Fire dynamics simulation of large multi-story buildings
Case study: Umm Al-Qura university campus

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Abstract. The computational fluid dynamics (CFD) technique is used to predict the fire dynamics in some main buildings of the campuses of Umm Al-Qura University using the Fire Dynamic Simulator (FDS). Important aspects of fire dynamics such as smoke propagation and temperature distribution were investigated. The study contributes in reducing the risks of fires by early prediction of the expected scenarios of fires and associated smoke movement. Hence, early evacuation plans can be established by authorities such as the civil defense. It was found that emergency openings (vents) in the ceiling or side walls that operate in cases of fire, according to appropriate sensors, have a significant role in directing the smoke outside the building. Based on the study, interesting conclusions are drawn and fruitful recommendations/suggestions are introduced. A simple smoke control-scheme is recommended to minimize smoke hazards.

1. Introduction
Big cities attract millions of people every year. People may gather at the same time and place with intensive density. This situation is likelihood to initiate series fires that may lead to heavy losses in human lives. Statistically, most of the deaths in fires are not due to direct fire, but because of suffocation with smoke, fumes and toxic gases. Examples of buildings where smoke-prediction and -control play a significant role include: large worship places, university campuses, shopping centers, large hotels, atrium buildings, large warehouse and industrial buildings, underground structures such as car parks and tunnels, etc. The problem of fire dynamics was investigated by many researchers numerically and experimentally. Men et al. [1] presented an approach to the study of gas-phase combustion and convection processes numerically. Kasheef et al. [2] conducted a research project to evaluate numerically and experimentally the effectiveness of the current emergency ventilation system (EVS) to control fire-smoke spread in two road-tunnels. He and Jiang [3] presented a case study using FDS to optimize the location of the Air Sampling-Type Detectors (ASD) for Langham Place1 in Hong Kong. Xin et al. [4] performed fire simulations of a 7.1-cm buoyant turbulent diffusion flame using a mixture fraction-based combustion model. Huo et al. [5] used FDS to simulate the typical ventilation in an air-conditioned office. They stated that the diffuser height has the main effect on office temperature. Rzdolsky [6] examined some differences and amalgamations between combined effects from multiple fires and “local” explosions on a structural system. Other researchers concentrated on the validation of FDS. Zhang et al. [7] assessed the accuracy of FDS (V4.07) using the heat flux and flame heights from fires of a single burning item (SBI) tests and concluded that FDS reasonably predicts the flame heights. Webb [8] performed hot smoke tests (HST) according to

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Australian Standard AS 4391 -1999 in several buildings such as cinema auditorium and airport concourse to show that fire protection consultants may predict reasonable computational results that are comparable to a full-sized simulation. Smardz [9] assessed the accuracy of FDS predictions for smoke spreading from a small compartment into an adjacent larger space (Hotel building), then extracted using powered-ventilation system. Sun et al. [10] used experimental data to evaluate the fire-plume properties simulated by FDS and the Clark coupled atmosphere-fire model. They indicated that FDS produces good agreement with the experimental results even at a relatively coarse horizontal grid size of 4 m. Coyle and Novozhilov [11] performed further validation of FDS using four smoke filling scenarios reported in the literature. They found that performance of the code varies considerably with complexity of scenario (e.g., geometry). Jahn et al. [12] analyzed the sensitivity of FDS to input parameters such as fire size and location as well as convection, radiation and combustion conditions. They stated that simulations of fire growth are significantly sensitive to location of fire and its area, flame radiative fraction, and material thermal and ignition properties.

The present study concerns the smoke propagation due to sample fires in two main large buildings of Umm Al-Qura University. A smoke control-scheme is recommended to minimize smoke hazards. Thus, the main objective of the present work is to predict the scenarios of smoke propagation in the university buildings to assist in putting evacuation plans of the students and to suggest simple control solutions to reduce smoke hazards. This objective can be easily adapted to other types of large buildings.

2. General features of the computational modeling

Fire Dynamic Simulator (FDS-Ver.5) program [13] is a computational tool for the prediction of fire scenarios and smoke spread that are expected in almost all types of buildings. FDS was developed by National Institute of Standards and Technology (NIST) [13]. The program prediction depends on the architectural plans of the building in addition to the burning materials. The program is based on the time-dependent solution of the governing equations of flow and combustion due to fire. The building domain is divided into a three-dimensional grid of small cubes (grid cells). The core algorithm of FDS is an explicit predictor-corrector scheme, second-order accurate in space and time. Turbulence is treated by means of the Smagorinsky sub-grid scale (SGS) model of Large Eddy Simulation (LES). More details of the FDS program can be found in [14]. There is a big number of attempts for the validation of FDS. Some of them are illustrated in the previous section and many others in [15]. Generally, based on these validation investigations, the results of FDS can be trusted for almost all fire cases. However, it is important to use a fine mesh to model the problem under-investigation as much as the available computer capacity. For all the present building models, the fire power was set considerably with complexity of scenario (e.g., geometry). Jahn et al. [12] assessed the accuracy of FDS predictions for smoke spreading from a small compartment into an adjacent larger space (Hotel building), then extracted using powered-ventilation system. Sun et al. [10] used experimental data to evaluate the fire-plume properties simulated by FDS and the Clark coupled atmosphere-fire model. They indicated that FDS produces good agreement with the experimental results even at a relatively coarse horizontal grid size of 4 m. Coyle and Novozhilov [11] performed further validation of FDS using four smoke filling scenarios reported in the literature. They found that performance of the code varies considerably with complexity of scenario (e.g., geometry). Jahn et al. [12] analyzed the sensitivity of FDS to input parameters such as fire size and location as well as convection, radiation and combustion conditions. They stated that simulations of fire growth are significantly sensitive to location of fire and its area, flame radiative fraction, and material thermal and ignition properties.

