COMPUTER SIMULATION OF FIRE IN A TUNNEL USING PARALLEL VERSION OF FDS

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Abstract

Using 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 disciplines which examine the ongoing processes in larger sizes, CFD was applied only during the last decade. 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. In the paper, we describe the use of a parallel version of FDS (Fire Dynamics Simulator) for the simulation of fire in a short road tunnel. Several versions of the fire simulation using different ways of computational domain decomposition and different numbers of processors are analysed.

Introduction

Recent large-scale catastrophic events, such as extensive forest fires, fires in high rise buildings, in large-scale parking spaces, or in tunnels, cause enormous material damages and sometimes lead to tragic losses of human lives. Preparedness to alternative rescue procedures against the extreme events is an inevitable prerequisite to mitigation or even prevention of devastating consequences of such events. There are different circumstances, which have influence on a fire occurrence. The increasing numbers of cars on roads, car parks and in tunnels and other human structures are very often a generator of car fires. Unfortunately, there is also an increasing number of fires caused by arson.

Over the last decade, computer simulation of fire has become effective tool for the preparation of rescue work in given fire environment, as well as for fire suppression. Such a simulation enables to visualize spread of fire and its basic parameters, such as temperature, air velocity, heat release rate, smoke transfer, and in some cases it enables to test strategy and effectiveness of fire suppression which may be useful for fire suppression staff.

Fire processes are very complicated and complex phenomenon consisting of combustion, radiation, turbulence, fluid dynamics and other physical and chemical processes. Therefore, using CFD (Computer Fluid Dynamics) theory requires good understanding of all these processes and qualified choice of all input parameters relevant to burning materials, to define the impact of environment and correct initial and boundary conditions. Moreover, existing software tools for fire simulation are composed from many computational procedures based on a discretization of relevant equations. It is important to know limitations of all these numerical procedures. However, computer simulation of fire is the most economical and feasible method to research and analyze fire processes in given particular environment with changing conditions. Very important factor affecting the possibility of wider use of fire computer simulation is computational complexity of such a simulation. Computation of the fire simulation in high buildings, car parks, or in tunnels on mono-processor can take several days. Therefore, application of a correct parallel version of CFD tool for fire processes with an adequate parallel computational system is necessary for practical use.

Number of tunnels is under the course of construction and the length and complexity of tunnel systems is increasing. It has become evident that it is not adequate to rely on traditional empirical approach to design fire protection and security system components. There are already quite a lot of publications dealing with the computer simulation of fires in tunnels comparing simulation results with corresponding full-scale fire experiments. In [1], fourteen full-scale fire tests were carried out during 2000-2001 in the Second Benelux Tunnel near Rotterdam. The tests were designed to assess the tenability conditions for escaping motorists in case of a fire in the road tunnel and to test the effect of mitigating measures on these conditions. In particular, the effects of detection system, mechanical ventilation and sprinklers were also investigated.

Once fire occurs, how to evacuate the people safely and quickly is not only a problem which should be considered carefully by researcher in tunnel fire design but also an important research project emergency scheme for tunnel operation. In [2], a model of people evacuation in tunnel during fire was described. Combination of the fire simulation CFD software PHOENICS and TUNEV model (TUNnel EVacuation) can be used to obtain the fire danger coming time. This is the time when the temperature at the height of people increases to 80°C. Thus, assuming that there are p persons passing the unit width of evacuation passage per unit time and we know the width w of the passage and the number of exits, we can compute the time that all the people pass the evacuation passage [3].

The numerical simulation of tunnel fire by the software FDS (Fire Dynamics Simulator) is presented in [4]. The objective of calculation was to quantify the peak gas and surface temperature that were likely reached over a several hour period during which the spilled tripropylene burned. The peak of calculated temperatures within the tunnel during the first three hours were approximately 1000 °C within the flaming regions, and approximately 500 °C when averaged over the length of tunnel.

The blast effects originating from the rupture of a 50 m^3 LPG pressure vessel in an urban tunnel system have been computed by numerical simulation and presented in [5]. The results show that an open space in the tunnel system has a significant mitigating effect on blast effects. As a consequence of the ingress of a high-velocity jet flow that follows on a primary blast wave, a second blast wave develops in the tunnel section following on an open space.

Detailed analyses of smoke movement from a burning vehicle in a road tunnel have been carried out for the westbound Melbourne City Link tunnel [6]. The time averaged equations for velocity, pressure, temperature and mass fraction of emissions were solved for transient condition using the CFD software tool FLUENT 6.0. Due to the action of jet fans, most of smoke was pushed downstream of the fire. The emissions released from the vehicles in jam, with their engine running, also posed a threat to human health. Therefore, quick evacuation of passengers is essential in the event of fire in tunnel.

Extensive studies about an influence of ventilation rate on fire growth and peak heat release rates in tunnel fires have been published in [7, 8]. Five possible means of fire spread from vehicle to vehicle often over large distance, such as flame impingement, flame spread, spontaneous ignition, fuel transfer (including flow of burning liquid fuels and “fire brands”) and explosion are analyzed. Relatively little research has been devoted to these mechanisms. Therefore, research of all aspects of these mechanisms, as well as the study of appropriate ventilation and its impact on the fire size, fire spread and fire growth is inevitable. It is important to investigate the maximum fire size and conditions under which it might spread to adjacent vehicle, for given longitudinal ventilation velocity to study how the increase of the ventilation velocity would tend to reduce the likelihood of fire spreading to adjacent vehicle. These problems are also the aim of our study.

