak Academy of Sciences, Bratislava. The cluster consists of 54 compute nodes, each comprising of two 6-core processors Intel E5645 @2.4 GHz, 48 GB of RAM and 2x500 GB scratch disks. All nodes are connected by the Infiniband interconnection network with the bandwidth of 2x40 Gbit/s per link and direction. In addition, the cluster includes 10 nodes with GPU accelerators NVIDIA Tesla K20 interconnected via the 8 Gpbs Ethernet network, two 72 TB disks, and several managing servers. The cluster is running the OS Scientific Linux.

For comparison purposes the source code of FDS 5.5.3 was compiled using two compilers: the GNU 4.4.7 (gfortran, gcc, OpenMP) and Intel 14.0.1 (ifort, icc, OpenMP). The source code of FDS 6.1.2 was compiled using the compiler Intel 14.0.1. Parallel models of FDS are built with Open MPI version 1.10.0.

The evaluation of simulations results requires carrying out a great number of experiments. In order to facilitate and automate the whole simulating process, for each model we have developed a couple of command line scripts, called *fds-manager* scripts, which enable the user in an efficient way to submit FDS jobs to the cluster. Scripts are created in the Shell language including submission commands of the underlying middleware. By default, the execution of jobs on a local cluster is performed through the PBS (Portable Batch System, Internet source) that represents a workload management system providing a unified batch queuing and job management interface to a set of computing resources. The *fds-manager* script is responsible for the accomplishment of the following actions:

1) Initially, it accepts and checks the given input parameters specifying the FDS input file and asked cluster configuration: the number of nodes and cores, and eventually, the number of MPI processes and number of OpenMP threads. Parameters values are used in the subsequent operations.

2) Based on given input parameters, it produces the description of the application, called *fds-submission* script, which serves as the input to the submission command “PBS *qsub*”. The *fds-submission* files are written in Shell including PBS commands.

3) Finally, it provides for the execution of the FDS simulation using the previously generated f*ds-submission* script. Each simulation instance is running in its own working directory.

The complete execution of the FDS simulation is realized by the invocation of the appropriate *fds-manager* script accompanied with the input parameters.

3. CAR FIRE EXPERIMENT AND ITS FDS SIMULATION

In November 2009 we performed a full-scale experiment of a passenger car interior fire in open air and its spread to an adjacent vehicle (see Fig. 1). The experiment was conducted in the testing facilities of the Secondary School of Fire Protection of the Ministry of Interior of the Slovak Republic in Povazsky Chlmec (Polednak 2010, Svetlik 2010). The fire was initiated in a new functional car Kia Cee'd. The right front and left rear side windows were broken in order to increase the oxygen supply. The second car was an older model of BMW, located lengthwise in the 50 cm distance. Gas temperatures inside and outside the cars were measured by thermocouples. The fire behaviour was observed and recorded by infra-red and digital cameras.

Figure 1: Fire experiment in Povazsky Chlmec

The fire was ignited by burning of a small amount of gasoline (about 10 ml) placed onto the back seat behind the Kia driver's seat. The fire grew progressively and after flashover at the 150 s into the fire the whole passenger compartment of the Kia was involved. During the next minutes remaining car windows were broken and the temperature inside the interior reached the value of 1000°C. After 7 minutes the rubber sealing of the nearest window of the BMW ignited. The fire was suppressed after 12 minutes of the experiment. The fire scenario was subsequently simulated by FDS.

The simulated scenario includes two cars in configuration corresponding to the experiment (see Figures 2, 3). The first car model includes the interior equipment consisting of seats, a dashboard with a steering wheel and interior lining. This equipment is modelled by two materials: ‘UPHOLSTERY’ for seats and ‘PLASTIC’ for other equipment. The fire source is represented by a 6 x 6 cm burning surface with the 1000 kW.m^{-2} heat release rate per unit area (HRRPUA) placed on the back seat. The second car includes a window rubber sealing at the place where ignition was observed during the experiment. According to the experimental observation its interior does not burn in the simulation. Material properties and the conditions of windows breakage are discussed in detail in (Weisenpacher, Glasa, and Halada 2016) in which FDS 5.5.3 simulation of the described scenario is performed and evaluated and the accuracy of the burning car representation is tested.

