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Computer Aided Modelling of Compartment Fires – an Overview

Počítačom podporované modelovanie vnútorných požiarov - prehľad

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Abstract:

Several programme environments, computer models, have been developed and used in recent years to model the dynamic of internal fire. It is a very progressive approach, which has its application both in the design of fire safety of buildings, the selection of suitable materials and structures, and the design of effective stable fire-fighting equipment or in the field fire investigation, in verifying concrete scenarios of fire initiation and development. This paper is devoted to detailed description of the issues of modelling itself and modelling of fires as well as individual programme environments used for this purpose, i.e. ARGOS, CFAST, BRANZFIRE, FDS and SMARTFIRE, and their application in safety research and safety practice.

Keywords: *compartment fire, computer aid, fire modelling, review.*

Abstrakt:

V posledných rokoch bolo vyvinutých a používa sa *viacero programových prostredí, počítačových modelov, ktoré umožňujú modelovať priebeh* vnútorného *požiaru. Ide o veľmi progresívny prístup, ktorý má svoje uplatnenie ako pri navrhovaní požiarnej bezpečnosti stavieb, výbere vhodných materiálov a konštrukcií, návrhu účinného stabilného hasiaceho zariadenia či v oblasti zisťovania príčin vzniku požiarov, pri overovaní konkrétnych scenárov vzniku a rozvoja požiaru.* Tento príspevok je *venovaný bližšiemu priblíženiu problematiky modelovania a modelovania požiarov, ako aj jednotlivých programových prostriedkov používaných pre tento účel, t. j. ARGOS, CFAST, BRANZFIRE, FDS a SMARTFIRE, ako aj ich aplikácii v bezpečnostnom výskume a bezpečnostnej praxi.*

Kľúčové slová: *vnútorný požiar, počítačová podpora, modelovanie požiarov, prehľad*

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Introduction

Fire modelling is one of the tools to understand fire behaviour. This tool can be used to verify individual hypotheses, respectively scenarios, fire or description of the course of the fire. For fire modelling several fire models are used. Fire models can generally be divided into three large groups. They are empirical physical and mathematical models. Mathematical and physical models are used to model compartment fires.

Empirical models [1] are based on experience (empiricism) gained from observations of previous fires and fire tests, which led to derivation of physical correlations and patterns describing fire behaviour under given conditions. The models solve the fire propagation using the 2D coordinates. They are mainly used for modelling fires on large areas, such as forests, meadows, pastures. The basis is the determination of the fire line spread rate with respect to the fire environment. Important is also the type of fuel, meteorological conditions and topography of the terrain (altitude, terrain slope, etc.).

One of the most commonly used methods is the cellular automata method, whereby the area is divided into regular cell structures (typically 10 x 10 m). It is based on an algorithm that allows spread of the fire from a burning cell to neighbouring cells at a discrete time for a given fuel type, meteorological condition, and terrain topology. The propagation of the fire line is calculated according to known physical principles.

The vector method uses the elliptical wave propagation principle (Huygens principle). The area on which the fire is modelled is taken as a continuous environment. For selected points on the fire line, Rothermel's mathematical model [2] is applied, according to which the rate of fire propagation is defined based on the reaction intensity (heat release per unit area). Each point on the fire line is a source of fire that is extended to the elliptical area in the immediate vicinity. It is based on an experimentally proven hypothesis that on a flat surface under absence of wind, the fire spreads in a circular line and under wind it spreads in an elliptical line.

Typical for empirical models is: they are intended for fires on large areas (tens of hectares); they realize two-dimensional simulation; they utilize space division into relatively large cells where average parameter values are assumed; they include a very limited range of physics and chemistry of burning and perform a quick calculation (usually a serial computer is enough).

The physical model is an artificially created object by which it is possible to clarify some physical phenomenon or new knowledge. Models to describe the course of the fire attempt to reproduce the phenomena accompanying the fire under simplified physical conditions. Therefore, no physical model captures all aspects of the real phenomenon and cannot identify with the real phenomenon. The real physical phenomenon is always more complex than its model. Physical models are also usually more time and cost demanding than mathematical models. [3]

The purpose of physical models [3] is to imitate fire under simplified physical conditions. While the dimensions of these models vary. The course of fire in real conditions resembles the most large-scale tests. However, their implementation often encounters obstacles, both in terms of cost and complexity in compilation. For this reason, research is also focusing more on exploring the behaviour of fire through models at a reduced physical scale.

