Computer Simulation of Course of Fire and Their Consequences

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Abstract
The dissertation thesis presents the main results achieved within the author's research in the field of computer simulation of fires realized on high performance computers using Fire Dynamics Simulator (FDS). Analysis of the FDS applicability on modelling of fire course and consequences in selected structures (cinema hall and road tunnel) and modelling of evacuation during road tunnel fire confirmed that FDS is able to model realistically the course of fire and specific phenomena related to the fire. Study of the impact of fire on people evacuation, their movement, behaviour and escape strategies as well as analysis of the impact of the turned and/or higher capacity vehicles occurrence on evacuation are also included. Parallelization of fire simulation by the parallel MPI model of FDS and the impact of parallelization on efficiency and accuracy of the calculation is investigated. A series of new shell scripts for fire simulation execution on the HPC computer cluster at the Institute of Informatics, Slovak Academy of Sciences in Bratislava (Slovakia) in which a set of basic strategies for mapping and binding of MPI processes to computing resources of the cluster were created and the impact of their use on the fire simulation efficiency was tested. The described new knowledge and experience are crucial for accurate, reliable and efficient realization of fire simulation on high performance computers.

Categories and Subject Descriptors
I.6.3 [Simulation and modeling]: Applications;
I.6.4 [Simulation and modeling]: Model validation and analysis

Keywords
computer simulation of fires, FDS system, MPI, high performance computing, shell script, cluster of computers

1. Introduction
The dissertation thesis described the main results of author's dissertation research in the field of computer simulation of fires and their consequences. The research was focused on simulation of fire and its consequences in two selected structures (cinema hall and road tunnel) using the FDS system and modelling people evacuation in road tunnel in fire conditions. Analysis of the impact of parallelization of the calculation realized on high-performance computer systems on the simulation accuracy and efficiency was a part of the research. The main research aim was to achieve new knowledge about realization of computer simulations of fire dynamics and fire effects in selected structures and to analyze problems related to parallelization and efficient realization of fire simulations on computer cluster. Sequential and parallel simulations of fires and evacuation were carried out on high-performance PCs and the high-performance computer cluster at the Institute of Informatics of Slovak Academy of Sciences in Bratislava (HPC cluster). The considered structures, where fire and evacuation were modeled, were selected on the basis of requirements of experts on fire safety in Slovakia.

Nowadays, computer simulation of fire is considered as a significant means of prevention and repression against fires which cause large economic and social damages and endanger people's lives and health. The knowledge on applicability of advanced simulation systems for fire course and consequences modelling as well as the knowledge and experience in the field of efficient and reliable realization of computer simulations and use of high performance computing systems for these purposes are applicable, require and very awaited by community of informaticians, specialists for computer modelling and fire simulation, specialists for management, fire fighting, planning and -prevention of fire and in community of firemen and rescue workers.

The submitted dissertation thesis has a standard structuring. It includes the state of the art of the research field (Chapter 1), dissertation theses formulated (Chapter 2), methodology related to the dissertation (Chapter 3), presentation of the main results of dissertation research (Chapter 4) and conclusions of the dissertation research (Chapter 5). The list of references and three appendices (containing tutorial material about the simulation realization on the HPC cluster and the list of papers related to the dissertation published by the thesis author) are attached as well.
2. State of the art

Progress in the field of fire prevention and fire safety supported by the development of information technologies and software systems capable to predict the fire spread and model fire effects belongs to urgent challenging research problems which have all-society impact. Fire is a complicated and complex phenomenon involving complex physical and chemical processes, such as pyrolysis, combustion, thermal radiation, turbulence, dynamics of gas spread, etc. Modelling of these phenomena, their reliable computer simulation and competent interpretation of simulation results require an interdisciplinary approach, sufficient knowledge of processes related to fire and knowledge of fire models and their implementation in program simulation systems. The fire processes dynamics generally requires a detailed space resolution and small time step of calculation in order to achieve sufficient accuracy of numerical computation. Therefore, large computer performance and memory demands are required. Current simulation systems have already achieved significant level of reliability and credibility for certain applications in the field of fire safety. Computer simulation allows to change parameters of the tested fire scenario according to user requirements. It enables to visualize the fire development from its origin, to visualize its spread, identify and provide to users basic fire parameters in selected places (e.g. the temperature, velocity, smoke, concentrations of toxic gases, etc.) as well as parameters applicable to the fire consequences analysis.

