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Simulation of Fire Spreading in a Residential Building: Comparing Alternative Building Techniques

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ABSTRACT: The Fire Dynamics Simulator CFD code is used to study the thermal behaviour of a two-storey residential house subjected to a typical domestic fire scenario. The fire resistance behaviour of the building is evaluated considering two alternative building techniques; steel-skeleton combined with drywall systems and reinforced concrete with brick walls. The physical properties of the utilized multi-layered construction materials are taken into account to accurately describe their thermal response; the highly detailed computational geometry is based on actual architectural drawings. Gas velocity and temperature predictions are used to visualize the developing flow-field and to estimate the heat flux to which each building element is exposed. Predicted wall temperatures allow the comparative assessment of the two investigated construction techniques in terms of fire resistance. Finally, toxic gas concentrations and smoke production and dispersion predictions enable risk assessment for the tenants of the building in the event of a fire.

1 INTRODUCTION

Fire is one of the most complex phenomena considered in combustion science, since it embraces nearly all the effects found in subsonic chemically reacting flows. Fluid dynamics, combustion, chemical kinetics, radiation and multi-phase flow effects are linked together to provide an extremely complex physical and chemical phenomenon. It is this complexity that delayed the development of fire research as a science until the 1950s. Fires are associated with a large range of hazards to humans, property and the environment. Amongst the variety of incidents of uncontrollable fires, unwanted fires in enclosures are the most frequently encountered (Yeoh & Yuen, 2009). In building fires, the confined space controls the air supply and thermal environment of the fire, which affect the spread, growth, maximum burning rate and duration of the fire. Fire safety regulations have a major impact on the overall design of buildings with regard to layout, aesthetics, function and cost.

According to National Fire Protection Association, there were 1,451,500 fires in the United States in the year 2008 (Karter, 2009). 84% of all fire fatalities occurred in homes, i.e. one- and two-family dwellings and apartments. According to Madrzykowski & Hammins (2007), the most important areas of origin in residential fires are the kitchen (34%), the bedroom (12%) and the living room (6%). Fires that start by lighted tobacco products occur mainly either in the bedroom or in the living room and constitute the leading cause of residential fire deaths (Ahrens et al., 2004). Cooking fires are often the result of the ignition of loose clothing or other nearby flammable materials from unattended cooking where grease or oil ignites. In 2003, there were

118,700 reported cooking-related home structure fires in the U.S.A., which resulted in 250 fatalities, 3880 injuries and $512 million in direct property damage (Hall, 2005).

In recent years, a variety of numerical tools have been developed to enable the prediction of fire growth within enclosures. Computational Fluid Dynamics (CFD) tools allow the numerical solution of the fundamental equations describing the transfer of mass, momentum and energy in an enclosure fire environment. These tools have been successfully used in a variety of fire safety areas, such as fire protection engineering (e.g. prediction and visualization of fire and smoke movement), building architectural design (prediction of fire behaviour to estimate the optimal place for fire exits or sprinkler placement and operation), fire safety strategy for a building (e.g. prediction of smoke flow patterns to estimate the optimal design of smoke control systems), accident investigation, building re-design etc. The role of CFD tools in fire research is steadily increasing as the models become progressively robust and sophisticated and validation studies make them more reliable. The CFD approach is considered to be fundamental to the future development of fire models, which can provide the basis for performance-based fire safety regulations.

In this context, the use of CFD tools is necessary to extend beyond simplified geometrical configurations in order to ascertain their applicability in real building fires (Yeoh & Yuen, 2009). However, most of the available studies focus mainly in single-room or two-room simulations (Hasib et al., 2007, Merci & Maele, 2008). Scarce reports are available in the open literature regarding multi-room compartment fire simulations; they mainly focus on the investigation of accidental fires (Rein et al., 2006). A round-robin study performed recently has revealed the difficulties associated with modelling fire dynamics in complex fire scenarios using CFD tools, suggesting that the respective accuracy of fire growth predictions is still generally poor (Rein et al., 2009). The main scope of the present study is to investigate the ability of currently available CFD tools to effectively simulate the flow- and thermal-fields developing in a full-scale two-storey residential house during a fire accounting for detailed material properties.

