Cinema Fire Modelling by FDS

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Abstract. Recent advances in computer fluid dynamics (CFD) and rapid increase of computational power of current computers have led to the development of CFD models capable to describe fire in complex geometries incorporating a wide variety of physical phenomena related to fire. In this paper, we demonstrate the use of Fire Dynamics Simulator (FDS) for cinema fire modelling. FDS is an advanced CFD system intended for simulation of the fire and smoke spread and prediction of thermal flows, toxic substances concentrations and other relevant parameters of fire. The course of fire in a cinema hall is described focusing on related safety risks. Fire properties of flammable materials used in the simulation were determined by laboratory measurements and validated by fire tests and computer simulations.

1. Introduction

Advances in computer fluid dynamics (CFD) and significant growth of computational performance of current computers have led to the development of fire models which are capable to describe fire in complex geometries and incorporate a wide variety of physical phenomena related to fire [3, 4]. In zone (multi-zone) models appeared in the seventies, the computational space was divided into two separated, relatively homogeneous parts, significantly more or less affected by fire. The theoretical background of zone models were conservation laws of mass and energy supplemented by models of physical processes describing the plumes spread, gas flow through vents, heat transfer and pyrolysis of solid substances. Their relative physical and computational simplicity has led to their widespread use especially for compartment fires analysis. However, in certain fire scenarios, more detailed spatial distributions of physical properties are required. Therefore, CFD models were introduced in the nineties. Such systems allow to describe fire in spaces with complex geometry and incorporate a broad scale of physical and chemical phenomena [4]. They represent a time-averaged approximation of governing equations of fluid dynamics describing the transfer of mass, momentum and energy by gas flows induced by fire. They are based on RANS (Reynolds averaged Navier-Stokes equations) which model low-speed gas flows driven by chemical heat release and buoyancy forces and are referred to in the combustion community as low Mach number combustion equations [3, 11]. Numerical solving of these equations requires to divide the physical space into 3D rectangular meshes, the density of which markedly affects the computational time and simulation accuracy.

Several fire simulators based on CFD models have been developed, such as for instance the CFX, SMARTFIRE and FDS systems. In this paper, we describe the use of Fire Dynamics Simulator (FDS) [8, 9] for potential cinema fire modelling.

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2. Fire Dynamics Simulator

FDS is an advanced CFD simulator intended for fire simulation in variable complex environments. The first FDS version was released in 2000 by National Institute of Standards and Technology, USA; at present, the FDS 5.5.3 version is available. FDS numerically solves a form of Navier-Stokes equations for low-speed fire induced flows with emphasis on transport of smoke and heat from fire. The heart of algorithm is an explicit predictor-corrector scheme of the second degree accuracy according to space and time. Turbulence is modelled by LES (Large Eddy Simulation) which is suitable for simulations in larger spaces. Combustion is modelled using mass fractions (ratios of combustible gasses originated in given place corresponding to all main reactants and products which can be derived from mass fractions of mixtures by laboratory analysis and measurements). Radiation heat transport is modelled by FVM (Finite Volumes Method). For solid surfaces and domain boundaries, thermal boundary conditions and reliable information about fire properties of materials must be entered. Fire suppression and activation of sprinklers and detectors of heat and smoke are also included. The methods, models and their implementation in FDS are completely described in [8]. All simulation inputs (the definition of input geometry, computational meshes, material properties, thermal and boundary conditions for solid surfaces and domain boundaries, initiation fire source, fire duration and the required outputs form) must be concentrated in a single text file. In the case of structures with a complex geometry, the input geometry creation can be labourious and time consuming because all objects in the computational space must conform with computational meshes. FDS has confirmed its usefulness for simulation of fire in structures with higher concentration of people such as theatre [13, 14], supermarket [6], room [7] and office [1].

