Fire in Confined Spaces: Reality and Numerical Simulations

***A.M. Lacasta*[1]*, S. López Moreno*[2] *and A.H. Romero*[2]**
[1]*Departament de Física Aplicada, Universitat Politècnica de Catalunya,*
Av. Dr. Marañon 44, E-08028 Barcelona, Spain.
[2] *CINVESTAV Unidad Queretano, Libramiento Norponiente No 2000,*
Real de la Juriquilla, 76230, Queretano, Qro, Mexico

Abstract

Fire and smoke in enclosed spaces behave differently from those in open ones. Depending on scenario dimensions, fuel and ventilation, the fire passes through different stages after ignition. Together with the performance of real experiments, the use of Computational Fluid Dynamic models can be very useful to understand fire propagation behavior. In this work, we compare numerical results with real observations and measurements. The "Fire Dynamics Simulator" (FDS), based on Large Eddy Simulation techniques, is used to reproduce some real scenarios under the same fuel and ventilation conditions. Dynamical evolution of several magnitudes such as temperature, pressure, oxygen concentration and combustion products is evaluated and discussed.

1 Introduction

The use of mathematical models to numerically reproduce fire propagation is quite recent mainly due to the complexity and diversity of all the physical phenomena involved: fluid dynamics, heat transfer and combustion (Drysdale, 1998). Depending on the fuel type, different combustion products will be generated, but their quantity and other magnitudes, such as the heat released or the temperature reached, will also depend on many other factors. In general, fire in enclosed spaces behaves differently from that in open ones. In the first case, the dimensions of the scenario where fire takes place, the openings and all the elements inside the scenario, determines its dynamical evolution (Novozhilov 2001, Baum 1994).

Basically, two different types of models have been developed to simulate fires: zone models and field models (Olenick 2003). Zone models describe how fires evolve in compartments (Quintiere 1984, Forney 1994). Each compartment is subdivided in two volumes, a hot upper layer and a cooler lower layer. Each layer is considered uniform in temperature and composition. Mass and energy conservation equations and some empirical laws lead to a system of equations which determines the physical parameters of interest. In general these models are able to predict the interface height between the two layers and their temperatures, but are unable to provide detailed spatial distributions of the physical properties.

Field models use Computational Fluid Dynamics (CFD) to solve numerically the 3D governing conservations equations (energy, momentum and species). The use of CFD models enables fires in complex geometries to be described, with the incorporation of a wide variety of other physical phenomena. Basically, the space is divided into a large number of rectangular cells within which the gas variables are assumed to be uniform but changing with time. The conservation equations are numerically solved, by expressing their differential forms in finite differences.

The main difference between the various CDF models when applied to fire problems refers to how turbulence is simulated. Direct Numerical Simulations (DNS) aims to resolve all the relevant scales of the turbulent flow. This is the most accurate procedure, but it is very computationally demanding, and thus inappropriate for many fire applications. Another possibility is to introduce a turbulent model, either for all the turbulence scales (RANS models) or only for the smaller ones (LES models). RANS model uses a Reynolds-average form of Navier-Stokes equations including additional equations for the turbulent kinetic energy and the energy dissipation rate. Because of its inherent time-averaged character, it is often argued that important transient events and the evolution of large eddy structures characteristic of most fires are lost with such an approach. With the development of more powerful computers, CFD models based on "Large Eddy Simulation" (LES) techniques have begun to be widely used in fire problems.

LES techniques imply that processes occurring on scales larger than the system cell size are calculated directly, and those on the sub-grid-scales (SGS) are modeled or approximated. The turbulent mixing of the gaseous fuel and combustion products with the local atmosphere surrounding the fire determines the burning rate. The basic idea of LES techniques is that the eddies that account for most of the mixing are large enough to be computed directly from the equations of fluid dynamics. The SGS dissipative processes can be approached in different ways, from the original Smogarinsky model (Smogarinsky, 1963) to the Dynamic Viscosity Models (Germano, 1991).