Physical modelling does not mean simply performing an experiment on a reduced physical model. A simple (linear) reduction in geometric dimensions is not sufficient. In the reduced model, mechanical, thermal and chemical similarity to the real object must also be kept. The principles necessary to maintain this similarity can be derived from dimensional analysis or from basic equations describing physicochemical phenomena.

Mathematical models are based on numerical solution of differential equations solved for real values or for discretized time or spatial quantities.

Mathematical models are used to model smaller-scale fires in 3D spaces. Their development was conditioned by the formulation of physical and chemical processes occurring during fires. These models are based on the laws of conservation of mass, momentum, energy, and component (state equation), fuel combustion models, and heat radiation. It is quite possible to determine the phenomena occurring at any point in the 3D space, while the individual points are interacting with each other.

In general, mathematical models can be divided into deterministic models in which the course of fire is determined by physical and chemical processes and probabilistic models in which the development of fire is described by a whole set of random processes or phenomena.

Deterministic mathematical models are further divided into zone models, field type models and simulation models.

Zone models began to emerge in the 1970s. Due to the small computing capacities of the computers at that time, a fire in one room was usually simulated. The zone models are considerably simplified, neglecting the heat capacity of the objects in the room, the friction of the fluids, the time needed to transfer the fumes of the fire to the ceiling of the room, etc.

Zone models are generally divided into one-zone and two-zone ones. The two-zone model consists of dividing the room into two homogeneous control volumes, while with one homogeneous space being considered for the one-zone model. The upper, hot control volume in the two-zone model is filled with combustion products, fire cone, and hot air in the upper room layer. The lower, cold control volume is made up of room equipment and cooler air at the bottom of the room, or air being sucked in. Flow patterns within the control volume are not considered in zone models. In the background calculations, the differential equations of mass and energy conservation, the Bernoulli equation dealing with the exchange of gases with the surrounding environment, and the heat transfer equation are solved.

Among the systems based on the application of zone models belong ARGOS [4], CFAST [5], BRANZFIRE [6].

In practice, the field models are often referred to as Computational Fluid Dynamics (CFD) models. The method consists of creating a three-dimensional computing network, while the properties within one cell are constant. CFD models of fire propagation are based on gas dynamics and the experience gained from using CFD computer programmes based on mass, momentum and energy conservation laws. The basis of the calculation are the partial differential equations, i.e. the Navier-Stokes equations, containing the second derivatives by space and the first derivatives by time. These equations solve the fluid flow, the dynamics of the gases induced by the heat released from the fire, considering the frictional internal forces. As a rule, CFD models contain partial models that address fire related processes such as combustion, heat transfer, gas turbulence, etc. Some of the CFD models are based on the RANS (Reynolds Averaged Navier-Stokes) equations, which represent time-approximated fluid flow equations originally designed to describe turbulent flow. The expression of the equations in the CFD models is modified from the original equations, which also describe the phenomena not present during the fire [7]. The described models of fire behaviour are implemented in programme systems, some of which are more specialized in a fire (e.g. empirical models are primarily designed to simulate fires in the natural environment), others are more universal. The most commonly used CFD systems, based on the application of field type models that can be deployed in case of modelling compartment fire behaviour include systems such as Fire Dynamic Simulator (FDS) [8] and its PyroSim and SMARTFIRE graphical interface [9].

1. Programme environments based on zone models and CFD systems suitable for modelling compartment fires

In this chapter, the characteristics of individual zone fire models used for fire and smoke propagation modelling in a compartment are described.

1.1. ARGOS

ARGOS is based on zone model application. It is used to calculate and evaluate the fire risk with the prediction of combustion products spreading, development of temperature during fire, heat transfer, etc. It can model the fire simultaneously in a range of several rooms. It allows to document risk analysis, online presentation of simulation results, includes a system for sprinkler response time calculation and includes fire-fighters arrival time. In the ARGOS archive, the user can select one of the different types of fire (solids fire, liquid fires, fire of a bottle with liquid, solid glowing). In addition, it allows the users to set their own fire input data [10]. It creates output information (texts, tables and graphs), and therefore does not require subsequent processing of results in another programme. It is mainly used by researchers, insurance companies, fire investigators and industrial companies to prevent major industrial accidents.