Simple Fire Scenario in Tunnel

We have constructed a two-lane road tunnel model with dimensions 10 m x 180 m x 7 m (width x length x height, xyz with two fans located on the tunnel ceiling at the distance 50 m and 140 m from the left ending of the tunnel (see Fig. 1). Cartesian coordinate system xyz chosen for the tunnel was x [-5.0, 5.0], y [0.0, 180.0] and z [-5.0, 2.2] measured in meters.

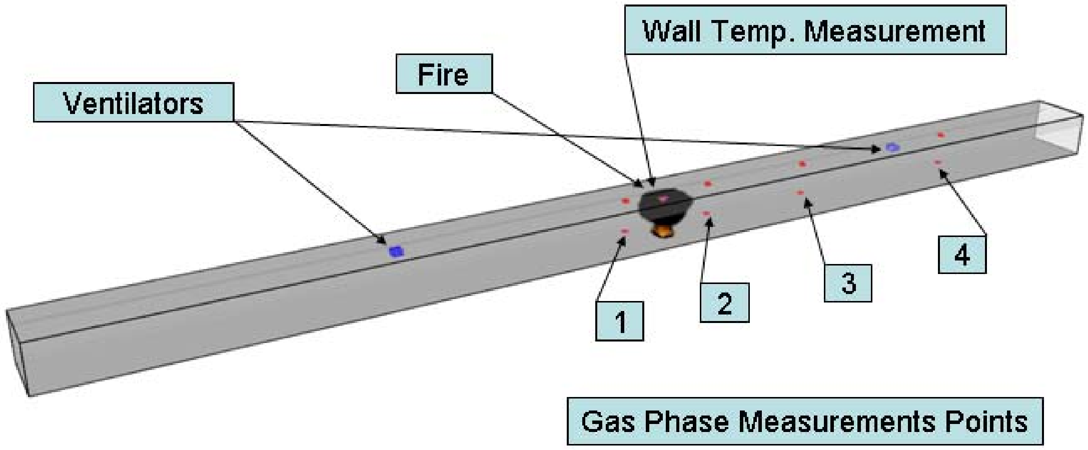


Figure 1. Tunnel model.

Fire source in simulation was represented by burning of flammable liquid in a pool with the dimensions 2 m x 3 m placed in the distance 92 m from the left end of the tunnel. The source of fire was represented by burning 2 x 3 m plate placed 1.1 m above the floor with the Cartesian coordinates x [0.0, 3.0] m, y [92.0, 94.0] m, z [1.1, 1.1] m (see Fig. 1). The maximum heat release rate per unit area (HRRPUA) of the fire was 1666.67 kW and the total heat release rate (HRR) was 10 MW. During the simulation, the fire did not spread along the tunnel, no other flammable obstacles were included in the simulation.

The total time for simulated burning was 150 s. The initial air temperature in the whole tunnel was set to 20 °C. The dynamics of the fire source and the tunnel ventilation was simulated as follows. At the beginning (at $t = 0$ s), both fans started to blow the air with the velocity of 5 m/s in y direction. At time $t = 40$ s, the fire started with linearly increasing power, so that it achieved the above mentioned maximum intensity at $t = 45$ s and then it was not changed until the end of the simulation. 10 s after the fire appearing, i.e., at $t = 50$ s, both fans started to increase their power linearly achieving the maximal air velocity of 20 m/s at $t = 55$ s, which was not changed until the end of the simulation.

Various control devices were installed inside the tunnel in order to record mean values of gas phase quantities (soot volume fraction, visibility, temperature and carbon monoxide mass fraction) inside small testing cube-like volumes placed under the ceiling of the tunnel and at places at human head level (see Fig. 1). The slices of gas temperatures, oxygen and carbon monoxide mass fractions were also recorded for several planes. The wall temperature of tunnel ceiling was detected above the fire.

Parallel Computation with Different Type of Meshes

The fire was simulated on the HP Blade Cluster at Institute of Informatics, Slovak Academy of Sciences, Bratislava using the parallel version 5.5.3 of FDS. This cluster consists of 16 computational nodes, each of them includes two quad-core Intel Xeon X5570 2.93 GHz CPU with 8 MB cache. Each node contains 24 - 48 GB of RAM. The Infiniband interconnection network has the bandwidth of 10 Gbit/s per link and direction.

Five variants of simulation were performed which differ from each other in the way how the whole computational domain was divided into particular computational meshes and/or in cell size inside the meshes. Each computational mesh was then assigned to one CPU core.

Simulation 1M is a sequential simulation. It contains only one computational mesh with the resolution 10 cm. In Simulations 3M and 24M, the computational domain was regularly divided into 3 and 24 meshes in y direction, respectively, whereas the 10 cm mesh resolution is maintained. Simulation 10M includes 2 meshes 60 m long in y direction with 10 cm resolution for outer parts of the tunnel and 8 meshes 7.5 m long with the resolution 5 cm for central 60 m of the tunnel. In Simulation 48M, the domain is divided regularly in y direction into 48 meshes with the cell size of 10 cm x 5 cm x 10 cm (see Table 1). The characteristic fire diameter of the simulated fire is D* = 2.4 m. Therefore, the mesh resolution used in all simulations is fine.