2 TWO-STOREY RESIDENTIAL BUILDING

The modelled two-storey, 152 m^2, residential house represents a typical Greek family two-storey dwelling (Figure 1), with a typical residential arrangement plan (ground floor: kitchen, office and living room, first floor: master and auxiliary bedroom). The house is constructed using a load-bearing steel frame combined with dry wall system (multi layered plasterboard assemblies), in accordance with earthquake, fire-resistance, thermal and sound insulation requirements. The external walls of the house are multi-layered, consisting of (from the interior to the exterior) two 12.5 mm plasterboards, a 182.5 mm void (allowing space for the steel frame and plumbing), a 12.5mm plasterboard, a layer of 80 mm rockwool, a 12.5 mm cementboard and a final layer of 50 mm EPS polystyrene. The internal walls consist of two 12.5 mm plasterboards, a layer of 80 mm rockwool and two 12.5 mm plasterboards.

Gypsum plasterboards are widely used in the building industry for a variety of applications as an aesthetically pleasing, easily applied and mechanically enduring facing material for walls and ceilings. In the context of building fire safety, gypsum plasterboards are capable of decelerating the penetration of fire through walls and floors, due to the endothermic gypsum dehydration process occurring in high temperatures. When a gypsum plasterboard is subjected to a high temperature environment, water molecules bound in its crystal lattice are released and transferred through the board, absorbing energy and thus reducing the mean wall temperature. This process is known to improve the global fire resistance of the building and it is suggested to enhance the safety margins of the building, by allowing longer evacuation times (Wang & Ang, 2004).

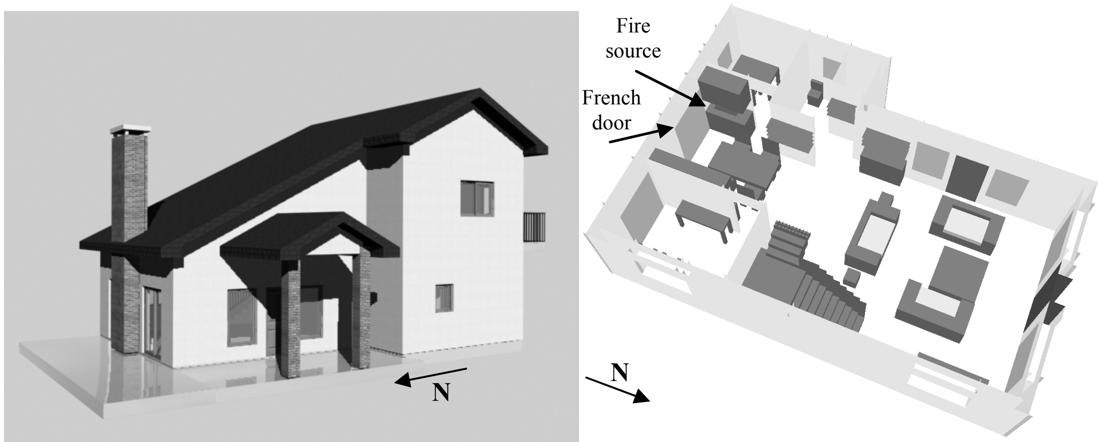

Figure 1. Photorealistic view of the building (left) and interior of the ground floor (right).

The thermo-physical properties of the construction and furniture materials used in the house were obtained from the open literature (Prasad et al., 2009, Matala, 2008, DiNenno et al., 2002). The physical properties of gypsum are varying with increasing temperatures, due to the occurring chemical reactions (dehydration). The utilization of temperature-dependent physical properties is known to yield more accurate results in heat transfer simulations of gypsum plasterboards, compared to mean values (Kontogeorgos et al., 2008). Therefore, temperature-dependent values for thermal conductivity (measured using the hot wire method) and specific heat (Wakili et al., 2007) were used in the simulations.

3 NUMERICAL SIMULATION

The Fire Dynamics Simulator (FDS) code is a CFD tool capable of studying fundamental fire dynamics and combustion, aimed at solving practical fire problems in fire protection engineering (McGrattan et al., 2010). The FDS code solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flows, with an emphasis on smoke production and heat transfer from fires. The core algorithm is an explicit predictor-corrector scheme that is second order accurate in space and time. Turbulence is treated by using the Large Eddy Simulation (LES) approach. The subgrid-scale turbulence is simulated using the Smagorinsky model, utilizing a Smagorinsky constant value of 0.2. The numerical time-step is continuously adjusted in order to satisfy the CFL criterion. The partial derivatives of the conservation equations of mass, momentum and energy are approximated as finite differences and the solution is updated in time on a three-dimensional, Cartesian grid. Thermal radiation is simulated using the finite volume methodology on the same grid as the flow solver. All solid surfaces are assigned thermal boundary conditions by taking into account information about the burning behaviour of the respective material.