1.2. CFAST

CFAST represents a consolidated model that allows modelling of fire and smoke propagation in entire space (in all rooms) of a building [5]. It was developed by the Fire Research Division of the National Institute of Standards and Technology (NIST). It is available as a freeware. It is a two-zone fire model that predicts the heat conditions caused by a fire within a rugged structure (it allows to model a fire in up to 30 rooms simultaneously). Each substructure of this structure is divided into the upper and lower gas layers (the zone in the meaning of the fire model zone indicates the layers that are modelled). In a fire, the combustion products are usually propagated by the ascending flue gas stream from the lower layer to the upper layer. The temperature in each layer is the same, and its development over time is described by a set of differential equations derived from the fundamental law of mass and energy conservation. The spread of smoke and heat from zone to zone is based on empirical correlations. Because the equations used to calculate fire and smoke propagation are relatively computationally inexpensive, simulations in CFAST typically only take a few tens of seconds to work with a regular PC. To display modelling results, CFAST uses SmokeView. This is used for displaying the colour three-dimensional animations of CFAST specific fire simulation results.

1.3. BRANZFIRE

BRANZFIRE is a commercial programme developed by BRANZ Ltd. from New Zealand. It is a computerized zone model that allows the modelling of spreading and calculating the selected parameters of fire and smoke simultaneously in up to 12 rooms. It includes flame propagation model and fire development fully applicable to model compartment fire. It is intended mainly for modelling the corner fires according to ISO 9705, i.e. corner test. The flame propagation and fire development models are based on the application of mathematical equations derived by Quintiere. Inputs to modelling are data obtained from a cone calorimeter. The model allows to calculate the temperature of the gases in the individual layers, the height of the neutral plane, the pressure and velocity of the air, the surface temperature, the content and concentration of the combustion products in each room of the building under assessment [6].

At present, BRANZ is gradually replacing this programme with the newly developed B-RISK programme, which is a combination of a deterministic / probabilistic fire model that allows fire and smoke to be simulated inside a compartment and uses the Monte Carlo's probabilistic simulation method for repeated iterations of the same scenario.

1.4. FIRE DYNAMIC SIMULATOR

Fire Dynamics Simulator (FDS) [8, 11] is a free-to-use computer simulation software system that implements a CFD fire model capable of utilizing the computing capacity of current computers. It was created by NIST (in collaboration with VTT (Technical Research Centre of Finland, Finland) and tested by many world universities, laboratories and science research centres.

FDS is used to solve fire engineering problems and it is also a tool to study fire and fire dynamics at the same time. To make it use easier, the graphical user interfaces such as PyroSim or BlenderFDS can be used. It is generally a complex programme system that simulates the flow of fire-induced gases, the propagation of heat by radiation, the burning, and the estimate of the concentration of substances released during a fire.

Among the necessary input parameters for body surfaces to be determined the material properties belong. In the FDS simulations, it is also possible to include the devices for measuring fire parameters, such as heat release, temperature of walls, bodies or gases at points of space or in sections, gas concentrations (e.g. CO, CO_2, and O_2), visibility, etc.

FDS can model a fire in two ways. When the first method is applied, in a simulated space, the amount of combustible material is first determined differing in its thermo-physical properties, chemical composition, and spatial distribution. Subsequently, the FDS can calculate the burning and mass loss rate, considering the fact that during the pyrolysis are produced the carbon residues and other combustion products, such as water vapour, gaseous fuel, that can affect fire dynamics. The second method is based on specification of the amount of heat released from the unit area per time unit (HRRPUA).

FDS only stores user-defined fire parameter information. The gas phase output parameters include temperature, flow rate, gas concentration (CO, O_2, N_2, and water vapour), smoke density, visibility, pressure, heat release index per unit volume, mass fractions, water droplet weight per unit volume. The influence of fire on building constructions is determined in terms of output parameters such as surface and body temperature, heat flow (total, radiant, and convective) and burning rate. It is also possible to monitor the total heat release, the time activation of sprinklers and detectors, or the spread of fire from the represented area through the openings, outside the compartment.