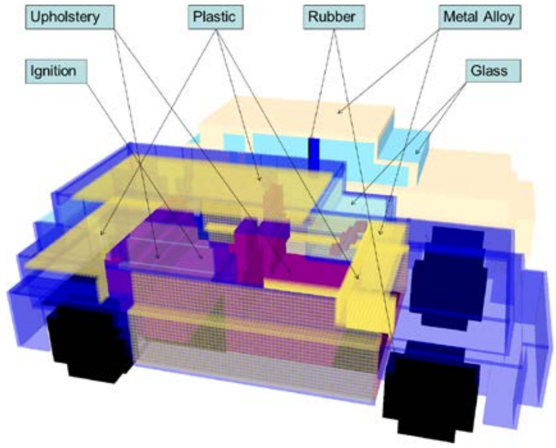

Figure 2: Car representation and used materials

In order to compare both FDS versions correctly, three modifications of the simulated scenario were made. First, we used more intensive initial fire to fulfil condition required by (McGratten et al. 2010) relating fire HRR and computational mesh resolution which is sufficient for accurate simulation (the condition is not fulfilled for less intensive experimental fire). Nine times more intensive fire produced by 18 x 18 cm burning surface with the same HRR prevents small random fluctuation of particular quantities, as discussed in (Weisenpacher, Glasa, and Halada 2016). Second, the duration of the simulated fire is 420 s to avoid extremely long CPU times. Finally, we explicitly determined chemical reaction ‘ETHYLENE’ (required in FDS 6) for both FDS versions. Due to these differences, simulated scenario outputs cannot be directly compared with the experimental values.

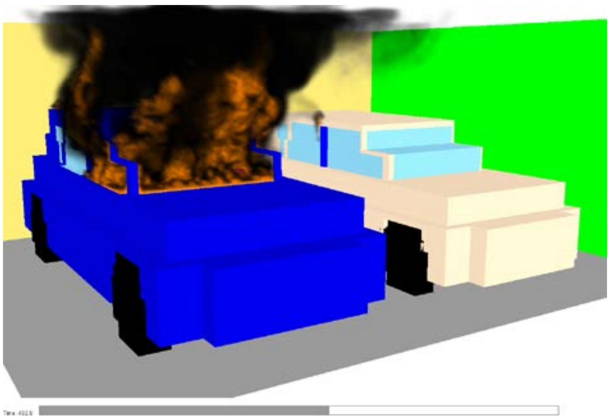

Figure 3: Fire behaviour after 400 s of fire

The computational domain size is 576 x 486 x 240 cm with the 3 cm mesh resolution. The total number of cells is 2,488,320. Sequential calculation (1M) and six variants of parallelisation are evaluated: 12M, 24M, 48M, 96M, 192M and 288M, in which the computational domain is divided into 12, 24, 48, 96, 192 and 288 computational meshes, respectively, each of which is then assigned to one CPU core.

4. SIMULATION RESULTS

4.1. Performance and accuracy of the simulations

The simulation results documenting the performance and accuracy of particular simulation variants executed by both FDS versions are shown in Tables 1 and 2 where t_{400} is the time at which the thermocouple located in the middle of passenger compartment front part (the same place as in the experiment) reached the value of 400°C for the first time, t_{br} is the time at which the windscreen of the first vehicle fell out, and t_{ign} is the time at which the window lining of the second car ignited. The parameter t_{400} indicates the time of flashover inside the passenger compartment.

Table 1: Simulation performance and accuracy, version FDS 5.5.3.

Simulation Results						
	CPU Time [hrs]	Speed up	Efficiency	t_{400} [s]	t_{br} [s]	t_{ign} [s]
1M	444.1	1.00	1.00	50	132	281
12M	58.9	7.54	0.63	49	131	288
24M	30.5	14.55	0.61	52	138	285
48M	15.9	27.95	0.58	51	135	289
96M	8.80	50.48	0.53	51	137	286
192M	4.32	102.9	0.54	79	175	-
288M	2.92	151.7	0.53	81	174	390

Table 2: Simulation performance and accuracy, version FDS 6.1.2.

