CFD SIMULATION OF A 2.5 MW OIL POOL FIRE IN A NUCLEAR POWER PLANT CONTAINMENT BUILDING USING MULTI-BLOCK LARGE EDDY SIMULATION

Jason Floyd
Building and Fire Research Laboratory
National Institute of Standards and Technology
100 Bureau Drive Stop 8663
Gaithersburg, Maryland, 20899, USA
P: (301) 975-6855, F: (301) 975-4052, jason.floyd@nist.gov

Introduction

Implementing performance-based regulations require the presence of analytical tools and analytical methods [1]. In the case of fire safety regulation, there are three categories of tools available for demonstrating the performance of a structure and its fire protection systems [2]. These categories include hand calculations, lumped-parameter models, and field models. For most scenarios, one of the first two methods should be all that is required to demonstrate performance. However, there will be instances where neither of the first two methods will be enough. Situations, for example, with highly complex geometry or where detailed knowledge of spatial effects are needed may require the use of field models. In some sense, this is unfortunate, since the use of field models requires a much large expenditure in terms of both time and computational resources [3]. However, the time required to use a field model can be greatly reduced by the use of a multi-block solution scheme. To demonstrate the potential of a multi-block field model for fire simulation, a multi-block version of FDS was used to simulate a portion of an oil pool fire experiment that took place in the HDR facility in Germany [4].

HDR Facility

The HDR test facility [slide 7] was the containment building from a decommissioned nuclear reactor in Germany. The facility was a cylinder 20 m in diameter and 50 m in height and was topped by a 10 m radius hemispherical dome. The facility had eight levels and over 60 compartments. Multiple vertical flowpaths were present in the form of two axially located sets of equipment hatches, two staircases, and an elevator shaft. The total free air volume in the facility was 11,000 m^3 of which the dome contained 4,800 m^3 [5].

The test simulated for this work is test T52.14 [slides 8-11] an oil pool fire test done in 1987 that occurred on the level below the dome. The T52.14 test used a 2 m^2 pool of Shellsol-T, a liquid hydrocarbon, placed on a weighing platform in a firebrick lined compartment beneath the dome. This compartment was connected to a second firebrick lined compartment beneath one of the equipment hatches. The hatches both above, leading to the dome, and below this compartment were open. The test started by igniting 50 liters of oil followed by adding additional oil at a rate of 5.6 L/min once the initial volume nearly depleted as determined by the weighing platform. The entire facility was instrumented with 56 velocity sensors, 155 thermocouples, and 43 gas sampling lines [5].

Multi-block FDS

FDS, Fire Dynamics Simulator [slide 3] has recently been released as version 2 by the National Institute of Standards and Technology [6]. FDS is a CFD model that solves the low-Mach number form of the Navier Stokes equations using a Smagorinski turbulence model. The FDS uses a simple mixture fraction combustion model [7] where the user can define basic parameters of the fuel chemistry. The FDS radiation model is a finite volume method radiation solver for the gray gas radiation transport equation [8]. RADCAL [9], a narrow band radiation model, is used to determine absorption coefficients based on the local mixture fraction and temperature. In both version 1 and version 2 of FDS, a single-block solver was implemented.

Single-block solvers [slide 4], common in many field models, use one computational grid that spans the entire domain of interest. For many fire problems, this is an efficient method of defining the computation. In fire simulation, a lower grid resolution is needed to track smoke movement than is required to adequately simulate the region of active combustion. Thus, with one grid being used, the requirement to finely node the fire means that many more cells than necessary are located in regions where only smoke transport is occurring [slide 5]. Also, if more than one compartment is being simulated, than there is the potential for many grid cells to be defined as dead space in order to encompass the compartments [slide 6]. Both situations, large numbers of dead cells or higher than needed resolution, increase both the time required for a computation and the computational resources needed.

In a multi-block solver, the user may define more than one computational grid. Thus a fine grid could be defined for the region of combustion and a coarser grid defined for non-combusting regions. Also each compartment could have a separate grid defined for it, eliminating the need to carry a large number of dead cells. However, as with many numerical schemes, while multi-block solvers remove some computational effort by eliminating grid cells, they do increase the overall computational overhead for a problem. This is because the solver must expend effort to share information between grids at their shared boundaries. This extra effort, however, can be easily outweighed by the time saved be reducing the number of nodes. As part of the development effort for the next release of FDS, a multi-block solver has been added.

Multi-block FDS Model of HDR Test T52.14

The T52.14 test was simulated using a multi-block version of FDS. The region modeled included the entire dome and the two firebrick lined compartments on the level beneath the dome, slides 17 and 18. An open vent located beneath the room adjacent to the fire room and in the dome floor opposite the fire room simulate the connections to the remainder of the HDR facility. A reasonable nodding of the fire room entails using grid cells on the order of 10 cm in size. Since the computational domain is 20 m x 20 m x 26 m, this would require over 1.2 million grid cells. However, this would result in many dead cells as only a small fraction of the space beneath the dome is being simulated, the fire room and its adjacent space. Also, in the dome there is no combustion occurring. Thus, the dome does not need to be as densely noded as the other two compartments. Instead three grids were used: one for the fire room, one for the room adjacent to the fire room, and one for the dome. The first two grids had a 10 cm resolution and the dome grid had a 25 cm resolution. This resulted in the use of 600,000 grid cells, a savings of 50%. A second FDS run was performed with a grid at ¾ the linear resolution. [slides 13,14]

