Progress in 3-D Modeling of Wood Fire Growth using a PC

Mark A Dietenberger, Ph.D.
USDA Forest Service – Forests Products Laboratory
Madison Wisconsin

The fire growth research at FPL is mainly focused on studies that would contribute fire performance data and engineering models of wood fire for use in performance-based building codes. Specially modified tests in the cone calorimeter are used to derive fundamental fire properties of various wood products such as composites with fire retardant treatments. These properties are used first in modeling fire performances in the ASTM E84 and ISO9705 full-scale tests required in prescriptive building codes, and to also be used in modeling a more general fire scenario for hazard analysis of wood products.

Progress in numerical modeling of fire growth begins with the successful PC-based 3-D model for cushioned mockup furniture developed under NIST-BFRL sponsorship more than a decade ago. This furniture fire model (FFM) is truly 3-D because it could simulate up to four furniture cushions in any orientation that are also subdivided into several surface elements. A small polygonal region ignited on any surface element gives rise to an initial fire that spread by expanding the burning region outward and adding more vertices to the burning polygon. The practical Hottel-Zonal method is used to calculate the 3-D thermal radiation fluxes from attached flames and upper gas layer for preheating the virgin surface elements and imposing radiation heat flux to the burning surface elements. The flame front velocities, which move burning-polygon vertices outward, vary in magnitude and direction as functions of flame front and surface orientations (due to air entrainment) and preheated temperature of an adjacent virgin surface element. This model executes rapidly on a PC because explicit time integrations is only applied to (1) radiation preheat of surface elements, (2) spread of flame front position vectors, and (3) burn-rate history (from cone calorimeter data) of ignited surface elements. The air entrainment, combustion, flame structure, emissions, and thermal radiation are treated as quasi-steady.

The FFM code was also linked to the FAST18 code, a PC-based multi-room model for the spread of smoke and product gases as driven by a heat release source. The thermal radiation in the fire-source room was computed with the Hottel-Zonal method as a replacement to FAST simple thermal radiation model. This combined code has just recently been brought up-to-date. Visual Fortran compiler was used to run the model in a Windows 2000 environment on a PC with a Pentium III chip. In the simulation, the 4-cushion mockup furniture was placed in the center of ISO9705 test room with concrete floor and walls/ceiling lined with gypsum board (The door soffit was removed to simulate more closely the environment of the furniture calorimeter at NIST). The original parameters (including 10 seconds time-step) for the FFM code resulted in 23 seconds CPU time. The time steps were then shortened to 1 second (same as used in the FAST18 code) and several more iteration cycles were applied to the quasi-steady portion of the model. This only increased the CPU time to 3 minutes, making it suitable even for a laptop computer. However, this improved performance required re-calibration of only one bench-scale parameter identified as the flame foot size (reduced by 35%) for creeping flame spread. The overall comparison with the furniture calorimeter data of HRR, MLR, soot production, and video flame-spread observations were also improved and is described in the presentation. Included in the presentation are model comparisons with several furniture calorimeter tests of various furniture mockups as found in the presenter's Ph.D. dissertation over a decade ago.

A more general model of a 3-D wood fire requires significant improvements to the furniture fire model, particularly in the processing of the bench-scale data. First, scaling of HRR and MLR data does not work very well for wood-based materials. For example, a thin, heavy, and inert board inserted behind the test sample (as in the ASTM E84 test) will result in eliminating the second-HRR-peak in some wood materials, and will even vary with the imposed heat flux. In another case, the wood surface subjected to considerable carbonization during the heat-up phase will have much reduced first-HRR-peak. The differing ignition burner and backing materials between ASTM E84 and ISO9705 tests will require differing specialized cone calorimeter test procedure. We conclude that if we want to avoid having to change around specialized testing procedures or accumulating many cone test results for input to FFM, then we need to resort to proper kinetic modeling of wood pyrolysis of thermally thin samples with small thermocouples inserted, and use the resulting model in a finite-element heat conduction solutions for thick wood.

The ignition and creeping flame spread properties for typical materials varies greatly with oxygen, temperature, and flow of entrained air to the flame front. However, variations in wood pyrolysis are also significant in affecting ignition and creeping flame spread and should not be overlooked. Unlike the PMMA, the wood volatiles have significant variation in heat of combustion depending if wood is undergoing flash-like pyrolysis at high temperatures or just carbonization at low temperatures. As an example, the LIFT apparatus (as described in ASTM E1321) imposes a long preheat time on the sample prior to lateral flame spread. The difficulty with this procedure is that wood surface carbonization becomes significant and one is not able to achieve lateral flame spread. In addition, one would not have a reliable minimum surface temperature for flame spread on the wood surface, largely because of the flash-like pyrolysis competing with carbonization process at different wood internal temperatures. Indeed, FRT in the wood can increase the charring process to the point where the spark plug cannot ignite the volatile-air mixture, but in which a nearby burner can still burn up the volatiles. For this we use an auxiliary 1 kW methane burner in the volatile stream flowing from the cone radiant heater.

Finally, the standard cone calorimeter tests for wood (and unlike PMMA or Polyurethane Foam) do not satisfactorily emulate smoke and CO production in full-scale tests. For the wood samples, we found the smoke production decreases suddenly when the HRR goes below 1 kW (or 100 kW/m^2 for HRR flux), acting as if the smoke point occurs at 1 kW. Using an auxiliary methane burner at 1 kW or greater seems to alleviate somewhat the smoke point problem. Since the flames in the cone calorimeter and room tests are quite over-ventilated, the source of carbon monoxide is from the wood pyrolysis. Evidence shows that at low temperatures, the potassium in the wood catalyzes some of the CO. Then most of CO results from the thermal cracking of heavy tar at temperatures above 450 Celsius. The soot and CO will then pass through the flame sheet (or even miss it) and they will oxidize to some degree. Modeling this process is important, but if it is a very fast process, it should be converted to quasi-steady form for use in FFM.

Analytical modeling for some full-scale tests was recently feasible through (1) the above specialized tests in cone calorimeter that better emulate full-scale exposure, (2) by better analytical characterization of imposed heat fluxes on the material from a growing full-scale flame, and (3) availability of novel Laplace transform solutions. The existence of these analytical solutions can be quite useful. If good predictions are found for fire growth in the ASTM E84 tunnel test or ISO9705 room test, then one can also identify combustibility parameters from the cone calorimeter in which to organize materials to different levels of full-scale fire performance. The analytical solutions also provide a benchmark for validating algorithms of numerical fire growth models. Finally, the analytical solutions serve an instructive purpose because of their easy implementation on spreadsheets typically found on PCs.