Simulation Results						
	CPU Time [hrs]	Speed up	Efficiency	t_{400} [s]	t_{br} [s]	t_{ign} [s]
1M	975.1	1.00	1.00	50	129	-
12M	208.2	4.68	0.39	44	121	-
24M	111.3	8.76	0.37	43	129	-
48M	63.1	15.46	0.32	41	126	-
96M	36.2	26.92	0.28	42	126	-
192M	21.1	46.05	0.24	43	127	385
288M	14.78	65.97	0.23	43	124	-

CPU time of FDS 6 sequential calculations is about 2.2 times longer than in the case of FDS 5 simulations, which is consistent with (McGrattan et al. 2013). Moreover, the values of speed up of FDS 6 parallel calculations are lower and their efficiency decreases more considerably than for the corresponding values obtained by FDS 5. CPU time of FDS 6 288M calculations is about 5 times longer than the CPU time of the corresponding FDS 5 calculation. The probable reason is larger information transfer between mesh boundaries (i.e., between nodes) which increases the simulation accuracy at increased cost of CPU time.

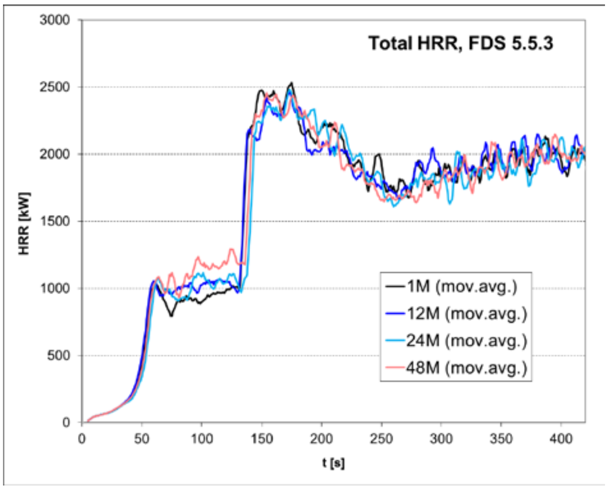

Figure 4: HRR simulated by FDS 5.5.3 for decompositions up to 48M

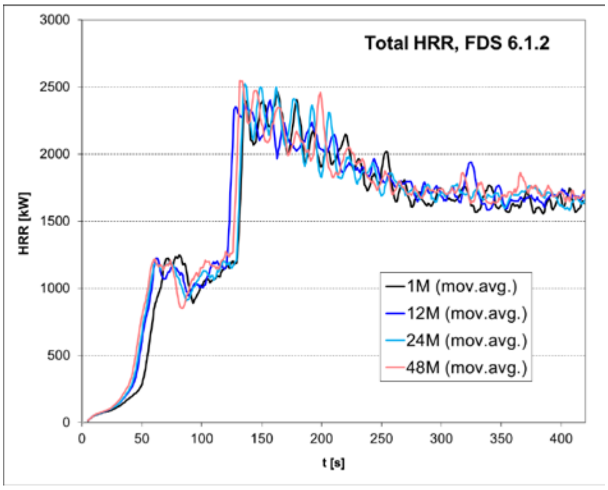

Figure 5: HRR simulated by FDS 6.1.2 for decompositions up to 48M

4.2. Heat Release Rate Behavior

Figures 4 – 7 show the HRR of simulations, which is the main quantity characterising the fire. The behaviour of 1M simulations during the first 250 s of fire is very similar for both FDS versions. The HRR increase at about 50 s into the fire is caused by the flashover in passenger compartment, while the HRR achieves the value of about 1MW. It is succeeded by another considerable HRR increase at about 130th s caused by a windscreen glass breakage and fall out which increases the HRR above 2.5 MW. Subsequently HRR decreases. After 250 s the fire behaviour starts to differ in both simulations and FDS 6 provides slightly lower values of HRR, probably due to the new turbulent combustion model leading to different results in under-ventilated compartment containing the objects which burn out. In the consequence of lower HRR the second car does not ignite in the simulation.