Simulation Results

In this paragraph we briefly summarize main results of parallel computation of the tunnel fire scenario described above. Basic characteristics of all variants of the simulation are shown in Table 1.

Table 1. Tunnel fire simulations characteristics.

Sim	Mesh Division Description	MPI process	Cells [mil.]	Max Cells Per Mesh [mil.]	Time Steps	Wall Clock Time [hrs]	Max/ Min Mesh CPU [hrs]	$c_{(1M)}/c$
1M	1M: 180m, 10cm	Seq.	12.96	12.96	33041	377.2	375.8 375.8	1.00
3M	3M: 60m, 10cm	3	12.96	4.32	31905	172.4	169.5 165.6	0.73
10M	1M: 60m, 10cm 8M: 7.5m, 5cm 1M: 60m, 10cm	10	43.20	4.32	60727	313.6	309.6 289.4	0.80
24M	24M: 7.5m, 10cm	24	12.96	0.54	31206	32.6	32.0 26.9	0.48
48M	48M: 3.75m, 10x 5x10cm	48	25.92	0.54	68759	63.2	61.5 53.8	0.50

Various mesh division choice used in above mentioned five variants have a direct impact onto the computational load and performance. Basic characteristics of all five variants of parallel computation are summarized in Table 1. Its second column describe mesh alignment. In the fourth and fifth column, the total number of rectangular cells and the number of cells per mesh, respectively, for each variant of computation is depicted. The sixth column contains the number of time steps needed in each variant for the simulation of 150 s. Recall that all processors compute in a fully synchronized manner, i.e., the same value of time step is used in each processor for the integration of the system of PDEs in a given parallel cycle. Hence, the difference in the number of parallel steps between particular variants can only reflect the difference in the size of actual time steps used in the integration in these variants. Therefore, the time step value for 10M and 48M is approximately one half of the minimal value for 1M, 3M and 24M. Consequently, the overall parallel execution time of these simulations (see columns 7 and 8) is proportionally larger. Notice that the time step is directly connected to the mesh resolution (see column 2), which, for 10M and 48M, is exactly doubled at least in one direction as compared to 1M, 3M and 24M.

Taking into account these considerations, we can assume that the overall simulation time depend on maximal cells number per mesh (N_{max}) and minimal resolution used (Res_{min}) as $t_{sim} = c.\ N_{max} / Res_{min}$. Column 9 of the Table 3 depicts the ratio $c_{(1M)}/c$, which roughly characterises the efficiency of parallelisation from the point of view of time savings.

The smoke development and air velocity in y direction at the 50th, 57th, 62.8th, 88th, 120th and 150th second of the simulation 1M is shown in Figs. 2 and 3. The simulation demonstrates that smoke was pushed away from the tunnel region on the left of the fire source by ventilation.