The Fire Dynamics Simulator (FDS), developed by McGrattan *et al.* at the National Institute of Standards and Technology (NIST), is a CFD model that uses LES techniques (McGrattan, 2004). In this paper, we present the results of applying FDS to describe fire evolution in a fire-tunnel (container) under some different experimental conditions. Since the container is provided with three thermocouples, a direct comparison between the experimental realization of a fire in the compartment and simulation can be carried out.

In Section 2, we summarize the main characteristics of the FDS model. In Section 3, we describe the real considered scenarios. In Section 4, we discuss the results of the comparison between reality and numerical simulations. Finally, in Section 5 we present our conclusions.

2 NIST Fire Dynamics Simulator (FDS)

Here we summarize the main characteristics of the FDS model. A complete description is given in Ref. (McGrattan, 2004). FDS is a Computational Fluid Dynamics model of fire-driven fluid flow. Equations are solved numerically by dividing the physical space where the fire is to be simulated into a large number of rectangular cells. FDS computes the temperature, density, pressure, velocity and chemical composition within each numerical grid cell at each discrete time step. The model solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow. This type of model solves the fundamental equations of mass, momentum and energy. Turbulence is treated by means of the Smagorinsky form of Large Eddy Simulation (LES).

With regard to the combustion, FDS uses a mixture fraction model. The mixture fraction is a conserved scalar quantity that is defined as the fraction of gas at a given point in the flow field that originated as fuel. The model assumes that combustion is mixing-controlled, and that the reaction of fuel and oxygen is infinitely fast (which is a good approximation while a typical fire time propagation is much larger than the combustion time). The mass fractions of all of the major reactants and products are derived from the mixture fraction by means of empirical "state relations".

Both Navier-Stokes Equations and the boundary conditions include terms of heat conduction, convection and radiation. Radiative heat transfer is included in the model by the solution of the radiation transport equation for, in general, a non-scattering gray gas. The radiation transport is discretized in approximately 100 solid angles. The behavior of solid surfaces depends on the burning and thermal characteristics of the material. FDS considers several thermal boundary conditions, and different kinds of materials such as thermoplastics or charring materials. The pyrolysis rate is modeled with a single Arrhenius reaction.

FDS is freely-available to researches and designers. It is widely used in a variety of problems, from the simulation of large scale fire experiments (Hamins 2004) to the reconstruction of accidental fires (Madrzykowski 2002, Rein 2004).

3 Experimental setup

Motivated by current research collaboration with the Fire Brigade of *Generalitat de Catalunya* (Spain), we have performed several studies addressed to better understanding fire behavior by comparing real fires with those obtained by simulation. Although most of our studies refer to real accidental fires, here we present results for deliberate ones in a fire-tunnel used by firefighters in their training. The fire-tunnel is shown in Fig. 1.

Figure 1. Experimental container with a diagram showing the thermocouple positions.

It is a metallic container of dimensions 12 m x 2.4 m x 2.5 m divided into two rooms: the main compartment, where fire takes place, and a small entrance compartment. The combustible material consists of wooden panels placed at the front part of the main container, fixed on the walls and the ceiling. Pieces from an additional panel are placed at one of the corners, where the fire will be started. Typically, between 6 and 10 pieces are used, each one of dimensions 2.15 m x 1.20 m x 16 mm.

With regard to the vents, the container has:

- Two lateral doors (2m x 1m) each one divided in two parts, upper and lower, than can be open and/or close separately.
- Two back doors, one on the container wall and the other on the compartment separation wall.
- A chimney with a cover that can be easily opened and closed.

Within the compartment, temperature is registered by three thermocouples, whose positions are also shown in Fig.1.

Several features of fire propagation can be observed by performing experiments in such a container. By managing the different openings, oxygen supply and temperature can be monitored. On the other hand, suppression or control of fire and smoke by water can also be tested.