Several classifications of fire spread models [3, 11, 7] and program systems for simulation of processes related to fire [2, 10] are presented with the aim to characterize the type of models implemented in FDS and the type of the FDS system itself.

The FDS (Fire Dynamics Simulator) system [9, 8] belongs to advanced simulation systems in which fire field model is implemented. It models low-speed fire-induced flows with an emphasis on the smoke and heat transfer from the fire. It is supplemented by several models of other complex processes, such as the model of turbulence, combustion, pyrolysis, etc. The system was developed by NIST (National Institute of Standards and Technology, USA) in cooperation with VTT (Technical Research Centre of Finland). It is a free downloadable software; its first version was released in 2000, the current version is the sixth version. The results achieved using the 5.5.3 and 6.3.2 version of FDS are concentrated in Chapters 4.1, 4.2 and 4.3, and in Chapter 4.4, respectively. FDS belongs to advanced simulation systems capable to model the interaction of fire with various types of fire safety systems (such as fire, ventilation, sprinklers, etc.) and the impact of fire on behaviour and movement of people in given area. Fundamental models implemented in FDS are discussed and the system’s main strongpoints and limitations which must be considered during the simulation preparation, realization and interpretation are characterized. FDS involves models of many complex processes associated with fire such as low-speed flows, heat transfer and conduction, pyrolysis, combustion, thermal radiation, turbulence, flames spread, sprinklers activation, heat and smoke detection, suppression and people evacuation. The FDS system solves numerically a form of Navier-Stokes equations for low-speed thermally-driven flow with an emphasis on smoke and heat transport from fire. The mathematical basis of the model is the system of partial differential equations representing the conservation laws of mass, species, momentum and energy, which are adapted for modelling flows with a low Mach number, discretized and numerical solved on rectangular 3D computational meshes by methods of the second order accuracy in space and time. The mentioned well-elaborate model of the fire-induced flows dynamics and 2D and 3D visualization of the course and parameters of fire belongs to the system’s strongpoints. People evacuation from environments threatened by fire are modeled using the Evac program module of FDS. FDS serves as a platform for the Evac module. It allows Evac the direct and easy access to relevant parameters of simulated fire. In the literature, this system is known as FDS+Evac [6]. Thanks to mutual interaction between FDS (fire simulation) and EVAC (evacuation simulation) the impact of fire on behaviour, movement and decision-making of people during the evacuation can be modeled. Individual people are represented in Evac as agents (independent, autonomous entities with their own personal characteristics and escape strategies) whose translation and rotational motion is modeled by the Helbing’s social force model [4] using methods from molecules dynamics modelling utilizing the information about visibility and knowledge of exits and smoke concentration.

FDS has been developed to allow the simulations realization on various computer platforms with various operating systems sequentially or in parallel; for each variant 32-bit and 64-bit versions of FDS are available. To utilize efficiently available computing resources of given configuration, FDS supports four programming model [12]: sequential model, parallel MPI model, parallel multi-threaded OpenMP model and parallel hybrid MPI&OpenMP model. The research was focused on the parallel MPI model that provides the most efficient parallelization. In the parallel MPI model, FDS uses MPI (Message-Passing Interface) [1]. The calculation is carried out as a single parallel job on a distributed memory system. The main strategy is to divide the computational domain into several computational meshes; calculation on each computational mesh is carried out as a single MPI process and communication between MPI processes is provided by MPI. Each mesh is normally assigned to a single MPI process. The procedure for preparation and realization of fire simulation on the HPC cluster as well as the hardware and software equipment used is described in details in the thesis.

3. The main aims of dissertation research

The following scientific aims were fixed:

1. to analyze the state of the art in the field of the dissertation research and elaborate the related methodologies utilized in the field
2. to analyze applicability of FDS for simulation of fire and its consequences in a cinema hall and modelling people evacuation in a road tunnel in fire conditions
3. to investigate selected issues related to parallelization and realization of simulation on HPC cluster.