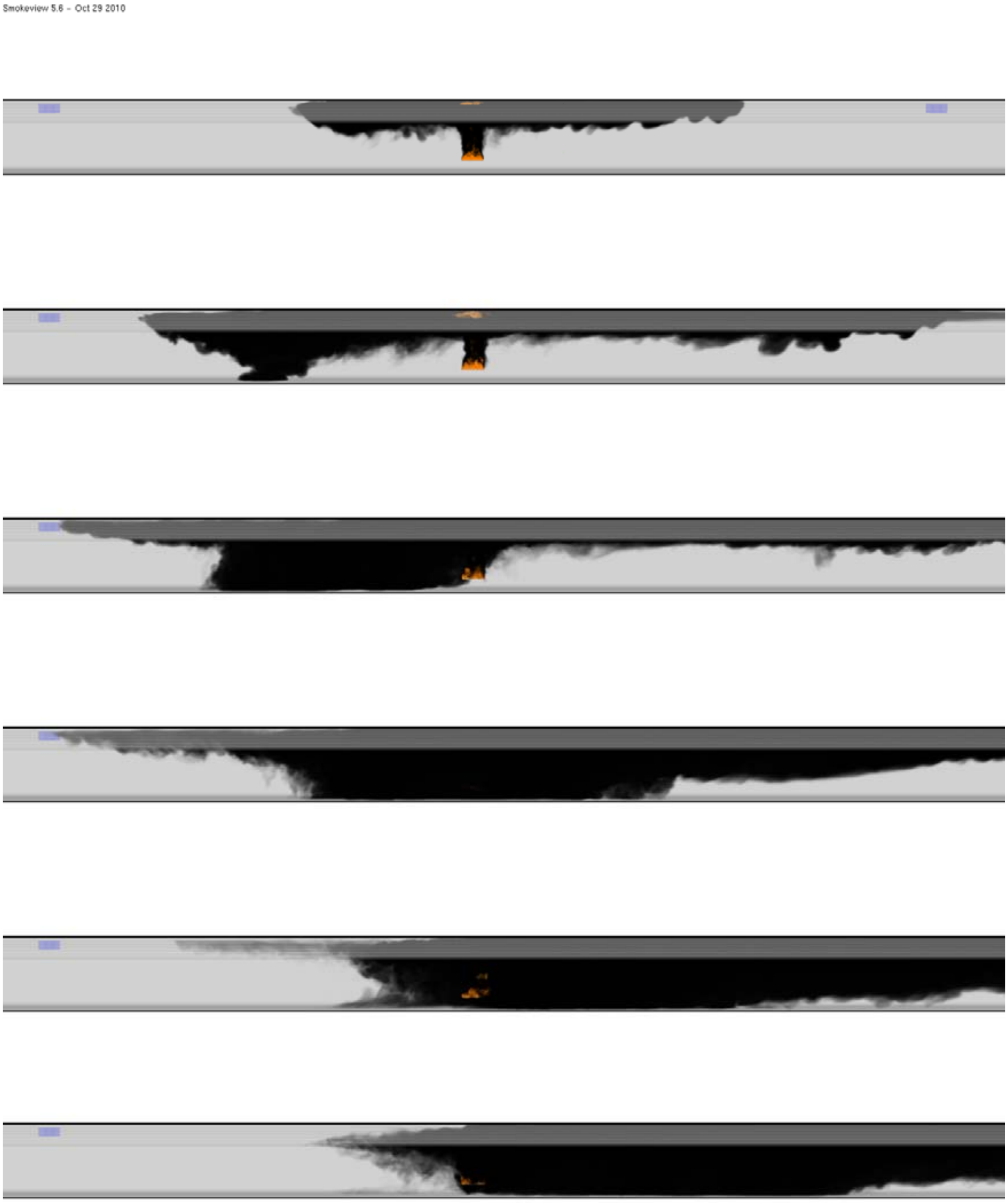


Figure 2. Smoke development.