4 Simulation results

The scenario to be simulated with FDS is shown in Fig.2. Dimensions and distribution of openings and combustible have been introduced to fit the real scenario described in the previous section. A volume discretization of about 90000 cells has been used.

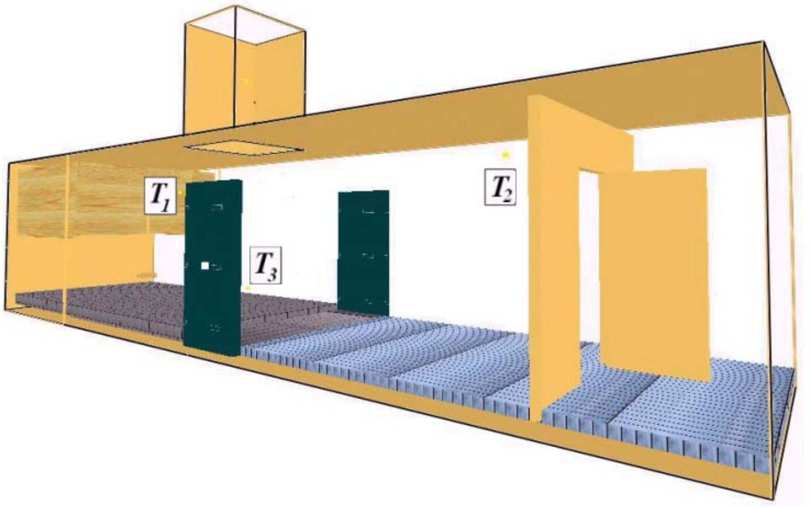

Figure 2. Computational scenario

Once the fire is initiated at the corner, part of the wood starts pyrolyzing, releasing inflammable gases which burn as they mix with air. Fire evolves first developing upward flames and, after some time, spreading in a lateral way under the ceiling. In Fig. 3 we show these stages of evolution both for experiment and simulation. A layer of flames and hot smoke is the formed in the upper part of the container, and the temperature distribution is stratified at a high-temperature and low-temperature zones. This can also be observed in the simulation, as shown in Fig.4.