To achieve the fixed aims, the following tasks were solved:

- to analyze available fire models and simulation systems
• to elaborate methodology related to the thesis
• to prepare input data for computer simulation of fire in a cinema hall, design the simulation parallelization, carry out the simulation and evaluate the simulation results; to describe the fire dynamics and analyze consequences of fire on spectators safety
• to prepare input data for computer simulation of fire and selected evacuation scenarios in road tunnels, design parallelization, carry out the simulation and evaluate simulation results; to describe the fire dynamics in road tunnels and analyze the impact of fire on movement, behaviour and intoxication of people during evacuation
• to study the impact of passenger cars and high capacity vehicles in a road tunnel on the smoke spread and the evacuation course
• to study the impact of turned vehicles on the evacuation course
• to analyse applicability of FDS+Evac for modelling group behaviour of people during evacuation in a road tunnel in fire conditions
• to study the impact of parallelization using the parallel MPI model on the simulation accuracy
• to analyse the impact of the way of parallel fire simulation realization on the HPC cluster on the simulation efficiency.

4. Methodology
Methodical procedures related to computer simulation of fires are discussed in the thesis; focusing on procedures for obtaining the information about fires and on procedures related to fire simulation using FDS. Procedures relating to input data preparation, choice of computational meshes, parallelization of calculation and simulation carrying out on high-performance computers as well as procedure for simulation results processing and interpretation are elaborated as well. Specific procedures related to testing, verification and validation of FDS are also discussed.

5. The main results of dissertation
This part contains the main results of dissertation. In the first part, applicability of FDS for computer simulation of fire and its consequences in the cinema hall is analyzed, illustrating the use of methodical procedures for preparation, realization and interpretation of simulation. In the second part, applicability of FDS+Evac for modelling people evacuation in the case of road tunnel fire is investigated. In the third part, some problems associated with the information loss caused by parallelization of fire simulation using the parallel MPI model, which can lead to the accuracy decrease of simulation results, are illustrated. In the fourth part, efficiency of simulation realization on the HPC cluster is investigated and the effect of several ways of the simulation execution on parallel simulation efficiency is analyzed.

5.1 Simulation of fire in cinema hall
In the field of research of applicability of FDS to computer simulation of fire, we systematically described the input data preparation, realization and simulation results related to a fire in a cinema hall. The cinema hall is furnished by 108 upholstery seats organized into nine rows placed on ascending floor. It has a stage and a curved ceiling (Fig. 1). For the cinema hall geometry preparation, we used the PyroSim graphical user interface. Upholstery was considered as a dominant flammable material. The fire properties of upholstery used in the simulations were verified by previous research (determined by laboratory measurements, validated by large-scale fire experiments with upholstered armchairs and verified by computer simulation using FDS [5]). A 60-second fire scenario with a fire source placed under the 1st seat in the 5th seats row was considered (Fig. 2).

The sequential simulation was realized on a single computational core of a high-performance 6-core personal computer (Intel i7-3930K, 3.2GHz, 64 GB RAM; in the next we will refer to it as PCi7) as a single computational process. The computational domain was divided into 35831808 cube cells forming a 3D cube computational mesh with the 2.5 cm resolution. The used methodical
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Figure 4: Illustration of the MTR measure values at the 4th second of fire for simulations with the 10, 2.5 and 2 cm resolutions. The values on the colour scheme for the 10 cm resolution vary from 0 (blue) to 0.5 (red). The values on the colour scheme for the 2.5 and 2 cm resolutions vary from 0 (blue) to 0.45 (red).

Figure 5: Illustration of the MSR measure values at the 4th second of fire for simulations with the 10, 2.5 and 2 cm resolutions. The values on the colour scheme for the 10, 2.5 and 2 cm resolution vary from 0 (blue) to 0.65 (red), 0 (blue) to 0.5 (red) and 0 (blue) to 0.45 (red), respectively.

Figure 6: Temporal curves of heat release rate for sequential (1M) and parallel (6M) simulations (5-point moving average).

Figure 7: Visualization of gas temperature corresponding to sequential (left) and parallel (right) simulations at the 20th second of fire.

procedures for the input data preparation, parallelization design, simulation realization and simulation results interpretation (described in the thesis’s Chapter 3) were presented in details, including the methodology related to the computational meshes choice, mesh sensitivity study and selected metrics for assessing whether the mesh resolution is fine enough for reliable calculation of the heat release rate and turbulent gas motion (Fig. 3-5).

