Application of COMSOL Pipe Flow Module to Develop a High Flux Isotope Reactor System Loop Model

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Abstract: Oak Ridge National Laboratory's High Flux Isotope Reactor (HFIR) is the highest flux reactor-based source of neutrons for research in the United States. RELAP5 is the primary transient safety analysis tool used at HFIR to perform thermal-hydraulic system safety evaluations. Recently, a pipe flow module was added into the COMSOL Multiphysics software for applications in fluid flow, heat and mass transfer, hydraulic transients, and acoustics in pipe and channel networks. To verify and validate this new pipe flow capability of COMSOL, a HFIR system model was developed using this new module, while keeping all the input parameters and model components as similar as possible to HFIR's existing RELAP5 model. Steady-state simulations and a postulated pump flow transient simulation were performed using this new COMSOL model and were compared against the RELAP5 predictions. Overall, the COMSOL results yielded a good agreement with the RELAP5 results.

Keywords: COMSOL Pipe Flow, HFIR, RELAP5.

1. Introduction

Oak Ridge National Laboratory's High Flux Isotope Reactor (HFIR) is the highest flux reactor-based source of neutrons for research in the United States. Thermal and cold neutrons produced by HFIR are used to study physics, chemistry, material science, engineering, and biology. HFIR is beryllium-reflected, light-water–cooled and –moderated, aluminum-clad fuel plate, flux-trap-type reactor that uses highly enriched U-235. The HFIR core resides in an 8-ft diameter pressure vessel located in a pool of water. The core has two fuel elements, the inner fuel element and the outer fuel element, consisting of 171 and 369 involute fuel plates, respectively, for a total of 540 fuel plates. These involute-shaped fuel plates are uniformly spaced to provide an equal coolant flow area for each plate within each element. The primary coolant enters the pressure vessel through two 16-in. diameter pipes above the core, passes downward through the core, and exits through an 18-in. diameter pipe beneath the core. The design total flow rate is 16,000 gal/min (1.0 m^3/s), of which 13,000 gal/min (0.82 m^3/s) flows through the fuel region and the remainder through the target, reflector, and control regions. The reactor is operated with an inlet pressure of 482.7 psi (3.33 MPa). The inlet temperature is 120^{o}F (48.9^{o}C), the core exit temperature is 157^{o}F (69.4^{o}C), and the pressure drop through the core is 105 psi (0.724 MPa). The primary coolant system is shown in Fig. 1 [1].

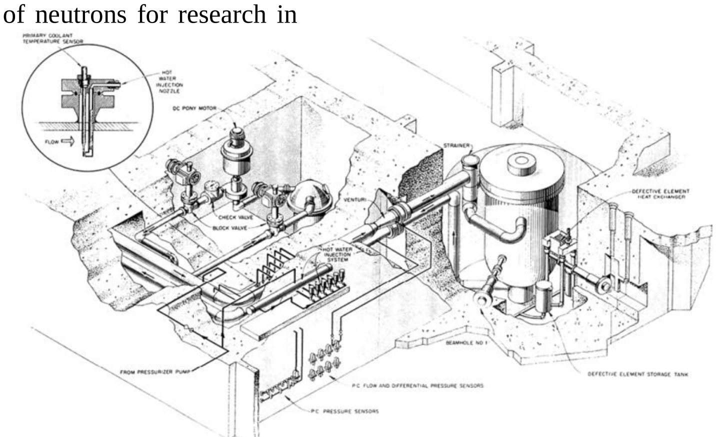


Figure 1. HFIR primary coolant system.

Currently, the RELAP5 code is the primary transient safety analysis tool used at HFIR to perform thermal-hydraulic system safety evaluations. RELAP5 is a 1D, best-estimate, single and two-phase flow capable, nuclear reactor systems analysis code that can analyze steady-state and transient system behavior in light water reactors under normal operating and off-normal accident conditions.

Recently, a pipe flow module was added into the COMSOL Multiphysics software for applications in fluid flow, heat and mass transfer, hydraulic transients, and acoustics in pipe and channel networks. This new module is suitable for modeling pipes and channels that have lengths large enough so that flow in them can be considered to be fully developed and represented by 1D approximation. Preset piping components such as bends, valves, T-junctions, contractions/expansions, and pumps are also available for use [2].

To verify and validate this new pipe flow capability of COMSOL, it was decided to develop a HFIR system model using this new module while keeping all the input parameters and model components exactly the same as HFIR's existing RELAP5 model. All geometrical dimensions and other thermal-hydraulic data for this model were obtained from the HFIR RELAP5 input deck and associated documentation.

Steady-state simulations and a postulated pump flow transient simulation were performed using this new COMSOL model and were compared against the RELAP5 predictions. Overall, the COMSOL results yielded a good agreement with the RELAP5 results.