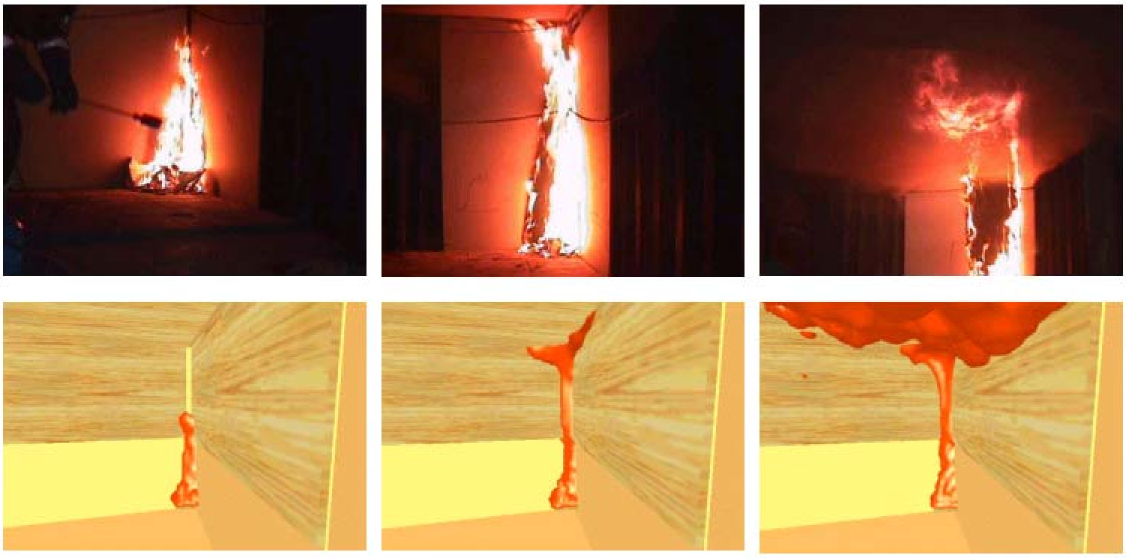

Figure 3. Experiment and simulation at the first stages of evolution

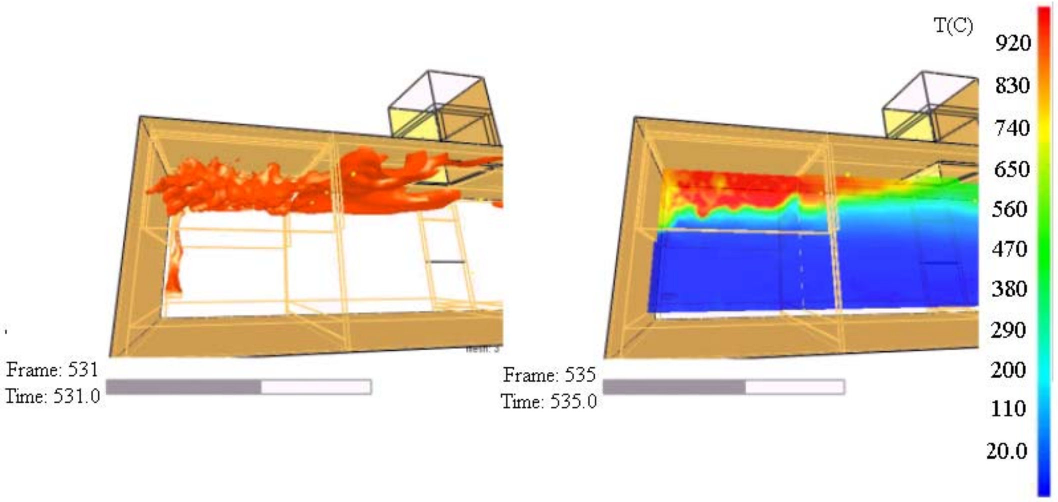

Figure 4. Left side: spreading of the flames when they reach the ceiling. Right side: temperature distribution at a central plane along the container.

The next stages in fire development depend very much on the ventilation conditions. In general, the fire continues growing to its "fully developed" stage where all of the fuel available is involved to its maximum extent according to oxygen limitations. In some conditions, the transition from a growing fire to a fully developed one can be very fast (flashover).

When a fire develops in the compartment, a pressure gradient is established between a layer with positive pressure (above atmospheric pressure) at the top, and a layer of negative pressure (below atmospheric) at the bottom. The interphase between both layers is the "neutral plane". During fire development, the thickness of the pressure layers change and a movement of the neutral plane takes place. When an opening is closed, the available oxygen decreases and, the neutral plane descend. This phenomenon can be clearly observed in the experimental container.

Fig.5 shows the real temperature evolution for the three thermocouples inside the compartment. Essentially, during the whole evolution three of the lateral doors remain closed while the other lateral door and the chimney are occasionally opened and closed. While the fire is growing, the back door remains open. For two periods of time the back door is closed, leading to the descent of the neutral plane and the presence of two peaks on the temperature levels.