The considered house is enclosed within a rectangular volume, measuring 12.8 m, 11.2 m and 8 m, in the x-, y- and z- directions respectively. The numerical grid used divided this volume into 798,720 cubic computational cells, each having a side of 0.1 m. Certain construction and decorative details were "roughly" approximated in order to limit the size of the computational grid required for the simulations. However, the house was considered to be completely furnished, following a standard residential configuration. At the beginning of the numerical simulation (t = 0 s), the entire computational domain (both indoors and outdoors) is assumed to be still (zero velocity), exhibiting a temperature of 20^{o}C. The total simulation time was 15 min, in order to be able to capture with sufficient detail the most important characteristic stages of the developing fire, namely initiation, spreading and decay. The total CPU-time needed for the complete simulation was approximately 24 hours on a 4 GB, Quad Core 2.4 GHz desktop PC, using the "parallel computation" version of the FDS code.

The selection of the proper physical properties and pyrolysis rate coefficients for the combustible materials is a very challenging task; especially for the latter, values derived from small and large-scale experiments may exhibit differences of several orders of magnitude (Hostikka & McGrattan, 2001). The simulated house was assumed to be equipped mainly with wooden furniture. A single step Arrhenius reaction was used to model the thermal decomposition of wood; the kinetic and thermal parameters used in the simulations were found in the literature (Matala, 2008). The combustible gases produced by wood pyrolysis were considered to be described by the collective chemical species $C_{3.4}H_{6.2}O_{2.5}$ (Ritchie at al., 1997); a mixture fraction model was used to simulate combustion.

Cooking equipment is the primary cause of reported home fires and home fire injuries in the U.S.A. (Ahrens et al., 2004). In this study, the ignition source was assumed to be a typical cooking fire represented by a 0.8 m by 0.2 m rectangular "patch" located on the upper surface of the birch wood kitchen bench (Figure 1). A constant 300 kW fire was assumed to appear at the beginning of the simulation (t = 0 s); the fire power was selected according to relative suggestions in the literature regarding fires related to kitchen equipment and cooking vegetable oil (Luo & Beck, 1994).

The computational domain extended approximately 2.0 m outwards from each side of the house; therefore, airflow in the surrounding environment could be also simulated, thus allowing studying of the effects of open external doors or windows. Glass surfaces (windows and French doors) were considered to break when their surface temperature reaches 300^{o}C (Su et al., 2010); in this case, "fresh" ambient air is allowed to enter into the house, thus increasing the quantity of oxygen that is available to the fire.

A parametric numerical study was performed aiming to evaluate the characteristics of fire initiation, spreading and suppression, as well as the fire resistance of the structure, when two different building techniques are used. In the first Test Case (TC1) the house is considered to be built using a dry-wall system (steel skeleton combined with gypsum plasterboard assemblies), whereas in the second Test Case (TC2), a more "conventional" construction technique is used (reinforced concrete skeleton combined with brick walls). In both Test Cases, all simulation parameters were kept identical, with the exception of the thermo-physical properties used for the skeleton and the walls of the building.

4 RESULTS AND DISCUSSION

4.1 Flow-field Characteristics

The main characteristics of the developing flow-field are similar in both the examined Test Cases. In fact, the French door glass is predicted to brake and fall-off approximately at the same time (39 s after fire initiation) in both Test Cases. A characteristic image of the developing flow-field is presented in Figure 2, which depicts predictions of the instantaneous gas phase velocity vectors for TC1, 30 s and 13 min after fire initiation. The largest velocity values are observed near the fire region, especially before the French door glass breakage (Figure 2, left), where the thermally induced buoyancy phenomena are very strong due to the large temperature gradients. A typical stratified fire-induced flow field is developed in the house; the large density variation forces the mixture of air and combustion products to rise, leading to the consequent entrainment of the cold ambient air to the lower part of the house. The strong buoyant upward flow from the kitchen room door to the ceiling of the living room is clearly visible. The entrainment of fresh air from the surrounding environment, through the French door, renders the developing flow-field more intense, exhibiting higher velocities. Notice that 13 min after fire initiation (Figure 2, right) the glass French door has already disappeared, due to the glass breakage; also, a part of the wooden cupboard, located just above the fire origin, has been fully burnt and is therefore missing.