Most of the output parameters are displayed by the SmokeView [12] visualization programme, which represents the smoke flow animation, the animation of cuts of the output gas parameters, and the animated area and spatial data. It also displays contours and statistical data vectors anywhere within the computational boundary at a given time, allowing some walls to be transparent in order to monitor physical phenomena and the course of the fire. FDS and SmokeView are used together to model and visualize fire.

1.5. SMARTFIRE

SMARTFIRE was developed by the Fire Safety Engineering Group (FSEG) several years ago and is mainly based on the experience of fire safety experts at Greenwich University in London.

Currently, the system contains a total of 5 basic modules:

- *Scenario Designer serving for importing the 2D CAD geometry into SMARTFIRE environment;*
- *Case Specification Environment, i.e. the user interface that allows the user to quickly create and configure complex modelling scenarios using a 3D object-oriented environment;*
- *Automated Meshing System, i.e. an expert automated generator to set the network parameters to meet the requirements of a particular fire analysis. In addition, it allows experienced users to set network parameters manually;*
- *Interactive CFD Engine, which provides full interactive background control and monitoring of the programme's background calculations;*
- *Data Viewer that makes it easy to create virtual reality-style graphics and animations.*

The advantage of SMARTFIRE is that it can simulate hot, turbulent and rising gas flows in any large and rugged object. It can also operate with an irregular control volume network. Combustion allows to define a volumetric heat source or a quantity of gaseous fuel. In addition, it also includes a predefined library of materials that can be added. It is also one of the few models to work with the EXODUS evacuation model. The results of this model are closer to reality. In effect, this will create a link between a fire simulation model with all fire patterns and a model for investigation of the time and course of the evacuation.

2. Computer aided compartment fire modelling applications

In this chapter we present several applications of compartment fire modelling tools, which were processed based on analysis of current sources of scientific literature obtained from foreign licensed databases.

Two different fundamental fire models, CFAST and SMARTFIRE for analysing and predicting the experimental results from a full-scale fire test used Chung et al. [13]. The comparison of results showed quite reasonable variations between numerical simulation and experimental data. Although the temperature data were higher than experimental data, the predicted smoke layer heights were lower than experimental data. However, the fire models presented correct trend of accumulated smoke layer height and temperature distributions in a multicompartment structure

Modelling of a fire test in Mokrsko, which was conducted by the Faculty of Civil Engineering, described Angelis et al. [14]. The Fire test was mathematically modelled using the programmes SMARTFIRE and Fire Dynamic Simulator (FDS) with Pyrosim. The results were then compared to measured data with data calculated using above mentioned programs. At the same time the results obtained from two programmes were mutually compared.

Guo et al. [15] investigated fire characteristics in the South Hongmei Road Tunnel located in Shanghai, China and developed appropriate smoke control strategies in fire accidents. They also conducted several numerical 3D simulations using SMARTFIRE. Three kinds of fire scenarios, namely 5 MW, 20 MW and 50 MW, were simulated in this work to evaluate the longitudinal ventilation system. The longitudinal velocities of each lire scenario were set to be 1.0 m/s, 2.5 m/s and 3.0 m/s. Based on the simulation results, smoke movement and temperature distributions within the tunnel under different smoke control strategies were presented. Further, according to the criterion of safe evacuation established by MARC, evacuation environment within the tunnel were carefully evaluated through investigating air temperature, minimum visibility and smoke toxicity at the position of evacuation paths. The air velocity of 1.0 m/s in the tunnel can provide suitable evacuation environment for fire size of 5WM, while the same velocity will not able to control the back-layering of the smoke for fire size of 20WM. For fire size of 50WM, the longitudinal velocity of 3m/s is needed for safe evacuation in tunnel. Finally, they stated that the findings from the CFD simulations provide useful numerical information for the smoke control strategy.

Verification and validation of a numerical model of fire and smoke development in a railway tunnel described Cabova et al. [16]. It was carried out in the Fire Dynamic Simulator numerical code. To evaluate the accuracy of the modelling results with respect to the mathematical model, the results were compared with results obtained from modelling in the SMARTFIRE numerical code. The influence of mesh size on the gas temperature results in the vicinity of the fire source was studied, too. The level of correspondence between the numerical model and a physical model was validated by comparing the calculated data with data measured during a fire test in the Valik road tunnel in the Czech Republic.