3. Governing equations, LES simulation and combustion model

FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires [9]. The basic set of the conservation equations for mass, momentum and energy solved by FDS is presented below:

Conservation of mass: \[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]

Conservation of momentum: \[
\frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) + \nabla p = \rho f + \nabla \tau_{ij}
\]

Conservation of energy: \[
\frac{\partial}{\partial t} (\rho h) + \nabla \cdot (\rho \mathbf{u} h) = \frac{\partial p}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) - \nabla q + \Phi
\]

Equation of state for a perfect gas: \[
p = \rho RT
\]

Where, \( u_i \) is velocity in \( i \)-direction, \( i = 1, 2, 3 \), \( \rho \) is fluid density, \( f \) is summation of external forces, \( \tau_{ij} \) is shear stresses, \( p \) is pressure, \( h \) is enthalpy, \( \dot{q}^w \) is heat release rate per unit volume \((HRRPUV)\), \( q \) is the heat transfer, \( \Phi \) is any heat source, and \( T \) is the temperature. Large eddy simulation resolves...
large scales of the flow field and models the smallest scales of the solution by a grid-filtering process. Thus, the filtered term $\overline{u_i u_j}$ is modeled using the sub-grid scale (SGS) model of Smagorinsky [17].

FDS uses the mixture fraction model as the default combustion model [9]. Mixture fraction is defined as the fraction of gas at a given point in the flow field that originated as fuel. Radiative heat transfer is included in the model via the solution of the radiation transport equation for a non-scattering grey gas.

4. Results and discussions
The first model represents the building of a typical academic department. The building is a part of a complete complex that contains a number of similar departments. It is a three-story building, Fig. 1, with overall plan dimensions of about $41 \times 17 \ m^2$. The offices and facility are concentrated in an area of $18 \times 13 \ m^2$. A central-rectangular hollow-section extends from the first floor to the roof of the third floor with a cross-section of $4.4 \times 3.2 \ m^2$. The furniture samples that appear in the third floor are placed in the office of the department head. The department council is in the opposite room. The source of fire is a wooden disk that is placed in a small room behind the council room. Figures 1 and 2 show the results after 20 minutes of the fire initiation for (a) smoke (b) temperature. In the first case, Fig. 1, the smoke propagated in all the three floors of the building. Unexpectedly, smoke moved from the third floor towards the two floors beneath through the central hollow-section. Smoke almost filled all the floors. This means all individuals in all the building are in great risk of smoke hazards.

Temperature slightly increased in the ground floor. The second case, Fig. 2, differs from the first one in putting an active outlet vent in the ceiling of the third floor. The vent, $1 \times 1 \ m^2$, is located in the ceiling at the center of the central-rectangular hollow-section. This vent is equipped with a fan to extract smoke out of the building and operates according to the signal of a temperature detector such that the flow speed is $1 \ m/s$. The vent sucked out the smoke to the outer surroundings from the third floor. The smoke did not propagate to the lower floors. The temperature of the first two floors remains almost the same without increase.

![Figure 1. First model, academic department building without a ceiling opening.](image)

![Figure 2. First model, academic department building with a ceiling opening (vent).](image)
the large size of the building, smoke did not get out from the openings of the ground floor till 30 minutes of fire. The same scenario was repeated in the case of the auxiliary building except that smoke started to get out of the openings of the ground floor within the thirty minutes of study. Thus, two different evacuation planes should be considered for the two buildings.

Figure 3. Second model, consisting of two connected buildings.

5. Conclusions/recommendations

Conclusions: (i) Emergency openings (vents) in the ceiling or side walls that operate in cases of fire, according to appropriate sensors, have a significant role in directing the smoke outside the building. (ii) Smoke propagation depends greatly on the location of the fire according to the building architecture. (iii) The increase of the number of openings between different stories increases the possibility of smoke propagation from one story to another. However, the smoke density becomes less. (iv) In buildings with complex architecture, smoke may be directed to lower stories instead of moving to the upper ones. This situation complicates both the fire fighting and the evacuation processes.

Recommendations: (i) The idea of smart buildings can be adopted by emergency openings (vents). The doors and fans of these openings may be powered by emergency batteries that are charged by solar cells to be independent of the main power supply that to be cut in case of fire. (ii) A control system, based on microcontrollers or Programmable logic controller (PLC), may be utilized to operate these vents depending on the signals of a matrix of temperature/smoke detectors. (iii) Air-Conditioning system must be turned-off or works in opposite direction to suck smoke outside the building. This is a vital point as air conditioning system is a major source of fresh air for fire supply.

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