MODELING FIRE GROWTH AND SPREAD IN HOUSES

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In cooperation with the fire protection engineering community, a numerical fire model, Fire Dynamics Simulator (FDS), is being developed at NIST to study fire behavior and to evaluate the performance of fire protection systems in buildings. Version 1 of FDS was publicly released in February 2000, and Version 2 in December 2001 [1, 2]. To date, about half of the applications of the model have been for design of smoke handling systems and sprinkler/detector activation studies. The other half consist of residential and industrial fire reconstructions. Throughout its early development, FDS had been aimed primarily at the first set of applications, but following the initial release it became clear that some improvements to the fundamental algorithms were needed to address the second set of applications. The two most obvious needs were for better combustion and radiation models to handle large, spreading fires in relatively small spaces like residences as opposed to industrial settings.

FDS 2 contains a relatively simple mixture fraction-based combustion model which assumes that the reaction of fuel and oxygen is infinitely fast, an appropriate assumption given the limited resolvable length and time scales of most practical simulations. Work is underway now to modify the combustion model to handle under-ventilated scenarios. Thermal radiation is handled via the solution of the radiation transport equation (RTE) for a non-scattering gray gas. The equation is solved using techniques similar to those for convective transport in finite volume methods for fluid flow, thus the name given to it is the Finite Volume Method (FVM). The new combustion and radiation routines allow for calculations in which the fire itself and the thermal insult to nearby objects can be studied in more detail than before when the fire was merely a point source of heat and smoke. Studies have been performed to examine in detail small scale experiments like the cone calorimeter [3], and fundamental fire scenarios like pool fires [4, 5] and small compartment fires [6]. These calculations are finely resolved, with grid cells ranging from a few millimeters to a few centimeters. However, the majority of model users still use the model for smoke and heat transport in increasingly complex spaces. The challenge to the model developers is to serve both the researchers and practitioners with a tool that contains the appropriate level of fire physics for the problems at hand.

Modeling flame spread in a complex enclosure requires an accurate calculation of the thermal flux onto the solid surfaces, and robust sub-models of the thermal decomposition and pyrolysis of the surface materials. Because of the cost of the three-dimensional, time-dependent calculation of the gas phase flow, the radiation and solid phase routines must be relatively simple and efficient. In FDS, the radiative transport equation for a non-scattering gas is solved using a finite volume method [3]. For the calculation of the gray mean absorption coefficients, a narrow-band model, RadCal [7], is combined with FDS. At the beginning of a simulation, the absorption coefficients are tabulated as a function of mixture fraction and temperature. During the simulation the local absorption coefficient is found from a pre-computed table.

Solid surfaces are treated as either thermally thin or thick, with constant temperature thermal properties. There is nothing that prevents the inclusion of more detailed properties other than a lack of a suitable database for common household furnishings and building materials. A simple one-dimensional heat transfer calculation is performed to obtain the temperature of the material in-depth. An ignition temperature is prescribed by the user, which once obtained, directs the code to generate fuel gases at the surface. No charring effects are considered. The materials burn at a rate proportional to the energy fed back from the fire. Recent work by Fleischmann and Chen [8] on the ignition properties of upholstery suggests that treating a fabric covered slab of polyurethane foam as thermally-thin produces a slightly better correlation than thermally-thick. Flame spread is achieved merely from the heating, igniting and burning of individual surface grid cells whose lateral dimensions are the same as the gas phase grid cells. An obvious problem with this approach is that sub-grid scale flame spread is not accounted for. Often the gas phase numerical grid is so coarse that flame spread is not achieved because the distance from one surface grid cell to another is too large and the temperature and heat flux from the gas phase is "smeared out." This phenomenon is often referred to as "grid dependence," and it is the most important consideration for the user.

The new combustion and radiation solvers have been applied to a wide variety of fire problems to assess the cost, robustness and accuracy of the new routines. One of the first concerns for the various sub-models was their cost. The mixture fraction combustion algorithm requires the solution of an additional transport equation, adding about 20 % to the overall CPU time. The radiation routine could cost an unacceptably high amount if the gray gas assumption was not applied, and if the entire RTE were solved every time step. Since radiation accounts for about 35 % of the energy transport in a typical fire scenario, it was decided that no more than 35 % of the CPU time ought to be devoted to the radiation transport. As a cost-saving measure, the gray RTE equation is solved gradually over approximately 15 time steps. Every 3 time steps 1/5 of the approximately 100 solid angle equations are updated, and the results stored as running averages. Although the user can control these parameters, it has been found that with the given defaults, the finite volume solver requires 15 % to 20 % of the total CPU time of a calculation, a modest cost given the complexity of radiation heat transfer.