Analysis of the simulation results focused on the description and visualization of the fire dynamics and characteristic phenomena endangering the spectators’ safety in the cinema hall. The simulation captured formation of toxic gas clouds that were formed after the hit of hot gases layer moving fast below the cinema hall ceiling on vertical and curved obstacles (vertical walls and curved parts of the ceiling). An increased risk for spectators was indicated at the places corresponding to upper rows of seats as well as at the places under the curved part of the ceiling and at the side parts of the cinema hall. The simulation also showed specific behaviour of fire causing that spectators sitting at the seats corresponding to the top row were threatened by increasing temperature (and toxic smoke) much earlier than standing spectators. This threat to spectators was caused by specific shape of the toxic turbulent gas cloud, formed after the hit of the hot gases layer moving fast under the ceiling on the vertical back cinemas hall wall. The fire course and security risk description documented ability of FDS to visualize important parameters of fire such as the heat release rate, flow velocity, temperature, visibility and individual gases concentrations which are useful for analysis of fire effects on spectators and the considered structure. The simulation showed that the ceiling thermal stress was relatively insignificant during the 1st minutes of fire.

For the design of simulation parallelization, the parallel MPI model was used. The computational domain was divided into six 3D cube computational meshes with the same size and resolution (the 2.5 cm resolution). The parallel simulation was realized on PCi7 as a parallel job consisting of 6 MPI processes, which corresponded to calculations on the 6 computational meshes considered.

The parallelization of simulation using 6 computational meshes provided 5.71-time speed up, which corresponds to high quality parallelization (parallel efficiency of 95.1%). The simulation showed that the use of relatively small number of computational cores (computational meshes), does not lead to significant times consumed for communication between individual MPI processes.

We also compared times of the occurrence of some characteristic phenomena in the fire behaviour (time in which smoke hit on the ceiling above the fire source, left curved ceiling, back wall, front wall and right curved ceiling) obtained by the sequential and parallel simulation. Deviations of values of the heat release rate and visualization of differences in distribution of temperature and gas velocity corresponding to sequential and parallel simulation showed that these differences were not significant for the case of smaller number of computational cores (computational meshes) (Fig. 6-7). The knowledge and experience
achieved in the presented study of cinema hall fire simulation are applicable for fire simulation in multiplex (several multi-purpose halls) in the future.

5.2 Modelling of evacuation in road tunnel

In the field of research of applicability of FDS+Evac to evacuation modelling in the case of fire, we carried out a series of computer simulations of fire in a part of road tunnel tube with longitudinal ventilation and single-directional traffic. We considered 180 and 300 m long road tunnel and two fire scenarios that differed by the location of fire source (Fig 8). We considered 5 traffic situations in the 180 m long road tunnel (24 passenger cars; 21 passenger cars, 1 bus and 1 transporter; 20 passenger cars and 2 buses; 24 passenger cars including 1 turned vehicle; 24 passenger cars including 2 turned vehicles) and 2 traffic situations in the 300 m long road tunnel (24 passenger cars; 21 passenger cars, 1 bus and 1 transporter) (Fig. 9).

We designed calculation parallelization using the parallel MPI model and realized the simulation in parallel on 4 computational cores of PCi7. Simulation of the fire course and evacuation was realized on 3 computational cores (3 computational meshes used) and one computational core (one computational mesh used), respectively. The fire dynamics in the tunnel is significantly affected by the tunnel ventilation system and natural air flow in the tunnel tube. Therefore, the ventilation action was included into the fire scenario. The simulation captured a characteristic fire behaviour (fire in semi-closed compartment). Hot gases spread from the fire source upwards, hit on the tunnel ceiling and propagated under the tunnel ceiling in both directions towards the tunnel portals. FDS enables to visualize realistically 3D stratification of smoke (smoke layering) in the tunnel tube and its break caused by natural cooling the layer moving towards the portal and by obstructions for the air flow (vehicles). The quasi-steady air flow in the tunnel at the beginning of the simulation caused fast smoke spread towards the right tunnel portal. Analysis of the fire course in the case of the tunnel without vehicles, the tunnel with vehicles and the tunnel with turned or higher capacity vehicles showed that differences in the fire spread and smoke stratification were relatively small, however, they could have strong impact on the safety risk increase (e.g. reduced visibility in the tunnel, intoxication by toxic combustion products). The fire simulation allowed 2D and 3D visualization of relevant parameters of fire and analysis of their impact on the course of evacuation (Fig. 10).