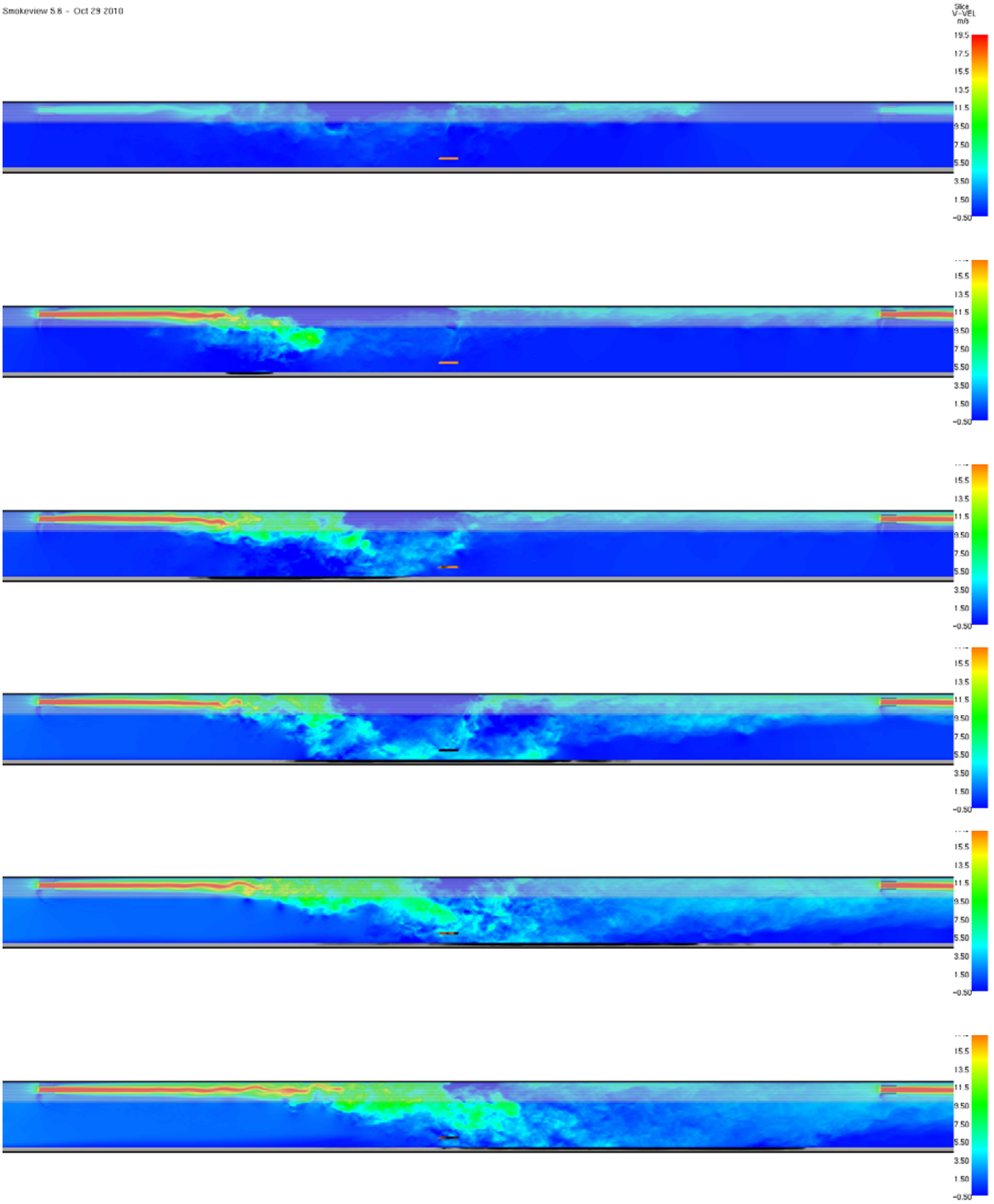
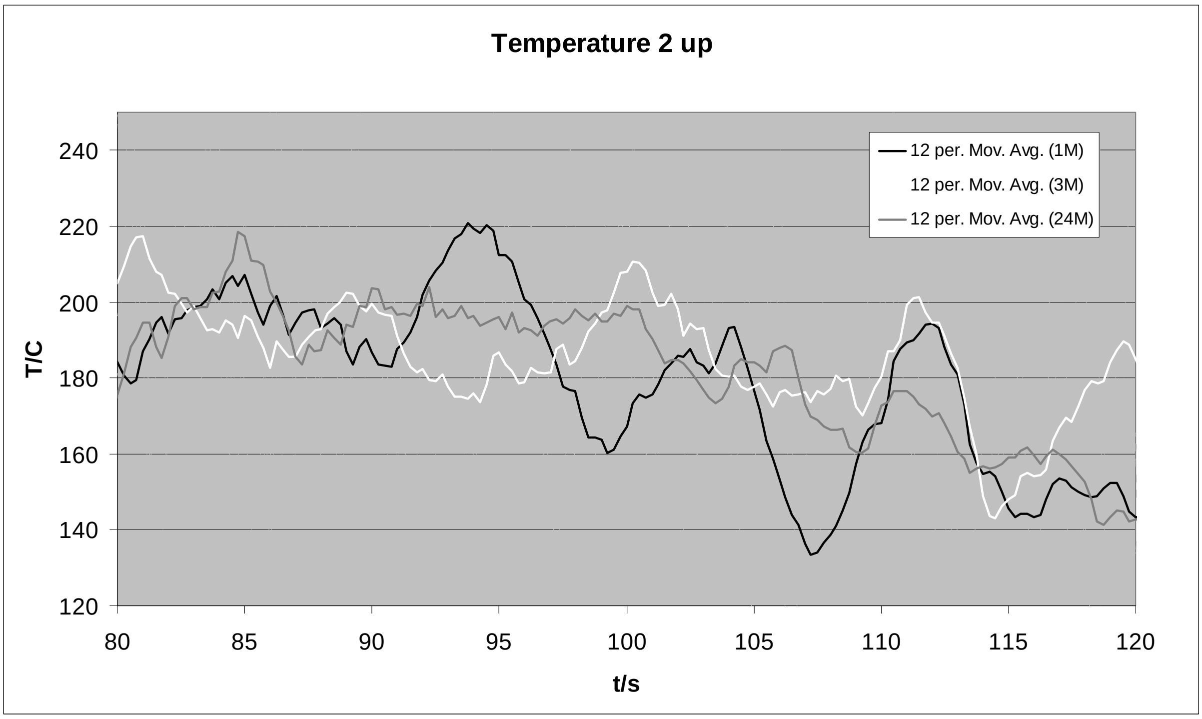
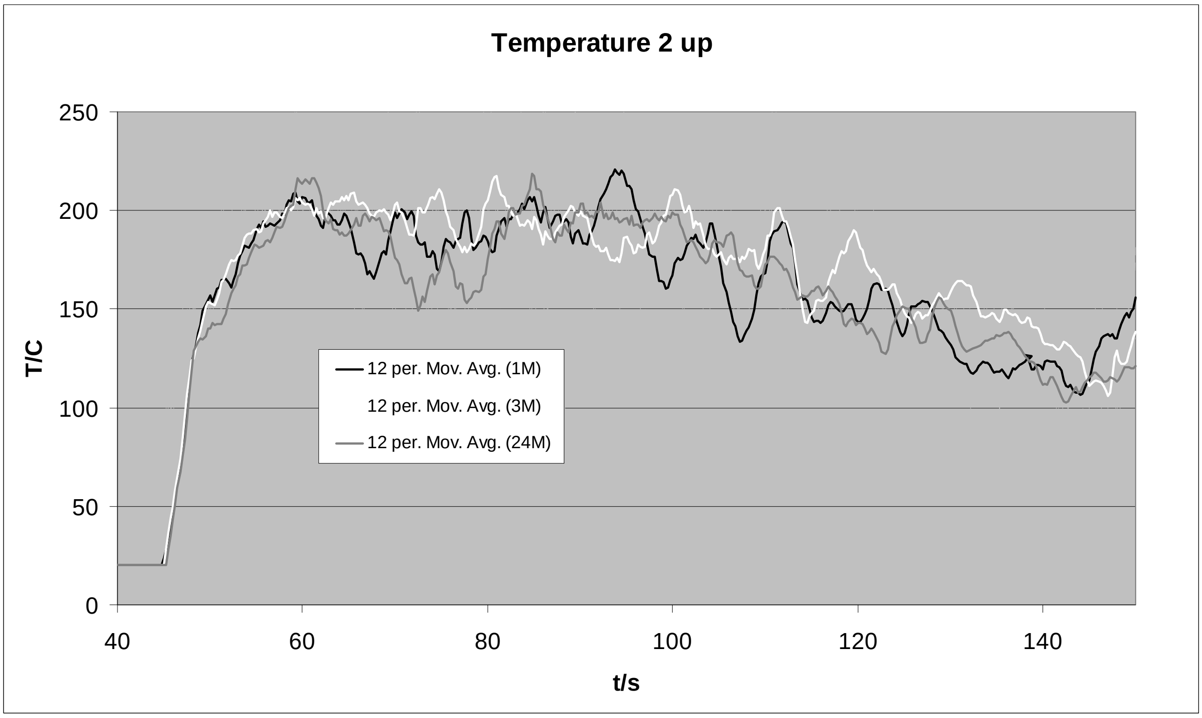


Figure 3. Air velocity in y direction.