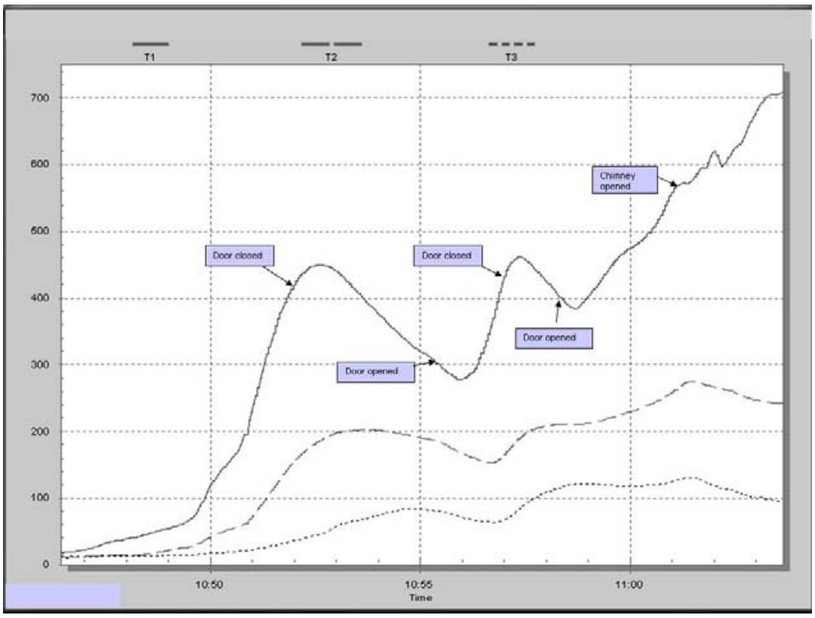

Figure 5. Temperature evolution for the experimental container

Data represented in Fig. 5 was registered during a firefighter training session where, in addition to the actions on the back door previously described, many other minor actions, on the laterals doors and the chimney, were also applied. Such actions, directed to control the initial fire growth and the amount of smoke in the container, depend on the particular fire evolution and are not registered. This means that it is impossible to reproduce Fig.5 in detail by simulation, although the main phenomena should still be observed. On the other hand, from simulation we can obtain not only temperature but also other magnitudes of interest, such as heat released or the concentration of the different gas components.

Several simulations have been performed, under conditions similar to that described for the real container. In order to show the effect of closing the back door of the container, in Fig. 6 we present the pressure distributions with the main focus on the neutral plane. When the door is closed, the layer of positive pressure gets wider and the neutral layer descends. In Fig. 7 we present the temperature at the three thermocouples as well as the mass of two gaseous components: the oxygen and one of the combustion products. As in the real container, here the back door remains closed during two specific time intervals. During such intervals, the oxygen (and thus the combustion reaction) decreases, leading to a decrease of temperature. When the door is opened, the oxygen increases and after some delay the temperature increases.