Alkhazaleh and Duwairi [17] dealt with mechanical ventilation system, manual method for the hydraulic calculations and fire design scenarios. This research showed an overview of the Consolidated Model of Fire and Smoke Transport (CFAST) modelling used to predict ventilation performance and smoke movement in an atrium. Authors referred the fact that the CFAST software has many uses in a wide variety of buildings and fire scenarios due to fast, reliable and affective accuracy of output data. In addition, CFAST approaches provide a link between outside building weather conditions and fire and smoke development. This work demonstrated the complete design procedure as an example for fire safety engineers.

The capability of a zone model (CFAST) and a field model (ISIS) to predict the interaction between mass loss rate and total relative room pressure or oxygen concentration in case of under-ventilated fire conditions investigated Bonte et al. [18]. Results were obtained using as input the mass loss rate measured during the experiment and the mass loss rate measured in free atmosphere. A sensitivity study had also been performed for the field model to analyse the influence on the outputs of soot production, radiation modelling, wall emissivity, turbulence modelling and branch flow resistance.

Kuffner and Hadjisophocleous [19] applied two algebraic models intended for unconfined ceilings, the two-zone computer model CFAST and the computational fluid dynamics computer model FDS and mutually compared each other and the experimental results. The ability to predict obscuration levels and detection times for these fires was evaluated. They elaborated the recommendations for using the various models in commercial applications, too.

Wu et al. [20] identified major limitations of CFAST, proposed solutions to the limitations, developed a system for data interchange between BIM and CFAST. They further developed a visualization module to visualize the simulation results to overcome the problems when using SmokeView, an application developed by NIST (National Institute of Standards and Technology). A pilot test was conducted using this system. This was expected to help architects to design buildings safer from building fires and students in learning building safety and fire related building codes.

The fire probability safety analysis on the main control room by using CFAST and Monte Carlo sampling method as a tool for fire modelling to simulate main control room on fire provided Wang et al. [21]. This way they were able to provide uncertainty analysis for the important parameters of CFAST.

The fire risk in the main control room (MCR) for a small modular reactor assessed Wang et al. [22]. In this study, they used the software CFAST to simulate fire scenarios caused by the main control board in the MC. They used the software, RiskSpectrum to calculate the Core Damage Frequency (CDF). The calculation results showed that CDF caused by the main control board (MCB) is of 6.112E-09/year.

Worrell et al. [23] explored the application of machine learning to generate metamodel approximations of a physics-based fire hazard model. The process involved scenario definition, generating training data by iteratively running the fire hazard model called CFAST over a range of input space using the RAVEN software, exploratory data analysis and feature selection, an initial testing of a broad set of metamodel methods, and finally metamodel selection and tuning using the R software. Twenty-five metamodel methods ranging in class and complexity were investigated. Linear models struggled because the physics of fire is non-linear. A k-nearest neighbour (kNN) model fit most calculations within +/- 10 % for maximum upper layer temperature and its timing. The resulting kNN model was compared to an algebraic model typically used in fire probabilistic safety assessments. This comparison illustrated the potential of metamodels to improve modelling realism over simpler models selected for computational feasibility. While the kNN metamodel is a simplification of the higher fidelity model, the error introduced is quantifiable and can be explicitly considered.

Wade et al. [24] investigated sprinkler response time predictive capability of the BRANZFIRE fire model. A set of 22 fire/sprinkler experiments are simulated where the sprinkler activation time and the heat release rate (HRR) for each individual experiment had been determined. The experiments provided data for use in validating the sprinkler activation prediction algorithms in the BRANZFIRE zone model. A set of base case values were chosen, and input files constructed for the simulations. The experiments were then simulated by the fire model using both the NIST/JET ceiling jet and Alpert's ceiling jet options, which are the two ceiling jet correlations available in the BRANZFIRE zone model). The fire model included a heat transfer calculation for the temperature of the heat sensitive sprinkler element. Different sprinkler operational parameters such as the conduction factor, response time index (RTI) and the sprinkler depth below ceiling were also varied to assess the sensitivity of their effect on the activation time. Results showed that using the NIST/JET ceiling jet algorithm gave a closer prediction of the sprinkler response time in a small room than Alpert's correlation. This was expected, since the former includes the effect of a hot upper layer while the latter applies to unconfined ceilings. The experiments available for comparison had been conducted inside an enclosure with a developing hot upper layer. The findings also signified that changing the sprinkler operational parameters can change the predicted sprinkler activation time significantly