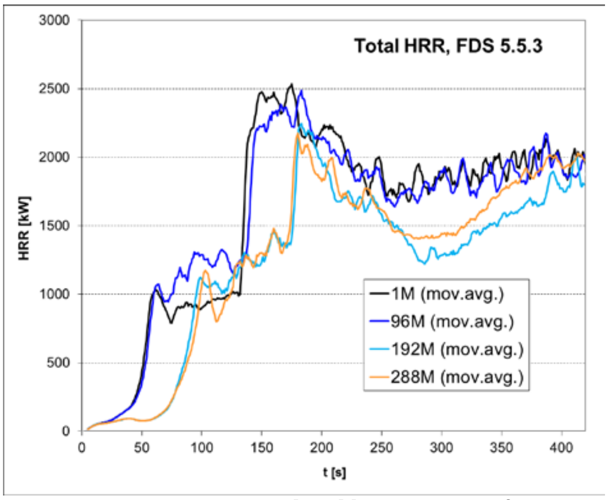

Figure 6: HRR simulated by FDS 5.5.3 for decompositions exceeding 48M

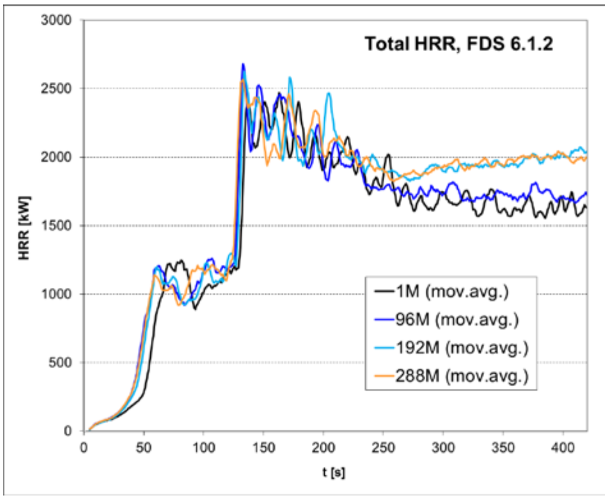

Figure 7: HRR simulated by FDS 6.1.2 for decompositions exceeding 48M

Parallel calculations of both FDS versions lead to very similar results as it is in the case of corresponding 1M calculation up to 96M (see Figures 4 - 7). The differences in the simulations 192M and 288M are more considerable and the simulation errors increase, although in FDS 6 they are significantly smaller (see Figures 6, 7). FDS 5 parallel calculations tend to delay fire behaviour (Weisenpacher, Glasa, Halada, Valasek, and Sipkova 2014) as can be seen in Table 1, columns 5 – 7. On the contrary, FDS 6 parallel calculations accelerate it slightly (Table 2, columns 5 – 6). While delays in FDS 5 increase relatively gradually with increasing mesh number, the differences between FDS 6 calculations look random. Even 12M simulations is distinguished by 6 s acceleration of the time of flashover in comparison with sequential simulation, which is a significant difference; however, in simulations containing more meshes this error is not considerably larger. Therefore, the impact of larger parallelisation on simulation accuracy is smaller in FDS 6. The values of energy released during the fire by particular simulation variants and their relative changes in comparison with sequential calculation illustrate this tendency as well (see Tab. 3, column 5).

Table 3: Energy released during the fire by particular simulation variants and its relative change in comparison with sequential calculation

	Released Energy			
	E_{FDS5} [MJ]	d_{FDS5}	E_{FDS6} [MJ]	d_{FDS6}
1M	663.0	0.00	624.9	0.00
12M	665.1	0.00	646.6	0.03
24M	653.3	-0.01	640.9	0.03
48M	662.5	0.00	649.9	0.04
96M	660.4	0.00	650.9	0.04
192M	515.7	-0.22	689.2	0.10
288M	537.0	-0.19	694.1	0.11

4.3. Temperatures Evolution

The evolution of temperatures inside the passenger compartment and the impact of parallelisation on it show similar patterns as can be observed in HRR behaviour (see Figures 8, 9).