A few calculations are presented here that are typical of the type of fire scenario that the model has been re-designed to address. Snapshots from the FDS companion package Smokeview are shown in Figs. 1 and 2. In Fig. 1 a small cushion is ignited on a couch in a room that is roughly 5 m by 5 m by 2.5 m with a single door leading out. The fire grows to the point of flashover in about 3 min. In Fig. 2, a house made entirely of wood burns from a fire on the stove. The room fire example is based on an actual experiment performed by the University of Maryland and the Bureau of Alcohol, Tobacco and Firearms. The house fire is entirely fictitious, and meant to serve simply as a demonstration of various features of the model.

The new combustion and radiation routines are crucial to these calculations because towards flashover and beyond, the room conditions are severely underventilated and radiation is the domi-

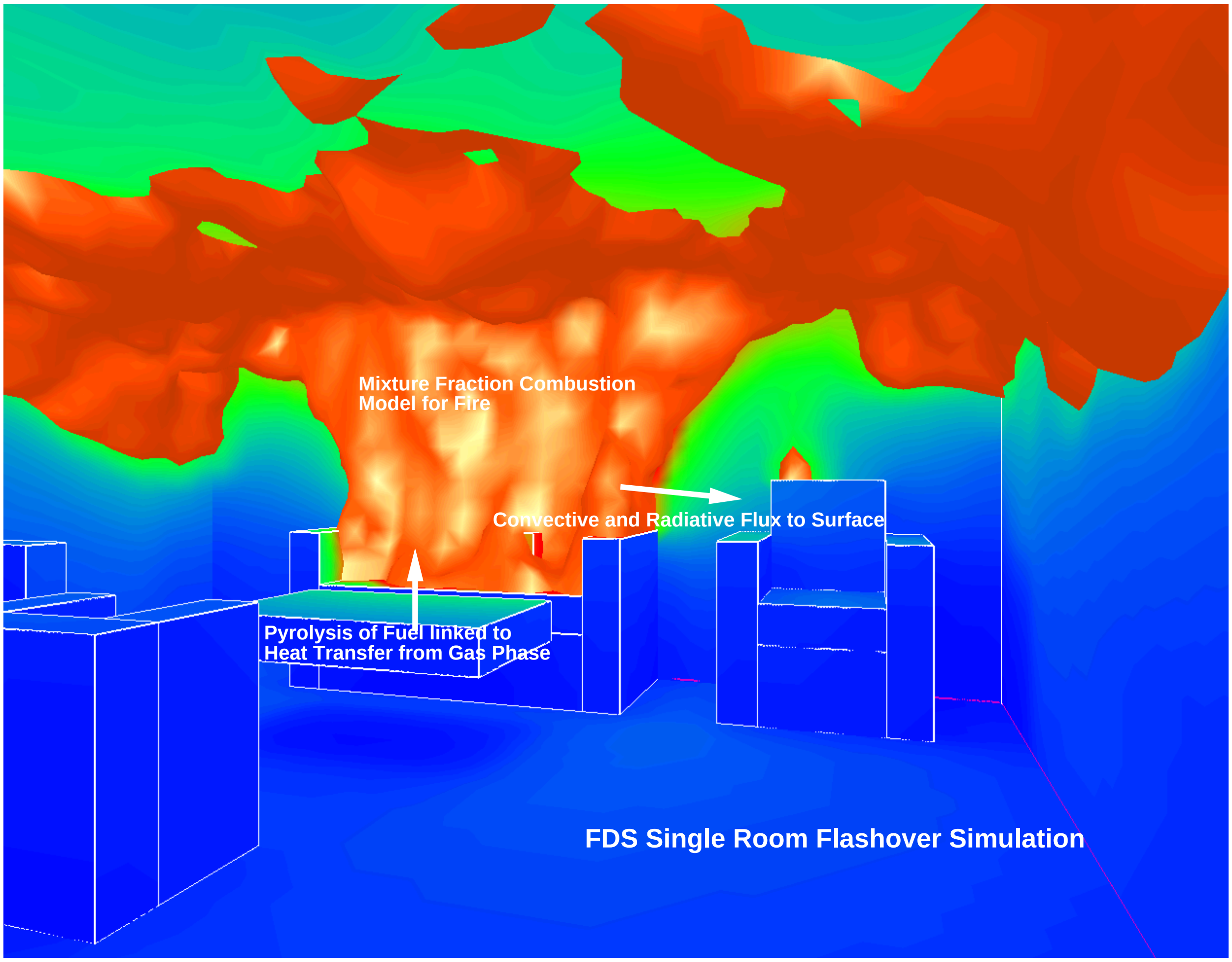

FIGURE 1: Sample simulation of a room fire using the new combustion and radiation routines. Shown is the flame sheet where the mixture fraction is at its stoichiometric value.

