Development of a 3D Production Model in COMSOL for Thermal Hydraulics Analyses of ORNL's High Flux Isotope Reactor

Prashant K. Jain[1], Vaibhav B. Khane[2], James D. Freels[1]

[1]Oak Ridge National Laboratory, Oak Ridge, TN, USA
[2]Missouri University of Science and Technology, Rolla, MO, USA

Abstract

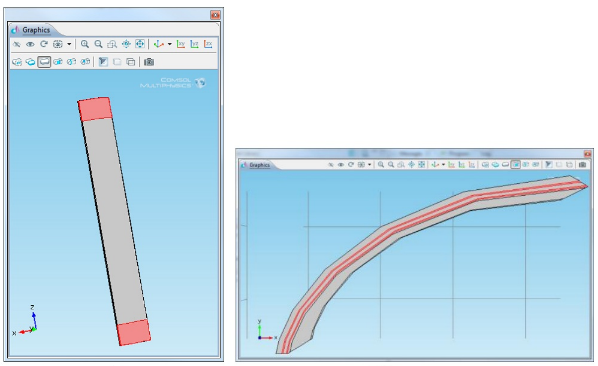
A production simulation model for thermal-hydraulics analyses of Oak Ridge National Laboratory (ORNL)'s High Flux Isotope Reactor (HFIR) has been developed in COMSOL Multiphysics. Development of the COMSOL model - which is now being applied to analyze HFIR's Low Enriched Uranium core - is guided by the following specific goals and criteria: (a) Model should capture the 3D involute geometry and other key features of the HFIR plates and channels. (b) Solution time for the steady state simulations should be within acceptable time and resource limits. (c) Accuracy of the production model in comparison with the detailed 3D model should be in an acceptable range. Only one fuel plate and one coolant channel of each HFIR fuel element (Inner and Outer Fuel Element, IFE and OFE) is modeled in 3D, known as 1P1C or One Plate One Channel model, and the effects of other plates and channels in each element are modeled through periodic boundary conditions. Side plates are not modeled explicitly. Their effects are captured by either a constant temperature or insulated boundary conditions at the side edges of the plate and coolant channels. Aluminum claddings of the HFIR fuel plates are captured accurately. In each fuel plate, the clad is present in the top and bottom 2" and in both 10mm thick layers sandwiching the 30mm thick LEU fuel/poison meat (Each HFIR fuel plate is 50mm thick). Radially contoured LEU fuel meat and poison along the involute is assumed to be uniformly smeared across the 3mm thick sandwiched region of each plate (heat generation zone). Furthermore, clads near the side edges of the fuel plate are not modeled explicitly and instead they are assumed to be made of smeared LEU fuel/poison material. No heat generation is assumed in these clad regions. Heat sources are calculated from separate MCNP calculations for the axially non-graded and axially graded LEU fuel types at the beginning of cycle. In MCNP calculations, HFIR core was divided into 19 longitudinal slices (along the height) and 8 radial slices in each fuel element (IFE: 19x8 elements, OFE: 19x8 elements). From MCNP results, volumetric heat generation (in W/m3) can be calculated for a given reactor power (100MW or 85MW) and specified in the clad-sandwiched region in the middle 20" of the fuel plate. Zero cut-offs are specified for the radial clad regions to ensure no heat generation near the side edges where the fuel plate touches the side plates. The developed COMSOL model simulates conjugate heat transfer with turbulent flow physics and thermal expansion physics. Both the standard k-ε Turbulence Model as well as the Low-Reynolds k-ε Turbulence Model have been used in the presented study. This COMSOL model will allow parametric studies to ascertain HFIR's thermal safety sensitivity on core fabrication and reactor operating parameters.