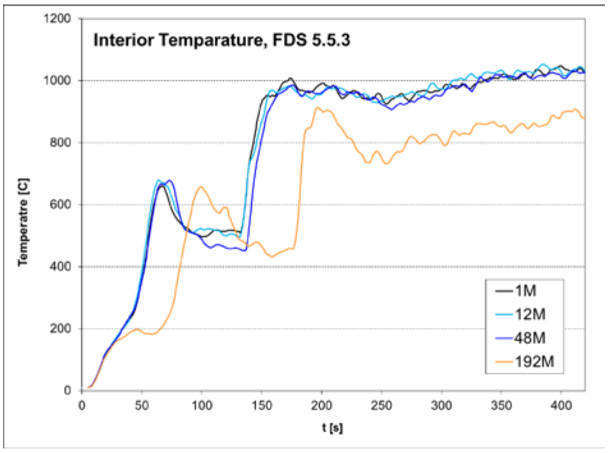

Figure 8: Interior temperature simulated by FDS 5.5.3

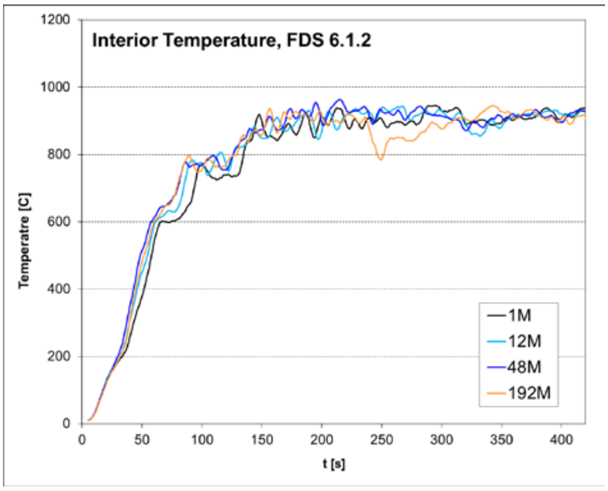

Figure 9: Interior temperature simulated by FDS 6.1.2

After initial gradual increase, temperature drops temporarily after flashover due to insufficient oxygen concentration. In FDS 6 simulation the drop is less pronounced. Temperature increases again after windows fall out and finally reaches the values corresponding to the fully developed state of fire. The most important difference between both FDS version is significantly lower interior temperature of this state simulated by FDS 6. The temperature difference between both versions is about 100 °C. The errors influenced by parallelisation are almost negligible in FDS 6 simulation, while in FDS 5 simulation significant deviations can be observed in the case of the 192M simulation.

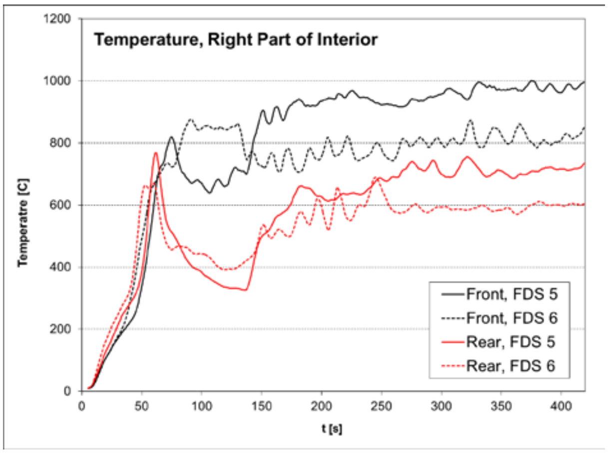

Figure 10: Temperature in the right part of car interior simulated by FDS 5.5.3 and 6.1.2

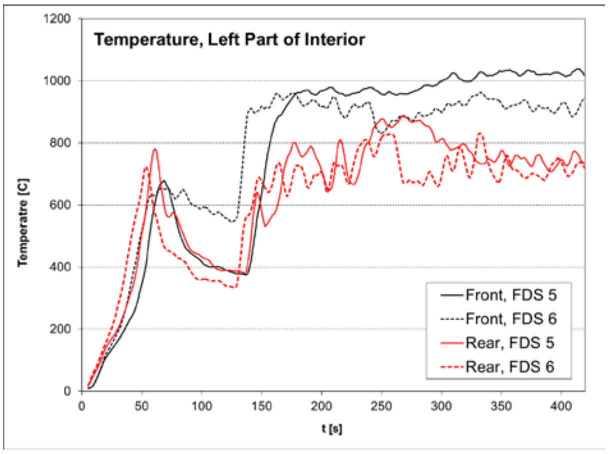

Figure 11: Temperature in the left part of car interior simulated by FDS 5.5.3 and 6.1.2