nant mode of heat transfer. The fuel consists of polyurethane, wood, and a variety of fabrics whose thermal properties are known only in the most general sense. The soot volume fraction is based solely on estimates of the smoke production; the actual values within the flames are unknown. In generating effective absorption coefficients with RadCal, it is assumed that the fuel is methane. Clearly more research is needed to fill in many of the missing pieces. Refinement of the numerical algorithm and comparison with experiment is ongoing.

As far as flame spread is concerned, we need relatively simple models of the thermal decomposition and pyrolysis processes that can be applied to the widest range of fuel types. Although there exist in the literature fairly sophisticated models, many are difficult to apply in large scale applications because of the uncertainties in the gas phase temperature and radiative flux to the surface.

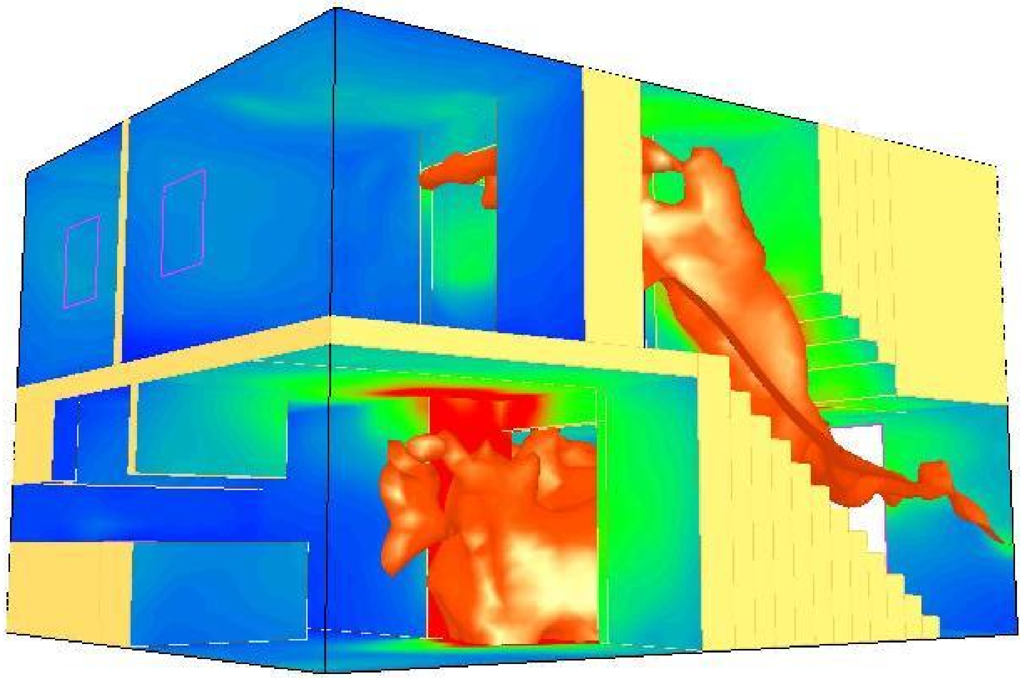

FIGURE 2: Sample simulation of a house fire using the new combustion and radiation routines. Shown are the flame sheet and heat fluxes on the walls.

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[2] K.B. McGrattan, G.P. Forney, J.E. Floyd, and S. Hostikka. Fire Dynamics Simulator (Version 2), User's Guide. Technical Report NISTIR 6784, National Institute of Standards and Technology, Gaithersburg, Maryland, November 2001.

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