Research focusing the increase of the functionality of the BRANZFIRE fire zone modelling software by converting it from a deterministic to a probabilistic model provided Baker et al. [25]. One of the objectives of the research was the development of a radiative fire spread submodel for which finding a suitable ignition criterion method was needed. They provided details of that ignition criterion procedure and its implementation into the submodel. The Flux-Time Product technique, and its associated ignition criterion, was selected to be incorporated into the fire spread submodel. To demonstrate the use of the technique in the submodel, series of ignition experiments were conducted on a single example of upholstered furniture using the Cone Calorimeter apparatus, with specimens tested in both the horizontal and vertical orientation, under piloted and auto ignition conditions. The experimental incident radiation and time-to-ignition data, for the piloted ignition mode, was analysed using a modified Flux-Time Product correlation procedure. To deal with the auto ignition mode, an empirical approximation, based on the modified Flux-Time Product procedure, is proposed. Data to be used in the submodel were therefore also derived for the auto ignition mode, based on an experimental determination of the minimum ignition flux.

Salem [26] provided parametric study using the latest version of one of the available fire models of the zone model type, called BRANZFIRE, in order to assess the effect of changing the size of the compartments on the time available for occupants of the plane board to escape safely.

Husted and Holmstedt [27] investigates the importance of using draft curtains to obtain faster sprinkler activation with three different models-two computational fluid dynamics (CFD) models (CFX 4.4 and fire dynamics simulator (FDS) 4.07) and a zone model (Argos) containing a ceiling-jet formula - for an actual scenario in an entertainment centre in Denmark. It was found that a draft curtain has some effect on sprinkler activation, reducing activation time from 8% to 15%, depending on the model implemented. The positions of the sprinklers with in the vertical computational grid of the CFD simulations had a greater influence on the activation of the sprinkler, where FDS was more sensitive than CFX. It is confirmed that heat transfer from the ceiling jet to the ceiling has little influence on the results. The zone model with a ceiling-jet formula gave 10-20% slower sprinkler activation than the CFD results when the sprinkler was close to the ceiling, but was still considered very useful in view of the faster calculation time

A computational methodology to calibrate the model STEPS for simulating assisted evacuation processes in the health-care facility applied Alonso-Gutierrez et al. [28]. They used Fire Dynamic Simulator (FDS) to simulate the fire and smoke spread in a table and a PC to compare fire and evacuation results The evacuation results show that the change of the smoke compartment size increases the mean evacuation time by 23%; however, the fire results show that the available safe egress time is 16 min for both smaller and large smoke compartment. The ratio of the number of patients per staff member is also a strong factor that increases the evacuation up to 82% when comparing the ratios of 2 patients per staff member and 4 patients per staff member.

Integrated deterministic and probabilistic safety analysis (IDPSA) to assess the performances of the firefighting means to be applied in a nuclear power plant carried out Kloos and Peschke [29]. The tools used in the analysis were the code FDS (Fire Dynamics Simulator) for fire simulation and the tool MCDET (Monte Carlo Dynamic Event Tree) for handling epistemic and aleatory uncertainties. The combination of both tools allowed for an improved modelling of a fire interacting with firefighting means while epistemic uncertainties because lack of knowledge and aleatory uncertainties due to the stochastic aspects of the performances of the firefighting means are simultaneously considered. Those results they used to derive probabilities of damage states based on failure criteria considering high temperatures of safety related targets and critical exposure times. The influence of epistemic uncertainties on the resulting probabilities was quantified.

Smoke spread to the elevator system using the Computational Fluid Dynamics (CFD) code Fire Dynamics Simulator (FDS) studied Cai et al. [30]. Different arrangements of smoke extraction with pressurization systems were evaluated by analysing the smoke dispersion and pressure distributions in this fire safe elevator system. Numerical results were compared with that by theoretical equations. The results showed that a smoke extraction system with a four-floor approach pressurization system can be an efficient method for smoke control in elevator system for supertall buildings.