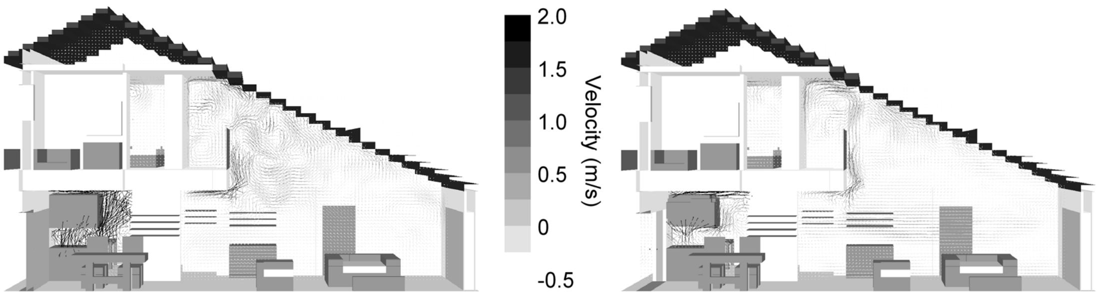

Figure 2. Predictions of gas velocity vectors 30 s (left) and 13 min (right) after fire initiation.

The temporal evolution of the gas temperature predictions for TC1 is depicted in Figure 3. As expected, the highest temperatures are observed in the region just above the fire source, where the main fire plume is established. Due to the large indoor openings that do not impede flow circulation and the large volume of the entire house, which serves as a "thermal fly-wheel" not allowing the local temperatures to rise significantly, "conventional" flashover is not observed. The stratification of the developing flow-field leads to the formation of a similarly stratified thermal field. Fresh air entrainment through the French door is evident in the lower part of the kitchen room. A similar thermal stratification, although less distinct, also develops in the upper floor, where relatively high temperatures are observed.

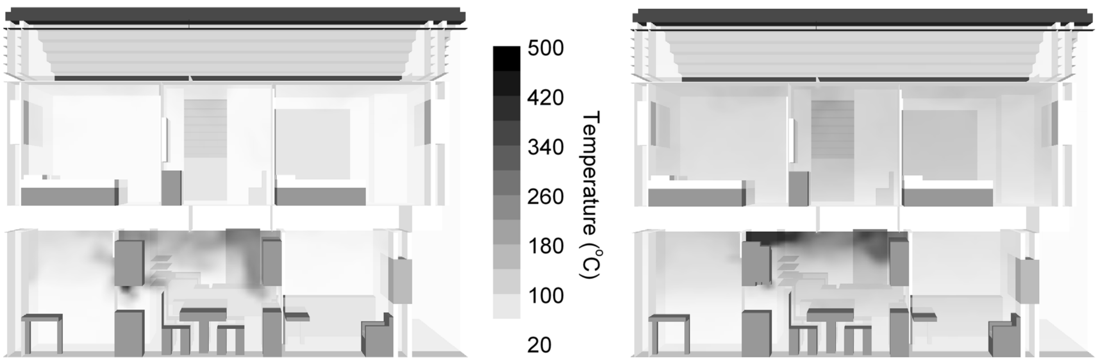

Figure 3. Predictions of gas mixture temperature 30 s (left) and 13 min (right) after fire initiation.

4.2 Parametric Study

CFD simulations allow the estimation of fire resistance of entire buildings. In this context, the mechanical strength of gypsum plasterboard wall assemblies is investigated. It should be noted here that plasterboard walls are not load bearing, therefore their failure cannot contribute in case of partial collapse of the building. Gypsum plasterboards exposed to fire are considered to exhibit mechanical failure when cracks or openings are observed through the wall (Manzello et al., 2007); however, since cracking phenomena cannot be accurately simulated in the CFD code, alternative failure criteria had to be used. According to the Australian Standard AS1530.4, a plasterboard wall fails when the maximum temperature rise (above the ambient temperature) of the ambient facing side (unexposed side) exceeds 180^{o}C (Clancy, 2002).

Surface temperature predictions for the interior assembly of the kitchen wall, which lies closer to the fire source, are depicted in Figure 4 (left). It is evident that the unexposed side of the interior wall assembly (which consists of a double layer of plasterboard) exhibits a very modest temperature rise. However, the side which is directly exposed to the fire source reaches high temperature levels, exceeding the "limiting" temperature of 180^{o}C quite early in the simulation. Similar temperatures are also observed in Test Case 2.