The sequential 1M behaviour seems to have larger fluctuations in some phases of the burning, but the shape of the curve seems to be smoother than in the case of parallel simulations (see Fig. 4a). It is probably due to numerical approach used to resolve the processes at the boundaries of the meshes. Nevertheless, the overall behaviour of all simulations is very similar (see Fig. 4b).



(a)



(b)

Figure 4. Selected parts of the temperature behaviour at the thermocouple No. 2. Smooth fluctuations of 1M simulation are visible at (a), while the overall temperature behaviour is in agreement with parallel simulations (b).

Mesh boundaries have the same effect as permeable barriers and slow down the the heat and smoke transfer slightly. At the device point 3, there is a visible lag in temperature increase depending on number of meshes of particular simulations (see Fig 5). The maximum lag is about 1 s (in the distance about 27 m from the fire source). Although this lags affect the simulation precision, their effect is not critical. The impact of mesh boundaries on the computation precision is nontrivial problem which requires another research.

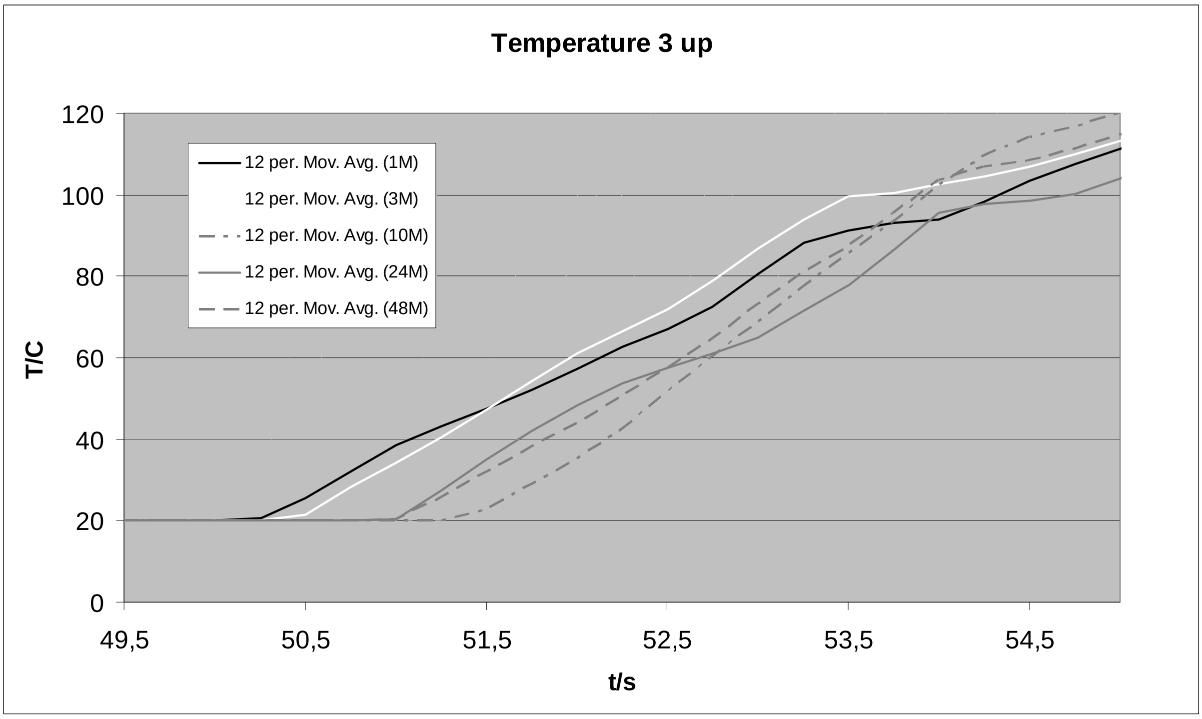


Figure 5. The impact of mesh division on temperature time behaviour lags.