3. Simulation inputs and fire scenario

Let us consider a 3D model of a cinema (see Fig. 1) consisting of the entrance hall, projection room and cinema hall [12]. The cinema hall has a curved ceiling, podium with 2 small stairways and seating space for spectators constructed as a stairway consisting of nine 20 cm high stairs with chairs. 108 chairs are ordered into 9 rows of chairs (3 rows of 10 chairs, 3 rows of 12 chairs and 3 rows of 14 chairs; the rows and chairs are numbered uplink and from the left, respectively). The cinema input geometry shown in Fig. 1 was created by the graphical user interface PyroSim which enables interactive creating of complex structures geometry using ground-plans and efficient drawing walls, repetitious objects, stairways, curved walls and other complex elements of buildings [12, 2].

![3D cinema model](image)

Fig. 1 3D cinema model (scheme of the building and its interior) and cinema input geometry

A simple fire scenario, in which a fire started under the left-most chair in the 5th chair row during the performance, was assumed. The initial fire source, represented by a hot 0.2 x 0.2 m surface (800 kW/m² HRRPUA, 12 s duration), was placed on the floor under the chair. All walls and chairs were composed of concrete and upholstery material, respectively. Other surfaces in the cinema (the floor, podium, doors, etc.) had specified material properties of inert material. The upholstery material
parameters used in the simulation have been determined by laboratory measurements and validated by fire tests and FDS simulations [5, 10]. For the 12.6 x 16 x 4.8 m cinema, a single computational mesh of 10 cm density was defined consisting of 967,680 cube cells (126, 160 and 48 cells in the direction of x-, y- and z axis, respectively). Simulation would confirm that spectators in the cinema hall would be endangered even during the 1st minute of the fire.

4. Simulation results

Simulation of the 1-minute cinema fire scenario described above was realized on a PC with Intel Core i7 990-X 3.46GHz, 24 GB RAM. The total computational time of was about 2 h 56 min 30 s.

The first plumes appeared already at the first second of fire in front of the 1st chair of the 5th chair row since the floor, chair seat, both side hand rests and the stair, on which the higher chair row was placed, formed a semi-closed space opened forwards. Then, a thin thread of smoke moving quickly up to the ceiling appeared. It reached the ceiling at the 4th s. After the smoke hit the ceiling, it spread under the ceiling and hit the nearer and farther vertical side wall almost immediately and at the 16th s, respectively. At the 7th s, the smoke reached the vertical back wall. The hit of smoke into the vertical and curved vertical obstacles caused its spread downwards, turbulent mixing of quick hot gases with cold fresh air and forming toxic gas clouds at first in the left back corner and the left side part of the cinema hall (see Fig. 2). Later, the toxic gases layer under the ceiling thickened and the toxic turbulent clouds were formed at the back part and under the left curved part of the cinema hall. At the 60th s of fire, spectators sitting in 5 highest chair rows would be endangered by the fire. The simulation captured several specific phenomena appeared during the fire and smoke spread in the cinema hall. It confirmed that the fire of upholstered cinema chairs belongs to very dangerous fires because of its fast development and toxic gases released by the fire.

![Image of fire and smoke spread](image_url)

Fig. 2 Fire and smoke spread under the ceiling and formation of toxic gas clouds: the 11th (top) and 22nd second of (bottom) of fire.

5. Conclusions

In this paper, the use of Fire Dynamics Simulator (FDS) for modelling potential cinema fires is illustrated. A great potential of CFD models implemented in FDS for modelling of fire and smoke and
safety risks evaluation was confirmed. The simulation results indicate that for the given fire scenario, the highest danger in the cinema hall is in its back and left side parts even during the first minute of the fire and that the curved ceiling increases the danger for spectators. A significant advantage of computer simulation for fire simulation and safety risks evaluation is its ability to vary parameters of tested fire scenarios according to user requirements.

6. Acknowledgment

This work was partially supported by VEGA 2/0216/10 and ASFEU ITMS 26240220060 projects.

7. References

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