Reference

1. Office of Global Threat Reduction. Web link: http://nnsa.energy.gov/gtri, last accessed on 03/14/2012.
2. Reduced Enrichment for Research and Test Reactors. Web link: http://www.rertr.anl.gov/, last accessed on 03/14/2012.
3. J. Rest, Y. S. Kim, G. L. Hofman, M. K. Meyer, and S. L. Hayes, U-Mo Fuels Handbook – Version 1.0, Technical Report, RERTR Program, Argonne National Laboratory, USA, 2006.
4. D. E. Burkes, G. S. Mickum, and D. M. Wachs, Thermo-physical Properties of U-10Mo Alloy, Technical Report, INL/EXT-10-19373, Idaho National Laboratory, 2010.
5. J. G. Stevens, "Technical Challenges for Conversion of U.S. High Performance Research Reactors," Presentation to NAS/RAS committee on conversion of research reactors, available at: http://dels.nas.edu/resources/static-assets/nrsb/miscellaneous/StevensPresentation.pdf, 2010.
6. L. Tschape, A. E. Ruggles, J. D. Freels, and R. T. Primm III, Evaluation of HFIR LEU Fuel using the COMSOL Multiphysics Platform, ORNL/TM-2008/188, Oak Ridge National Laboratory, 2009.
7. J. D. Freels, R. V. Arimilli, K. T. Lowe, and I. T. Bodey, "The Role of COMSOL towards a Low Enriched Uranium Fuel Design for the High Flux Isotope Reactor," Proc. COMSOL Conference 2009, Boston, Mass., October 8–10, 2009 (2009).
8. I. T. Bodey, R. V. Arimilli, and J.D. Freels, "Upgrading the HFIR Thermal-Hydraulic Legacy Code using COMSOL," Proc. COMSOL Conference 2010, Boston, Mass., October 7–9, 2010 (2010).
9. J. D. Freels, R. V. Arimilli, and I. T. Bodey, "Exploiting New Features of COMSOL Version 4 on Conjugate Heat Transfer Problems," Proc. COMSOL Conference 2010, Boston, Mass., October 7–9, 2010 (2010).
10. J. D. Freels, I. T. Bodey, R. V. Arimilli, and K. T. Lowe, Two-Dimensional Thermal Hydraulic Analysis and Benchmark in Support of HFIR LEU Conversion using COMSOL, ORNL/TM-2010/18, Oak Ridge National Laboratory, 2010.
11. G. Ilas and R. T. Primm III, Fuel Grading Study on a Low-Enriched Fuel Design for the High Flux Isotope Reactor, ORNL/TM-2009/223/R1, Oak Ridge National Laboratory, 2010.
12. R. T. Primm III, D. Chandler, J. D. Feels, T. Guida, G. Ilas, B. C. Jolly, J. H. Miller, and J.D. Sease, Design Study for a Low-Enriched Uranium Core for the High Flux Isotope Reactor, ORNL/TM-2009/313, Oak Ridge National Laboratory, 2010.
13. P. K. Jain, J. D. Freels, and D. H. Cook, "COMSOL-based Multiphysics Simulations to Support HFIR's Conversion to LEU Fuel," Trans. Amer. Nucl. Soc. 104:1064–1066, 2011.
14. J.D. Freels and P.K. Jain, "Multiphysics Simulations in the Complex 3D Geometry of the High Flux Isotope Reactor Fuel Elements Using COMSOL," COMSOL Conference, Newton, Mass, October 13–15, 2011.
15. J. D. Freels, I. T. Bodey, R. V. Arimilli, F. G. Curtis, K. Ekici, and P. K. Jain, Preliminary Multiphysics Analyses of HFIR LEU Fuel Conversion using COMSOL, ORNL/TM-2011/07, Oak Ridge National Laboratory, 2011.
16. R. T. Primm III, D. H. Cook, J. D. Feels, G. Ilas, B. C. Jolly, J. H. Miller, D. L. Pinkston, D. G. Renfro, and J. D. Sease, Design Study for a Low-Enriched Uranium Core for the High Flux Isotope Reactor, ORNL/TM-2011/06, Oak Ridge National Laboratory, 2011.
17. H. A. McLain, HFIR Fuel Element Steady State Heat Transfer Analysis—Revised Version, ORNL-TM-1904, Oak Ridge National Laboratory, 1967.
18. COMSOL Multiphysics Simulation Software. Web link: http://www.comsol.com/, last accessed on 03/14/2012.

19. R. D. Cheverton and W. H. Kelley, Experimental Investigation of HFIR Fuel Plate Deflections Induced by Temperature and Pressure Differentials, RNL-TM-2325, Oak Ridge National Laboratory, 1968.
20. R. B. Rothrock, Thermal-Hydraulic Bases for the Safety Limits and Limiting Safety System Settings for HFIR Operation at 100 MW and 468 psig Primary Pressure, Using Specially Selected Fuel Elements, ORNL/TM-13694, Oak Ridge National Laboratory, 1998.

Figures used in the abstract



(a) (b)

Figure 1: 1P1C or One Plate One Channel model for the HFIR inner fuel plate and coolant channel. (a) Side view with top and bottom clads visible. (b) Top view with 10mm thick clad layers.