The FDS simulation was done for the steady-state portion of the test and was run until temperatures at the upper dome measurement grid were observed to reach a quasi-steady state solution. Both cases were run on a 2.2 GHz, Pentium IV, Linux machine. The full resolution case required 7.5 minutes of CPU time to one second of realtime, and the ¾ resolution case required 2.5 minutes/s. [slide 15]

Results

Computational results of the two models show that the multi-block version of FDS performs well for a number of parameters. FDS results for the fire room [slide 16] compared to both the collected data and some hand calculations show that FDS is accurately predicting the major conditions of the fire room. One great advantage of a field model, the ability to generate 3D data for visualization can be seen in the image showing the calculated flame sheet superimposed on a temperature contour centered over the pool of oil [slide 17]. This image shows that the flame sheet is entirely within the room; however, with the fire size being simulated one would expect that external burning would be occurring. FDS would appear to be under predicting the flame lengths. In the door way, FDS matches well the measured velocity profiles; however, temperatures are not as well predicted in this location [slide 18]. The measured data shows flame temperatures, which would suggest external burning. Since FDS is not predicting external burning, its doorway temperatures are low. An animation of the entire plume structure shows how the velocity is smoothly continuous across all three grids [slide 19]. An indication that the multi-block solver is handling the grid transition well.

Comparisons of temperatures in the hatch leading to the dome show that FDS is underpredicting temperatures at this location by 100 K [slides 20,21] and that FDS is predicting the plume in a slightly different location in the hatch. The velocities, however, appear to be reasonably well predicted by FDS [slide 22]. Some of these differences are probably due to the external boundary conditions. FDS simulates these as open boundaries, whereas in the HDR facility the two external openings were actually hydrodynamically coupled. In the dome, comparisons of temperatures [slides 23,24] show that FDS is now over predicting the bulk temperature by 30-40 K, but matching well the plume center temperature. This may be due to FDS not transferring enough heat to the dome structures as compared to the test. The predicted velocities [slides 25,26] indicate that FDS is predicting a somewhat narrower plume, which could result from the numerical grid and a slightly different location of the plume centerline. However, this measurement location is close to 20 m from the fire, and the FDS plume center is <2 m from the position given by the data. An animation of the plume in the dome is shown. [slide 27]

Concluding Remarks

A multi-block version of FDS clearly has tremendous potential as a tool for simulating fires in large, multi-compartmented structures. The current prototype version maintains well flows across grid boundaries, even for grids of varying mesh sizes. Energy fluxes across the boundary also appear to be well maintained. Lastly, FDS was able to accurately predict the location of the plume after 20 m of travel from the fuel source.

References

[1] Bertrand, R., and Dey, M., 2001, "International Collaborative Project to Evaluate Fire Models for Nuclear Power Plant Applications: Summary of 2nd Meeting," NUREG/CP-0173, US Nuclear Regulatory Commission, Washington, DC.

[2] Floyd, J., 2002, "Comparison of FDS and CFAST for Fire Simulation with HDR T51 and T52 Tests," NISTIR-6866, National Institute of Standards and Technology, Gaithersburg, MD.

[3] Floyd, J., 2002, "Numerical Simulation of a Compartment Fire in a Nuclear Power Plant Containment Building," ICONE10-22299, *Proceedings of the 10th International Conference on Nuclear Engineering*, ASME, Alexandria, VA.

[4] Schall, M., and Valencia, L., 1982, "Data Compilation of the HDR Containment for Input Data Processing for Pre-Test Calculations", PHDR Working Report 3.143/79, Project HDR Nuclear Center, Karlsruhe, Germany.

[5] Floyd, J., and Wolf, L., 2000, "Evaluation of the HDR Fire Test Data and Accompanying Computational Activities with Conclusions From Present Code Capabilities, Volume 4: Test Series Description and CFAST Validation for T52 Oil Pool Fire Test Series," NIST GCR 01-809, National Institute of Standards and Technology, Gaithersburg, MD.

[6] McGrattan, K., Baum, H., Rehm, R., Hamins, A., Forney, G., Floyd, J. and Hostikka, S., 2000, "Fire Dynamics Simulator (Version 2): Technical Reference Guide." NISTIR-6783, National Institute of Standards and Technology, Gaithersburg, MD.

[7] Floyd, J., Baum, H., and, McGrattan, K., 2001, "A Mixture Fraction Combustion Model for CFD Fire Simulation," *Proceedings of the International Conference on Engineered Fire Protection Design*, Society of Fire Protection Engineers, Bethesda, MD.

[8] Hositkka, S., and McGrattan K., 2001, "Large Eddy Simulation of Wood Combustion," Franks, C. ed., *Proceedings of Interflam '01*, Interscience Communications, London, England, Vol 2., pp 755-765.

[9] Grosshandler, W., 1993, "RADCAL: A Narrow-Band Model for Radiation Calculations in a Combustion Environment," NIST Technical Note 1402, National Institute of Standards and Technology, Gaithersburg, MD.