2. Development of HFIR COMSOL Model

The HFIR COMSOL model was developed based on a RELAP HFIR model, using the COMSOL Pipe Flow module. All geometrical dimensions and other thermal-hydraulic data were obtained from the HFIR RELAP5 input models and their documentation. The RELAP5 nodal diagram of the HFIR primary coolant system model is shown in Fig. 2 [1]. Three operating heat exchanger loops are modeled explicitly. The COMSOL system model consists of three primary coolant loops and reactor vessel/core model, as shown in Fig. 3.

The following is a detailed description of the development of the HFIR COMSOL model.

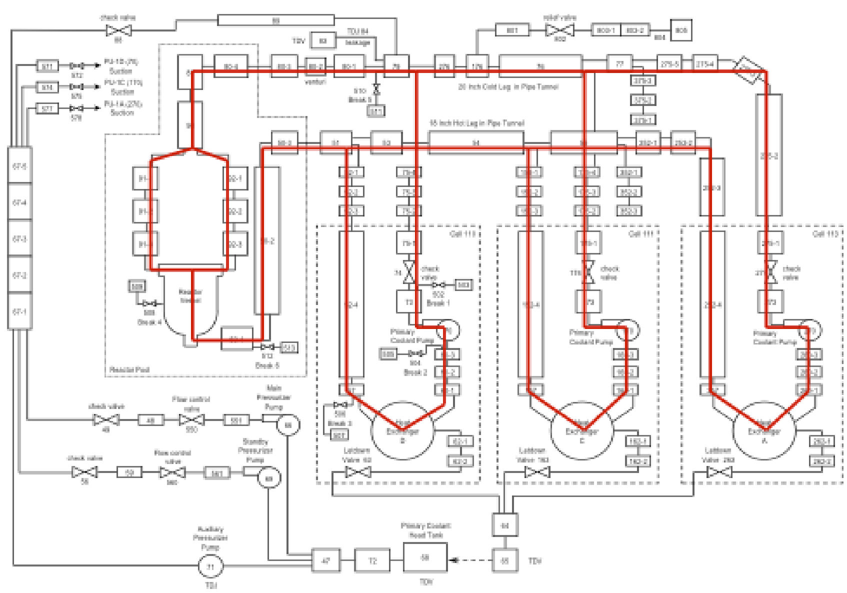


Figure 2. HFIR RELAP5 nodal diagram.

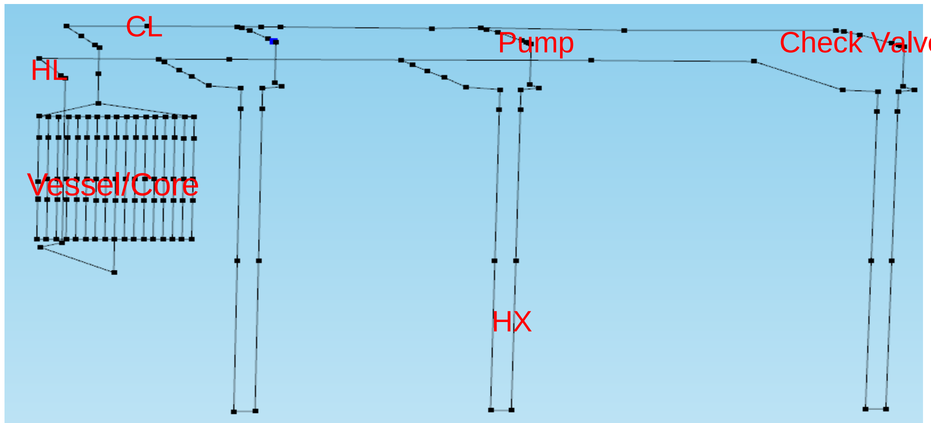


Figure 3. HFIR system model using Pipe Flow Module.

2.1 Vessel/Core Components

The COMSOL model of the vessel/core components is a replication of the RELAP5 model. In the RELAP5 model the fuel element is divided into six regions, as shown in Fig. 4. The two average inner fuel element lumps are each composed of 85 fuel plates and flow channels, Inner Fuel-1 (Pipe 1) and Fuel-2 (Pipe 14). The remaining fuel plate and flow channel, of the total 171 fuel element plates and channels, represent a hot fuel region, hot inner fuel (Pipe 10). Similarly, the two average outer fuel element lumps are each composed of 184 fuel plates and flow channels, outer fuel-1 (Pipe 2) and -2 (Pipe 15). The remaining fuel plate and fuel channel, of the total 369 outer fuel element plates and channels, represent a hot fuel region, hot outer fuel (Pipe 16). The flow area (FA) and hydraulic diameter (HD) for each fuel flow channel are extracted from the RELAP model. The wetted perimeter is calculated as Z = 4FA/HD.

The fuel labyrinth, the flow passage between the inner and outer fuel elements, is modeled as a single volume in RELAP5. In the COMSOL model, it is modeled with Pipe 19. The target assembly is located inside the 5-in.-diameter (12.7 cm) hole within the inner fuel element and is modeled with Pipe 5. In addition, the control cylinder, reflector, and core bypass are modeled the same as the RELAP model, as shown in Fig. 4.