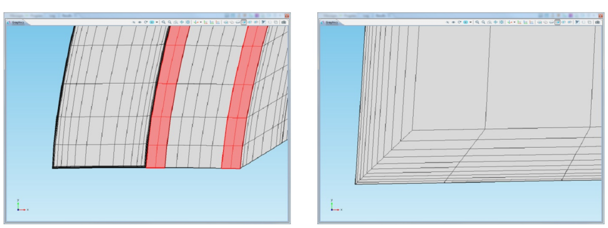


Figure 2: Mesh across the fuel plate and coolant channel thicknesses. Boundary layer mesh is used alongside the channel walls whereas a relatively coarser mesh is used for the fuel and clad regions in the plate.

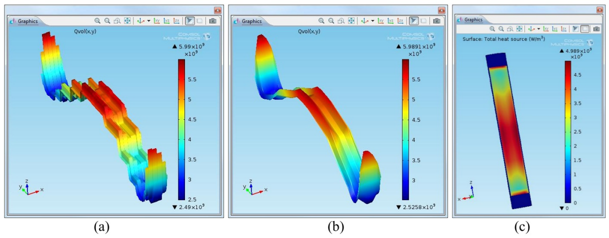


Figure 3: Heat generation in an axially non-graded LEU fuel. (a) Heat source slices as provided by MCNP results (19 axial, 8 radial); (b) COMSOL generated smoothing using linear interpolation; (c) Volumetric heat source as provided to a LEU fuel plate (notice the non-fueled region in the top and bottom, and near the side plate edges in the longitudinal direction).

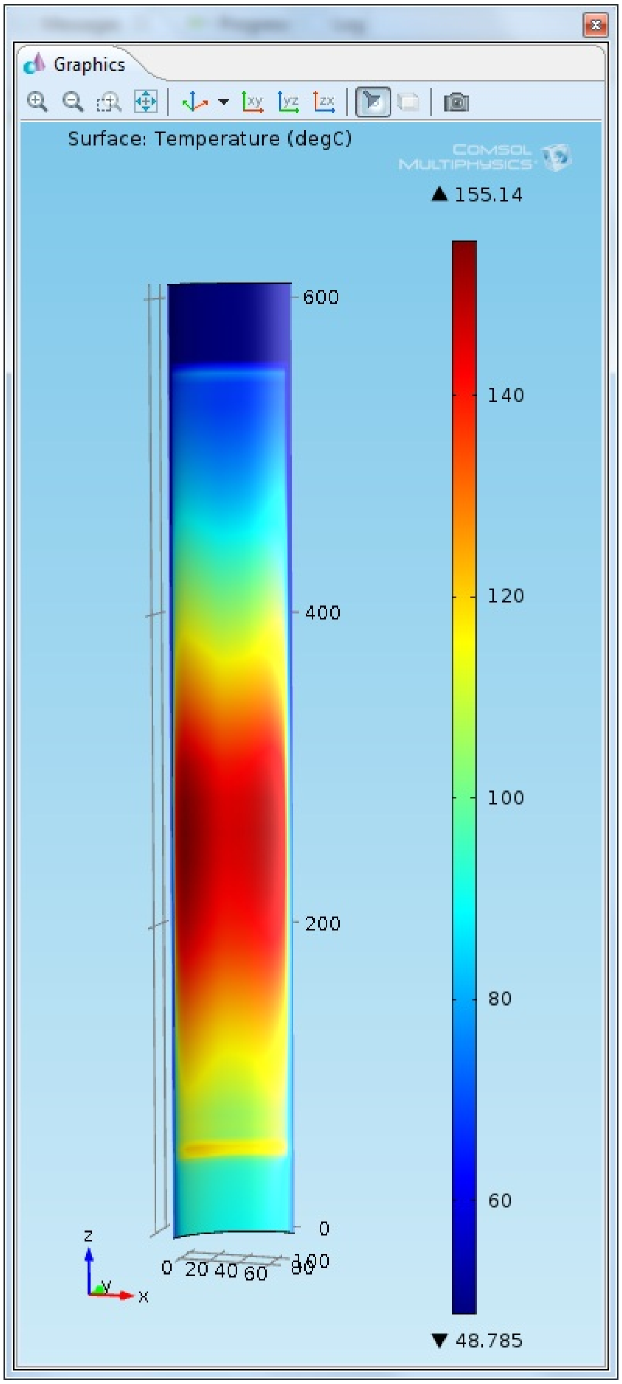


Figure 4: Clad surface temperature (in C) for the LEU fuel plate in nominal HFIR conditions for an axially non-graded LEU fuel.