Figure 8: The 180 m long road tunnel: 3D model, side view and ground plan.

Figure 9: Chosen schemes of the traffic situation.

Figure 10: The course of fire in road tunnel.

Figure 11: Crowding of escaping agents in front of emergency exit.
We made an analysis of the implementation of models of motion, behaviour and decisions of individual people (agents). We also studied the impact of the agent’s parameters setting and his/her/its intoxication on the agents’ escape strategies. The analysis showed that FDS+Evac does not distinguish between "high" and "low" obstructions because both they are represented in one data layer and form an obstruction from motion and seeing emergency exits. However, high obstruction inhibits agents from motion in given direction and from seeing emergency exits and low obstructions inhibit agents from motion, but does not inhibit them from seeing emergency exits. In the case of the road tunnel evacuation modeling, passenger cars can be considered as low obstructions and higher capacity vehicles (because of their height) as high obstructions. Since this problem significantly affects the quality of evacuation results obtained by FDS+Evac (reliability of agents’ escape strategies), we suggested specific method of emergency exits representation (emergency exits as well as tunnel portals) which eliminated the problem partially. The proposed method reflected the implementation of the preferred direction field algorithm and contributed significantly to more realistic motions of escaping agents and more reliable course of evacuation. The simulations demonstrated the ability of FDS+Evac to model crowding of persons in front of emergency exits (increasing risk of injury, prolongation of evacuation times of individual people) and reaction of individual agents to the queue length in front of emergency exits (Fig. 11). The ability of FDS+Evac to model the group behaviour of agents in the case of road tunnel fire was illustrated by an example of movement of four passengers escaping from a given passenger car (Fig. 12). The elaborated study confirm a good potential of FDS+Evac for modelling people evacuation in road tunnels. The system is one of few systems directly modelling the impact of fire on evacuation modelling (strongpoint). It benefits from the agent approach and personalization of agents’ properties which enables to model diversity of people, their parameters, behaviour and escape strategies. The system allows to realize parametric studies of evacuations for a given evacuation scenario choosing some of agents’ parameters randomly; capturing large variability of evacuees and their behaviour. The obtained results can be useful for modelling of people evacuation in large structures with complex geometries (road tunnels, high buildings, etc.). Despite of some mention substantial limitations, FDS+Evac has proved to have a good potential for practical safety applications.

5.3 The impact of parallelization on accuracy

In the field of research of the impact of parallelization on simulation accuracy, we carried out a series of fire simulations in a 24 m long rectangular corridor with the fire source with the 62500 kw/m² HRRPUA and compared differences of results obtained by parallel simulations in regard to results obtained by sequential simulation (Fig. 13-14). The sequential simulation (denoted by 1M) on one computational mesh of the 10 cm resolution and three parallel simulations (denoted by 3M, 6M and 12M) which used 3, 6 and 12 computational meshes of the same resolution and the same size were realized. For the simulation parallelization, the parallel MPI model was used. By comparison of the mean values of temperatures measured by selected thermocouples located at the top part of the corridor which were obtained by the sequential and parallel simulations, we achieved the extent and distribution of the error caused by parallelization of the simulation. It follows from the detailed analysis that in the part of the corridor, where the flows induced by fire were accumulated, the error values for the considered thermocouples did not exceed 5% in that part of the corridor, where turbulent mixing of hot and cold gases was not arises. The extent and fluctuations of errors were influenced by temperature fluctuations and turbulences caused by mixing of hot and cold gases moving fast along the corridor. On the other hand the extent of errors in the part of the corridor with turbulent flows above the fire source, where hot and cold gases did not mix, did not increase significantly. The analysis also showed that although the values of the error caused by parallelization were not significantly high in given fire scenario (because of relatively small number of computational meshes considered), the problem of impact of parallelization on simulation accuracy must be carefully investigated particularly in the cases, where higher degree of parallelism and higher numbers of computational meshes are considered.