However, this behaviour does not capture differences between the evolutions of temperature in different parts of the passenger compartment. Figures 10 and 11 show the temperature behaviour in the front left, front fight, rear left and left right part of the passenger compartment. Fig. 12 shows gas temperature in the horizontal cut of car interior (20 cm under the roof). It can be seen that the temperature differences between both versions in the right part of the interior are significantly higher than in the left part. Table 4 quantifies these differences.

Note that rear right window of the car was set "unbreakable" in the simulation, considering experimental observation that the window remained intact up to the 10th minute of the fire. Therefore, the right part of the compartment is more under-ventilated than the left part, which supports the hypothesis that FDS 5 overestimates the temperatures in under-ventilated compartment fires, while FSD 6 prevents such error.

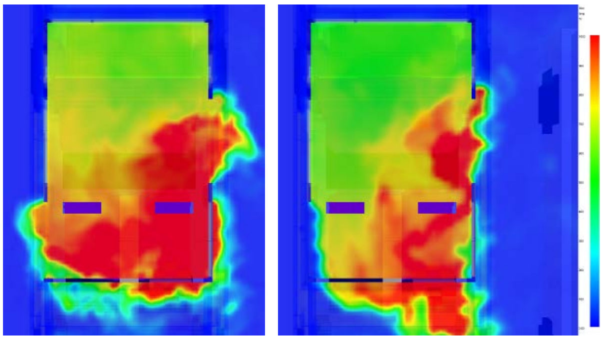

Figure 12: Gas temperature in the horizontal cut of car interior (20 cm under the roof) simulated by FDS 5.5.3 and 6.1.2 at the 350th s of fire.

Table 4: Average temperatures during the last 250s of the fire in different parts of the passenger compartment by both FDS versions and their differences D_{56} and relative differences d_{56}.

Average temperatures				
	FDS 5	FDS 6	D_{56}	d_{56}
Front, right	956	796	160	0,17
Front, left	993	914	79	0,08
Rear, right	689	591	98	0,14
Rear, left	774	723	51	0,07

CONCLUSION

Series of parallel simulations of passenger compartment fire have been performed by FDS versions 5.5.3 and 6.1.2. Simulations have confirmed and quantified several differences between the results obtained by both FDS versions. Due to a larger information transfer between computational mesh boundaries in parallel computations the FDS 6 simulation accuracy is preserved at the cost of lower parallel efficiency and CPU time. FDS 6 simulation are distinguished by considerable accuracy even when 288 meshes is used, while in FDS 5 simulations accuracy drops more significantly if more than 100 meshes is used.

FDS 6 gives slightly lower values of HRR and temperature in some situations, especially if burning occurs in significantly under-ventilated compartments. These results suggest that the representations of the burning cars and their interiors should be adjusted for use in FDS 6 simulations.

ACKNOWLEDGMENTS

The authors would like to thank to P. Polednak, J. Svetlik, M. Simonova, and J. Flachbart for organizing the car fire experiments and to M. Dobrucky and J.

Astalos for technical support for SIVVP cluster computing. This work was supported by the National Science Foundation VEGA (project No. 2/0184/14) and by Slovak Research and Development Agency under the contract No. APVV-15-0340.

REFERENCES

Deckers, X., Haga, S., Tilley, N., Merci, B., 2013. Smoke control in case of fire in a large car park: CFD simulations of full-scale configurations. Fire Safety Journal, 57, 22–34.

Mangs J., Keski-Rahkonen O., 1994. Characterization of the fire behaviour of a burning passenger car. Part I: car fire experiments. Fire Safety Journal, 23(1), 17–35.

McGratten, K., Baum, H., Rehm, R., Mell, W., McDermott, R., Hostikka, S. and Floyd, J.: Fire Dynamics Simulator (Version 5), Technical Reference Guide, NIST Special Publication 1018-5, NIST, Gaithersburg, Maryland, USA, 2010.

McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., Weinschenk, C. and Overholt K.: Fire Dynamics Simulator, Technical Reference Guide. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition, September 2013

Okamoto, K., Watenabe, N., Hagimoto, Y., Chigira, T., Masano, R., Miura, H., Ochiai, S., Satoh, H., Tamura, Y., Hayano, K., Maeda, Y. and Suzuki, J., 2009. Burning Behaviour of Sedan Passenger Cars. Fire Safety Journal, 44, 301–310.

OpenMP (Open Multi-Processing), API Specification for Parallel Programming. Available from: http://openmp.org/

Open MPI (Message Passing Interface), A High Performance Message Passing Library. Available from: http:/www.open-mpi.org/

Partanen, M. and Heinisuo, M., 2013. Car fires with sprinklers: A study on the eurocode for sprinklers. Proceedings of International Conference Applications of Structural Fire Engineering, pp. 23-28. April 19-20, Prague (Czech Republic).

PBS (Portable Batch System). Available from: http://www.adaptivecomputing.com/ http://www.mcs.anl.gov/research/projects/openpbs

Polednak, P., 2010. Experimental Verification of Automobile Fires (in Slovak). Proceedings of the 4th International Conference on Fire Safety and Rescue Services. June 2-3, Zilina (Slovakia).

Shipp M., Spearpoint M., 1995. Measurements of thes severity of fires involving private motor vehicles. Fire and Materials, 19(3), 143–151.

SIVVP – Slovak Infrastructure for High Performance Computing. Available from: http://www.sivvp.sk/ , http://hpc.ui.savba.sk/

Svetlik J., Flachbart J., 2012. Skip fire from vehicle to vehicle – experiment. Proceedings of the 3rd International Scientific Conference on Safety Engineering and the 13th International Scientific Conference Fire and Explosion Safety, pp.113–118. October 18–19, The Higher Education Technical School of Professional Studies, Novi Sad (Serbia).

Weisenpacher P., Glasa J., Halada L., Valasek L. and Sipkova V., 2014. Parallel computer simulation of fire in road tunnel and people evacuation. Computing and Informatics, 33(6), 1237–1268.

Weisenpacher, P., Glasa, J. and Halada, L., 2016. Automobile interior fire and its spread to an adjacent vehicle: parallel simulation. Journal of Fire Sciences, 34(4), 305–322.

Zhao B., Kruppa J., 2004. Structural behaviour of an open car park under real fire scenarios. Fire and Materials, 28, 269–280.

AUTHORS BIOGRAPHY

Peter Weisenpacher studied theoretical physics at Comenius University, Faculty of Mathematics and Physics, Department of Theoretical Physics, Bratislava, Slovakia and received PhD. in 2003. He works as research scientists at Slovak Academy of Sciences, Institute of Informatics. His current research interests include computational fluid dynamics, fire computer simulation and parallel computing. He participates in various research projects on fire simulation.

Jan Glasa graduated in numerical mathematics in 1986, received the RNDr. degree in numerical mathematics and optimization methods and algorithms in 1986 at the Faculty of Mathematics and Physics of Comenius University in Bratislava. He has received the C. Sc. degree (equivalent to Ph.D.) in computer science at the Slovak Academy of Sciences. He is with the Institute of Informatics of Slovak Academy of Sciences in Bratislava as senior scientist. He serves as head of scientific council of the institute. His current research interests include mathematical modelling and computer simulation of fires and parallel computing.

Viera Sipkova received the M. Sc. degree in mathematics and the RNDr. (Rerum Naturalium Doctor) degree in computer science at the Comenius University in Bratislava, Slovakia. Her research deals with parallel and distributed computing technologies. For several years she has officiated at the Vienna University, where her research efforts were focused on the high performance Fortran compiler and the automatic parallelization of scientific applications for distributed memory systems. At present she works at the Institute of Informatics of the Slovak Academy of Sciences and her main research interests include technologies for high performance computing (cluster, grid, cloud), preferring the development and porting complex scientific applications into a HPC environment.