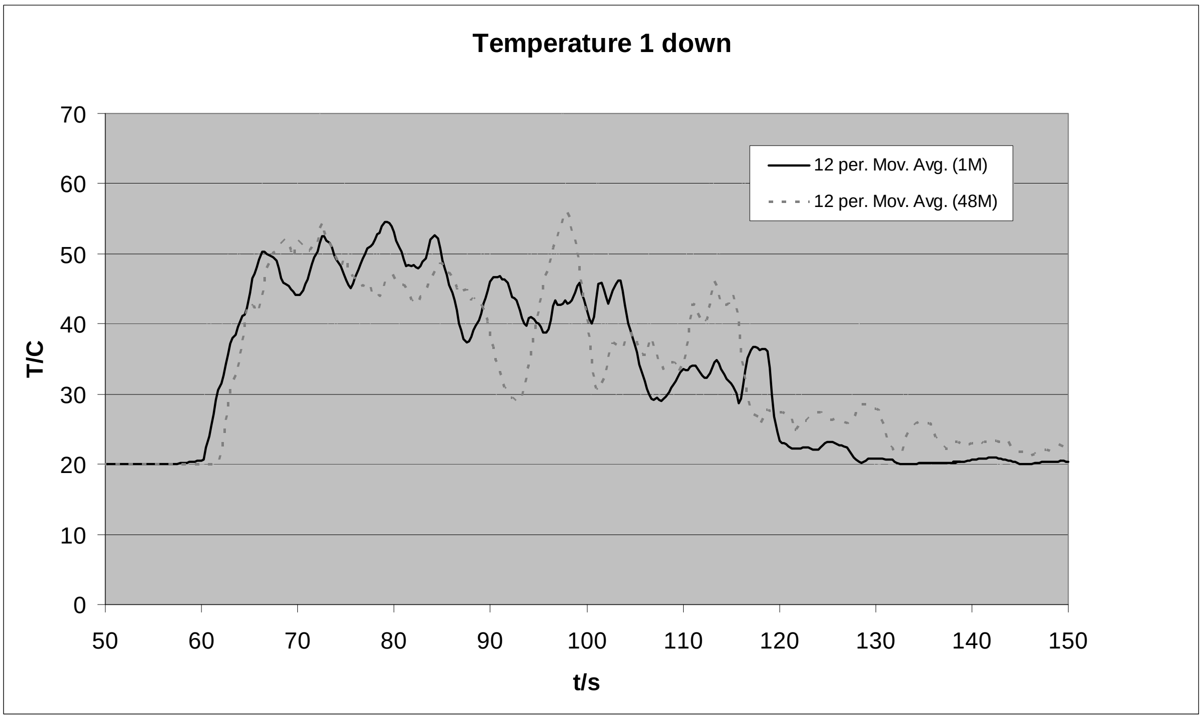
Cells aspect ratio of the simulation 48M is 2:1, which is not recommended by FDS User Guide [9]. Probably this is the cause for physically not well-founded fluctuations which can be observed in the temperature 1 behaviour (see Fig. 6a).

The simulation 48M used very fine division of the computational domain into numerical meshes. However, the impact of this division on overall simulation results was not considerable (see Fig. 6b). It means that FDS should be used for large tunnel simulation with many meshes to obtain reliable fire behaviour description.

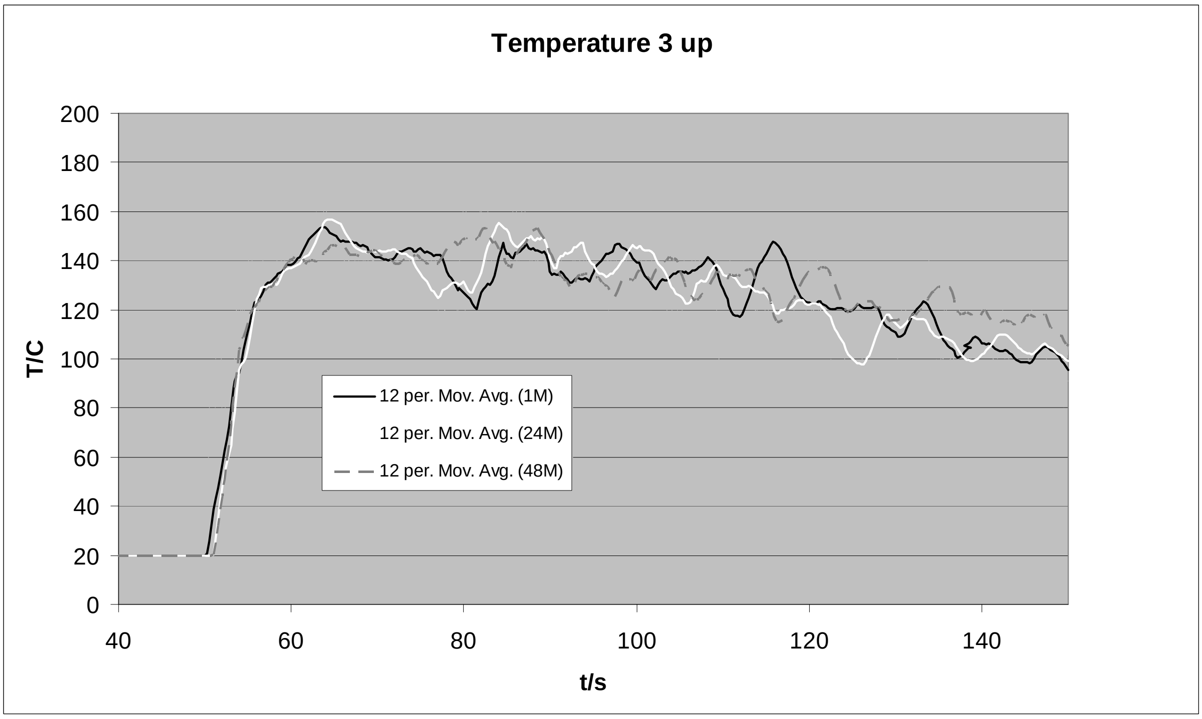
Some quantities show different behaviour according to particular simulations (see Fig 4). The problem of this behaviour requires further investigation. Nevertheless, the simulations provide reasonable rough estimates of these quantities.