Drean et al. [31] carried out computational fluids dynamics simulations with the FDS code for two full-scale experiments of facades performed by Efectis France laboratory. The first objective of this study was to evaluate the ability of numerical model to reproduce quantitative results in terms of gas temperatures and heat flux on the tested facade for further evaluation of fire performances of an insulation solution. When experimental results were compared with numerical calculations, good agreement is found out for every quantity and each test. The proposed models for wood cribs and geometry gave correct thermal loads and flames shape near the tested façade.

Floyd and McDermott [32] developed and evaluated two novel numerical approaches to fire simulation. The first was based on an analytical solution that relaxes the cell composition and temperature toward the equilibrium values. The second method was an implicit solution to the droplet equations. The two approaches were implemented in the FDS and verified and validated using both single droplet and practical sprinkler calculations. Ultimately, the implicit approach was deemed the most cost effective for practical fire simulations.

Hasnain et al. [33] investigated the effect of down stand depth on smoke contamination occurrence and severity in atrium upper balconies by varying the down stand depth together with the previously investigated parameters by utilizing Fire Dynamic Simulator (FDS), a computational fluid dynamics (CFD) software. Results demonstrated that the extent of smoke contamination increased with increased down stand depth. CFD simulation results showed that as down stand depth increased, from no down stand to 0.1 m in 1/10 scaled model, smoke severity increased by up to 40%. An empirical correlation was also developed to predetermine the smoke contamination height by relating the above-mentioned variables in a single correlation.

Meher et al. [34] used fire dynamics simulator (FDS) code, based on large eddy simulation (LES) technique, for simulation studies of smoke spread due to fire in a multi-storied building. The existing natural ventilation system is found to be inefficient in smoke extraction. To safeguard the stairs from smoke accumulation, various methodologies of mechanical ventilation have been adopted to analyse the situation. Suggestions on improving the safety of the building have been provided and their feasibilities have been discussed.

Valasek and Glasa [35] concentrated particularly on the impact of a computational meshes choice on resolving flow field and turbulence in the simulation and indicates problems related to parallelization of the calculation illustrated comparing sequential and parallel MPI calculation using 6 CPU cores. Results of the simulation described, and their discussion demonstrated the ability of FDS simulation to capture main tendencies of smoke spread and to forecast the related safety risks realistically.

Johansson and Ekholm [36] published results from a round-robin study in which practicing fire safety engineers simulated the same scenario are presented in this paper. The simulation task included the simulation of an 800 mm heptane pool in a three-room apartment. The participants, representing eight Swedish consultancy firms, simulated the well-specified scenario with FDS 5. The participants received information about the building, the fire mass loss rate and initial conditions. The task was performed a priori, meaning that the participants were not given any experimental or simulation results prior to performing the task. The study shows that there is a variation between the participants in how the input file was specified, the choice of input data and the types of devices used in FDS. The differences in how the fuel and the burner were described were relatively large, which resulted in large differences in mass loss rate and heat release rate. Furthermore, several of the participants made mistakes when the fire was prescribed and this resulted in a variation in the calculated parameters like the temperature increase, which was 300 K in the fire room and 50 K to 150 K in the adjacent rooms. However, the study shows that when the heat release rate and wall boundary conditions were well defined, good temperature predictions could be made.

Conclusions

The results of mathematical modelling can be used to assess and subsequently propose measures for the purpose of ensuring the fire safety of buildings prior to their construction, assessment of fire protection of existing buildings, reconstruction of building fires to determine the probable scenario of fire initiation and development in terms of fire investigation, but also as a tool for training fire-fighters-rescuers, commanders of intervention and, last but not least, the fire investigators themselves.

An important aspect of the entire modelling process is entering input parameters. It is necessary to prepare a database of data on physical, chemical and fire properties of materials, which occurrence we consider in the space under assessment. Only by entering as many input parameters as possible we can achieve a relatively high accuracy of modelling results. Obtaining these parameters requires to provide fire tests, especially for materials that are not yet sufficiently described. However, in most cases, large-scale fire tests are required to verify the accuracy of the modelling results. However, this is time consuming and costly. It is therefore important to look for other ways of validating and verifying the results of own modelling with the results of already modelled fire scenarios. Many of them are provided by the American National Institute of Standards and Technology (NIST) in its user manuals and on its website.

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