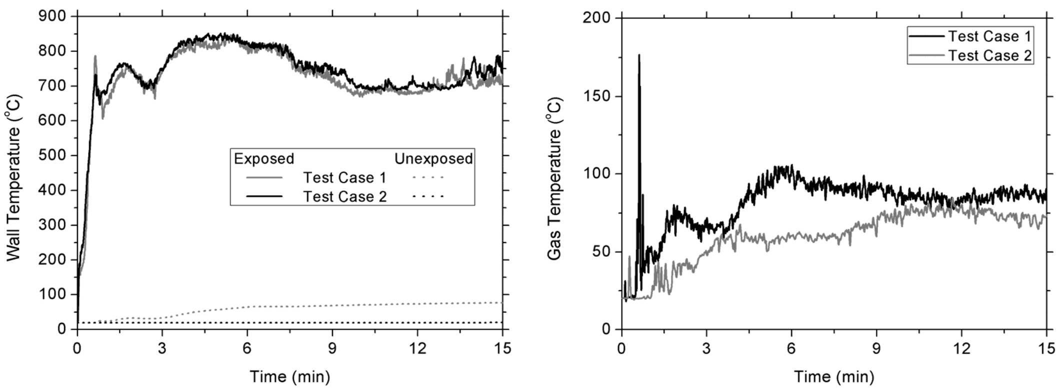

Figure 4. Temporal evolution of the surface temperature of the kitchen wall adjacent to the fire origin (left) and the gas temperature in the middle of the kitchen, at a height of 1.6 m (right).

In order to evaluate life safety in fire conditions using a numerical simulation tool, quantitative tenability criteria are needed. An average person exposed for more than a few minutes to high levels of temperature and heat flux, is likely to suffer burns and die, either during or immediately after exposure, mainly due to hyperthermia. According to the S.F.P.E. Handbook (DiNenno et al., 2002), the tolerance times for air temperature of 126^{o}C is 7 min, whereas for 180^{o}C is 4 min. Temperature predictions in the kitchen room (Figure 4, right) suggest that this region does not become untenable, at least for the simulated initial 15 min.

Predictions of combustion products concentrations in the kitchen room at the mean breathing height are depicted in Figure 5. The tenability limits (CO > 6000 ppm, CO_2 > 7%, O_2 < 13%,) reported in the S.F.P.E. Handbook (DiNenno, 2002) are not exceeded in any of the considered Test Cases. TC1 exhibits slightly higher toxic gas concentrations, without, however, reaching dangerous levels.

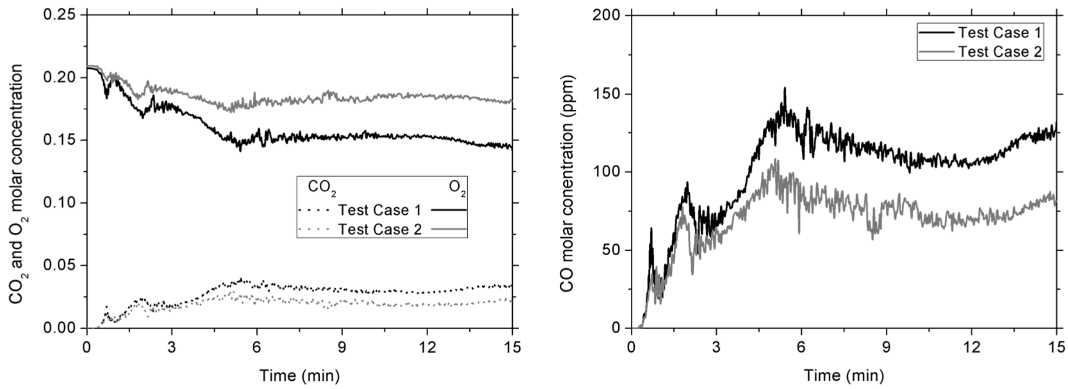

Figure 5: Time evolution of O_2 and CO_2 (left) and CO concentrations (right) in the middle of the kitchen, at a height of 1.6 m.

5 CONCLUSIONS

A CFD tool has been used to simulate the thermal flow-field developing in a full-scale two-storey residential building during a fire. The fire resistance behaviour of the building is evaluated considering two alternative building techniques; steel-skeleton combined with drywall systems and reinforced concrete in conjunction with brick walls. Detailed physical properties have been used to describe the thermal behaviour of the various building materials; the effects of gypsum dehydration were taken into account by utilizing temperature-dependent properties for the gypsum plasterboards. Gas velocity and temperature predictions have been used to visualize the developing flow-field. Predicted wall temperatures allowed the assessment of the fire resistance behaviour of the investigated building techniques. Finally, gas temperature and gas species concentration predictions allowed risk assessment for the tenants of the building. The ability of currently available CFD tools to effectively simulate fire spreading in realistic residential fire scenarios has been demonstrated. However, due to the complexity of the occurring physico-chemical phenomena, further validation studies are needed to assess the quantitative accuracy of the obtained predictions.

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