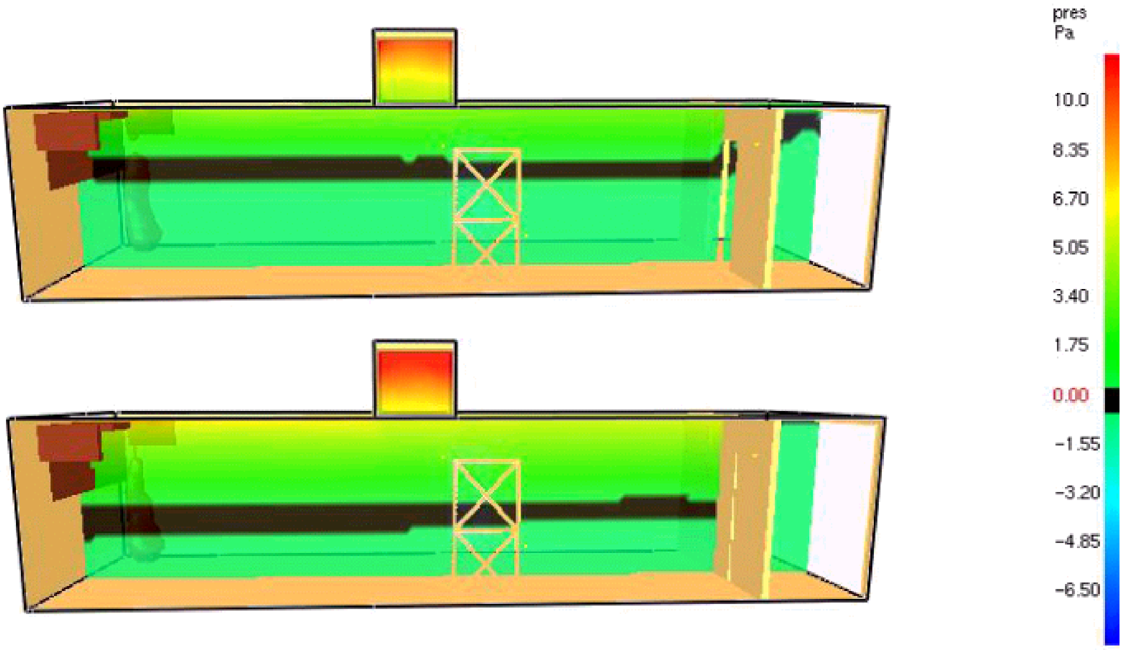

Figure 6. Results from simulation. Descent of the neutral plane (black line) when an opening is closed.

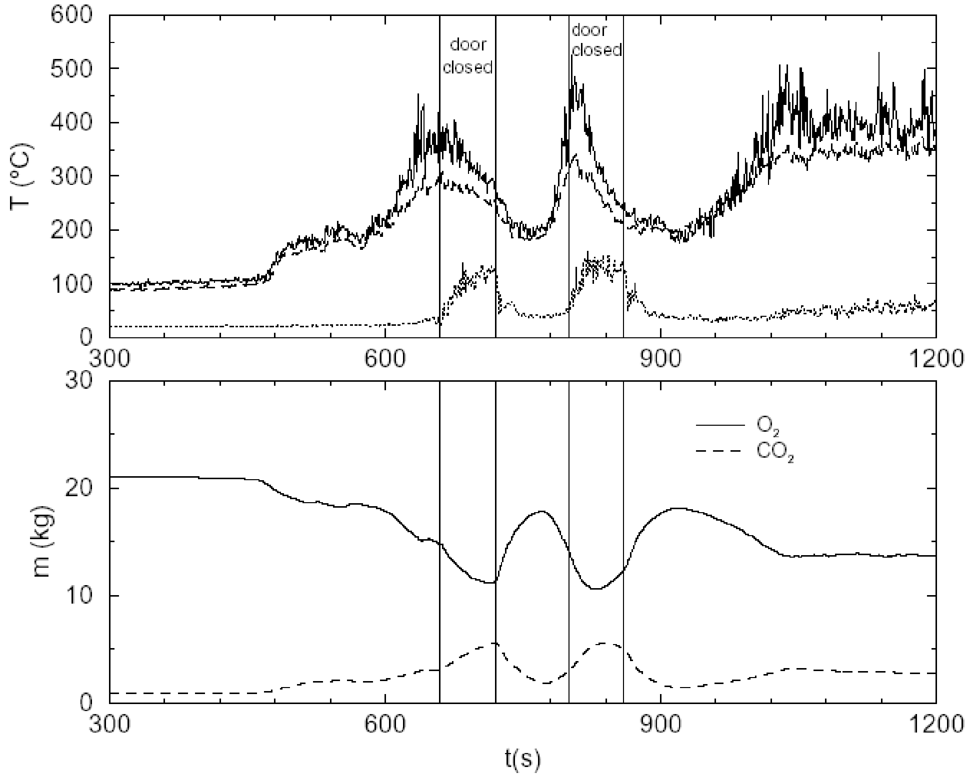

Figure 7. Results from simulation. Temperatures and masses of two components as function of time. Vertical lines indicate the moments when a vent is being opened/closed: the black door remains closed between t=660s and 720s and between t=800s and 860s.