Conclusion

In this paper, several parallel versions of smoke transfer simulation in a road tunnel were performed using FDS and the impact of mesh division of computational domain on the simulation results reliability was under investigation. Simulations led to realistic smoke transfer behaviour and confirmed that the used parallel version of FDS is able to provide results with reasonable precision even for simulations with a considerable number of meshes. Therefore, significant time savings can be achieved without severe impact on the simulation precision if the domain division is chosen appropriately. Another research is needed to evaluate the precision of parallel fire scenarios, especially the influence of numerical approach describing the processes on mesh boundaries.

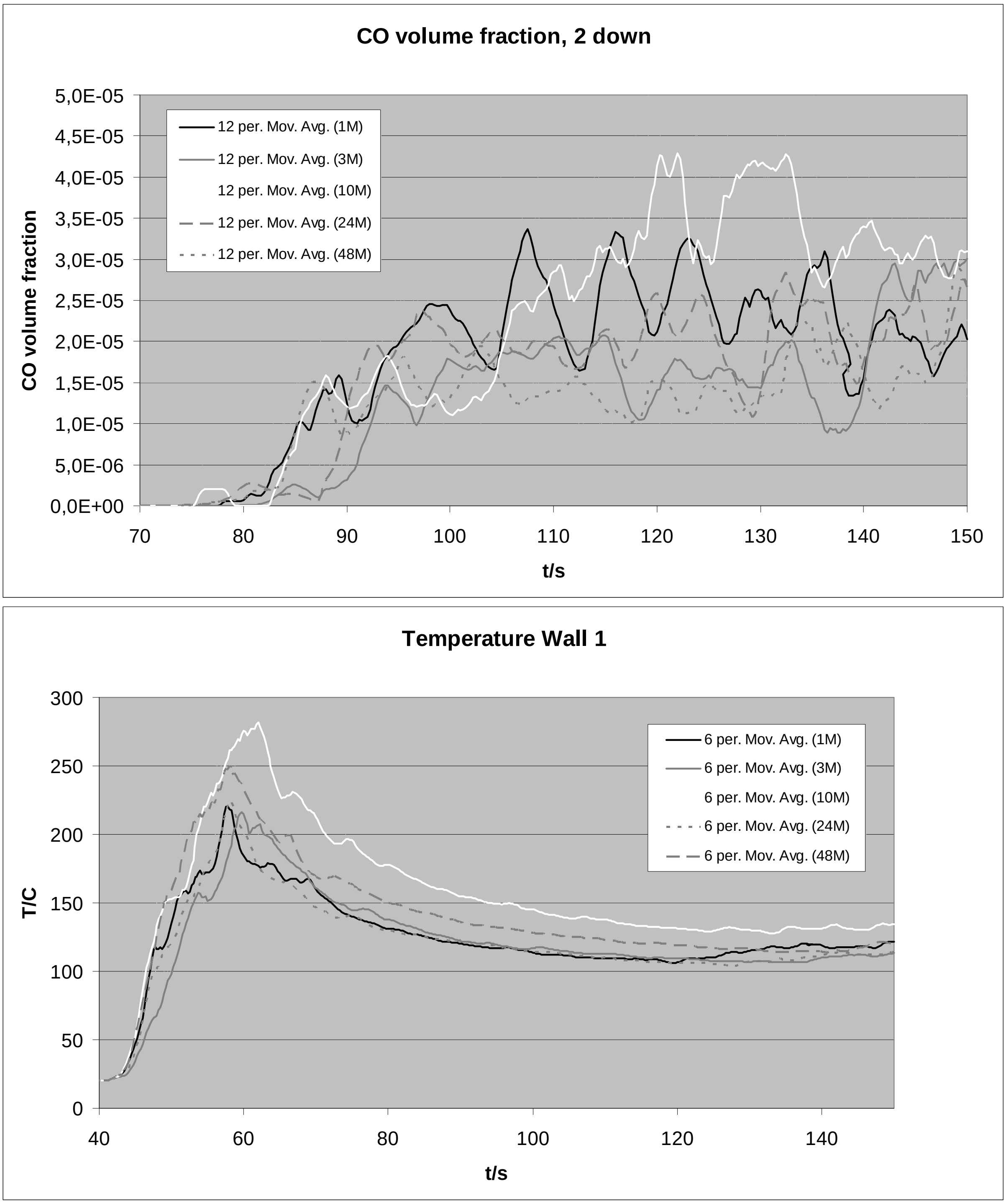


(a)



(b)

Figure 6. Comparison of the simulation 48M behaviour features with other simulations.



(b)

Figure 7. CO volume fraction (a) and the wall temperature above the fire source (b).

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Acnowledgements

The authors would like to thank to our colleagues V. Sipkova, M. Dobrucky and P. Slizik for their technical support during FDS simulations. This paper was partially supported by Slovak Scientific Research Agencies APVV (project APVV-0532-07), VEGA (project VEGA 2/0216/10) and ASFEU (project OPVV CRISIS ITMS 26240220060).