In the thesis, the delay of some characteristic phenomena during fire, which is caused by parallelization by the parallel MPI model, and the increase of this delay with increasing number of the used computational meshes are also illustrated. The detail analysis of temperature slices calculated by the sequential and parallel simulations showed, that local differences can be relatively high, however, the main tendencies of fire behaviour and specific phenomena observed in the sequential simulation are maintained also in the parallel simulations in the case of lower number of computational meshes. Therefore, we considered the mean temperature measured by the set of 240 thermocouples schematic ally represent 12 selected thermocouples. The values on the colour scheme vary from 0°C (blue) to 1000°C (red).
5.4 Simulation realization efficiency on HPC cluster

In the field of research of efficiency of the fire simulation realization on computer cluster, we investigated the way of realization of parallel fire simulations by the parallel MPI model on the HPC cluster in Bratislava (Slovakia) and its impact on simulation performance. The HPC cluster is an IBM dx360 M3 cluster consisting of 54 computational nodes (2 6-core Intel E5645 @ 2.4 GHz CPU, 48 GB RAM); the nodes are connected by the In-
finiband interconnection network with the bandwidth of 40 Gbit/s per link and direction. We described systematically basic strategies for the allocation of computing resources of the cluster and analyzed actual variants of simulation realization on the HPC cluster. The analysis of the allocation strategies was focused on strategies for allocation of computational cores of a given cluster node, i.e., for simulations represented by 1-12 MPI processes. In actual executable scripts for the simulations realization on the HPC cluster, only two basic allocation strategies (options -map-by core and -bind-to core and -map-by socket, -bind-to socket denoted by CC and SS, respectively) were implemented. We created four new executable scripts, where other four basic allocation strategies (options -map-by core, -bind-to socket; -map-by socket, -bind-to core; -map-by ppr:n:socket, -bind-to core and -map-by ppr:n:socket, -bind-to socket denoted by CS, SC, SnC and SnS, respectively) were implemented. Then we tested the impact of the implemented allocation strategies on the simulation performance. We carried out a series of computer simulations of fire in a 7.2 m long rectangular corridor with the constant fire source with the 1000 kW/m² HRRPUA on the HPC cluster and evaluated the simulation efficiency. We realized nine parallel simulations represented by 2, 3, 4, 5, 6, 8, 9, 10 and 12 MPI processes using 2, 3, 4, 5, 6, 8, 9, 10 and 12 computational meshes (denoted by 2M, 3M, 4M, 5M, 6M, 8M, 9M, 10M and 12M) (Fig. 15-16). We analysed the performance of simulations realized by all available executable scripts. This analysis showed that four allocation strategies (SC, SS, SnC and SnS) have better performance than 2 other allocation strategies (CC and CS) (Fig. 17). The analysis of computational times showed that the simulation realized by the allocation strategies SC, SS, SnC and SnS have very similar computational times. Similar tendency was observed in the case of simulation realized by the allocation strategies CC and CS. A similar analysis was done for the speedup and the parallel efficiency of the tested simulations (Fig. 18-19). The research results showed that for efficient realization of fire simulation, it is not sufficient only to use the most efficient parallelization model (the parallel MPI model), but it is necessary to take into account also the way of realization of the parallelized simulation on the computer platform available. It was illustrated one the test example that the loss of simulation performance (realized by some less effective allocation strategies) can exceed the value of 30%.

6. Conclusions

The dissertation has brought several new knowledge and experiences in the field of applicability of the program system FDS for the simulation of fire course and fire affects in closed and semi-closed structures (cinema hall and road tunnel) and modelling people evacuation in road tunnels as well as new knowledge about the impact of parallelization on accuracy and efficiency of fire simulation realized on computer cluster. The obtained research results are applicable in the field of fire safety and protection of population and environment. The new knowledge in the field of parallel realization of fires on high-performance computer clusters are considered by the author as the most important contribution of the dissertation because they can contribute significantly to efficient and reliable realization of fire simulations and to credibility of the simulation results interpretation.

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References

Selected Author’s Papers