5 Conclusions

We have studied some features of fire propagation in enclosed spaces. Fire Dynamics Simulator (FDS) has been used to reproduce some of the phenomena observed in a real container. After the experimental realization, a computer simulation was set up to mimic the experiment. We did use the same container dimensions and same number of rooms. The simulation is able to give the temperature, density and species mass evolution for almost the same experimental conditions. With those parameters we can compare directly with the experimental measured temperature inside the container. In this work we have focused in the particular case where the openings were closed during the time of the fire development. As well as in our simulations, the experiment reveals changes on the neutral plane (plane where the environment pressure happens to be the atmospheric one). The plane movement can be also correlated to changes in the mass concentration of several species. Even though in the simulation we did not account for all the experimental changes, our simulations reproduces rather well the temperature behavior during the closings. We can conclude that in enclosed environments, fire behaves rather different and depend very much on the oxygen availability. If during the fire the oxygen conditions changes, changes on other physical variables such as pressure, chemical concentration of some species, etc will change accordingly.

Acknowledgments

The authors would like to thank Sebastià Massaguer, Félix González and Santiago Rovira, from Firefighter Brigades of the Generalitat de Catalunya, for their support and fruitful discussions. AML acknowledge support from the Ministerio de Educación y Ciencia (Spain) under Project No. BFM2003-07850-C03-01-02. AHR and SLP thanks to Conacyt-Mexico under Project No J-42647-F and CINVESTAV-Mexico, for supporting our visit to Spain.

References

Baum, H.R., Ezekoye, O.A., McGrattan, K.B. and Rehm, R.G., 1994. Mathematical Modeling and Computer Simulation of Fire Phenomenon, *Theoretical and Computational Fluid Dynamics*, 6 pp 125–139.

Drysdale, D., 1998. *An Introduction to Fire Dynamics*, John Wiley & Sons, Ltd, Chichester, England.

Forney G.P. and Moss W.F., 1994. Analyzing and Exploiting Numerical Characteristics of Zone Fire Models, *Fire Science and Technology*, 14 pp 49–60.

Germano M., Piomelli U., Moin P., and Cabot W.H., 1991. A Dynamic Subgrid-Scale Eddy Viscosity Model, *Physics of Fluids A*, 3 pp 1760–1765.

Hamins, A. et al, 2004. Report on Experiments to Validate Fire Dynamic and Thermal-Structural Models for Use in the World Trade Center Investigation. NIST,Gaithersburg, Maryland, 2004.

Madrzykowski, D., Forney, G.P. and Walton, W.D., 2002. Simulation of the Dynamics of a Fire in a Two-Story Duplex – Iowa, December 22, 1999. NISTIR 6854, NIST, Gaithersburg, Maryland.

McGrattan, K.B., Baum, H.R., Rehm, R.G., Hamins, A., Forney, G.P., Prasad, K., Floyd, J.E., Hostikka, S., 2004. Fire Dynamics Simulator (Version 4), Technical Guide. NISTIR6783, National Institute of Standards and Technology, Gaithersburg, Maryland.

Novozhilov, V., 2001. Computational fluid dynamics modeling of compartment fires*, Progress in Energy and Combustion Science*, 27 (6) pp 611-666.

Olenick, S. and Carpenter, D., 2003. Updated International Survey of Computer Models for Fire and Smoke, *Fire Protection Engineering*, 13(2) pp 87–110.

Patankar, S.V., 1980. *Numerical Heat Transfer and Fluid Flow*. Hemisphere Publishing, New York.

Quintiere J., 1984. A Perspective on Compartment Fire Growth. *Combustion Science and Technology*, 39, pp 11–54.

Rein, G., Bar-Ilan, A., Alvares, N. and Fernandez-Pello, C., 2004. Comparison of three Fire Models in the simulation of Accidental Fires, Internacional Conference on Computacional Simulation Models in Fire Engineering and Research, October 2004, Spain, pp 213-234.

Smagorinsky, J., 1963. General Circulation Experiments with the Primitive Equations. I. The Basic Experiment. *Monthly Weather Review*, 91 pp 99–164.