The heat load in the fuel channel is modeled with the COMSOL "heat source" component. In the current steady-state COMSOL model, no equivalence of RELAP5 heat structures is modeled. However, it should be modeled for transient simulations.

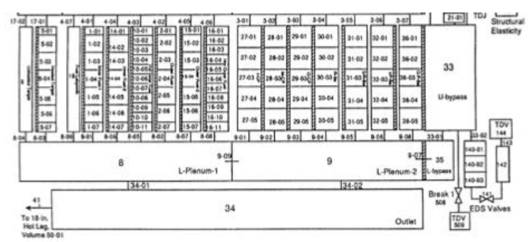


Figure 4. Vessel/core modeling.

2.2 Primary Coolant Pump Modeling

Three primary pumps drive the system flow through the loop. The COMSOL pump component has only three modeling options: fixed flow rate, downstream pressure, or pressure increase. For flow transient calculations, the pump curves need to be implemented. In the current COMSOL model, the pump flow rate is given for steady-state calculations. The homologous head curve and toque curve of the HFIR main circulation pumps are shown in Figs. 5 and 6. These pump curves could be implemented into the COMSOL pump model or by explicit modeling using the COMSOL equation solving capability.

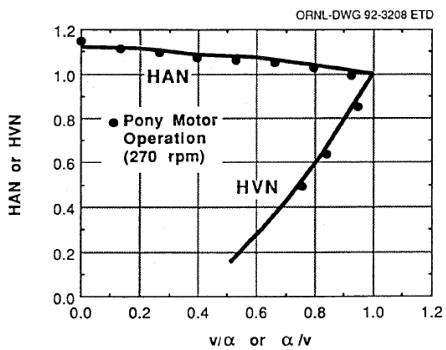


Figure 5. Homologous head curves for main circulation pumps.

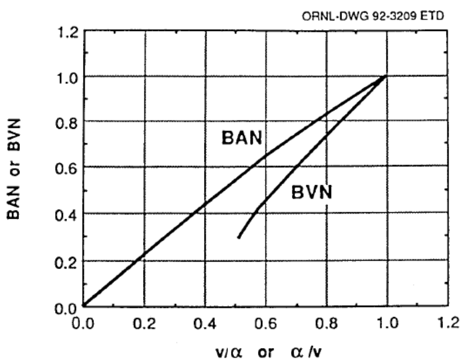


Figure 6. Homologous toque curves for main circulation pumps.

2.3 Heat Exchanger Modeling

The heat exchangers (HX) are ~30-ft (9.14-m) high and 4 ft (1.22 m) in diameter. The flow paths taken by the primary and second water are indicated in Fig. 7. The heat exchanger bundle consists of 1200 stainless steel tubes. The average tube length is 710.52 in., and has an ID/OD of 0.555/0.625 in. Heat transfer between the primary and secondary is modeled with heat structures. Because of flow complexity in the secondary side, the flow area and hydraulic diameter of the secondary side are estimated to maintain the heat exchanger performance.

As in the RELAP model, all HX tubes are lumped into four single pipes for each heat exchanger in the COMSOL model. Heat transfer between the primary and secondary is modeled with the COMSOL "Wall Heat Transfer" component. The primary convection heat transfer model employs a user defined Nu number, which is calculated based on the Gnielinski correlation using the flow Re number and Pr number.

$$Nu_{turb} = \frac{hd}{k} = \frac{(f/8)(Re-1000)Pr}{1+12.7\sqrt{f/8}\left(Pr^{2/3}-1\right)},$$

where,

$$f = 4(1.58 lnRe - 3.28)^{-2}$$

$$Pr = \frac{C_p\mu}{k}$$

For the secondary side, heat transfer is calculated based on the user-defined Nu and sink temperature. For simplicity, the RELAP5 calculated Nu number is used for the COMSOL HX model. As in the RELAP5 model, the effective heat transfer area is calculated by multiplying the total heat transfer area by a factor of 90.25%.

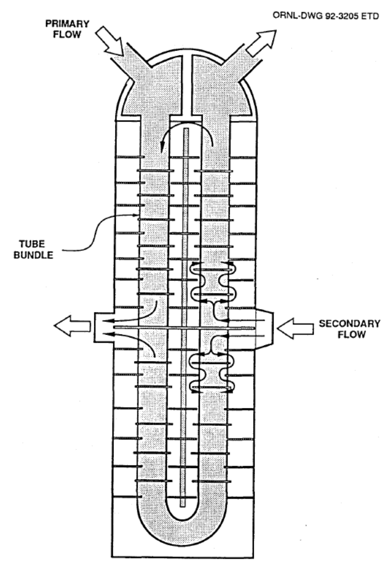


Figure 7. Heat exchanger flow path.

3. COMSOL Results and Conclusions

As described in the previous sections, the HIFR COMSOL model has been developed based on the COMSOL Pipe Flow module. The model consists of three primary coolant loops and reactor vessel/core model.

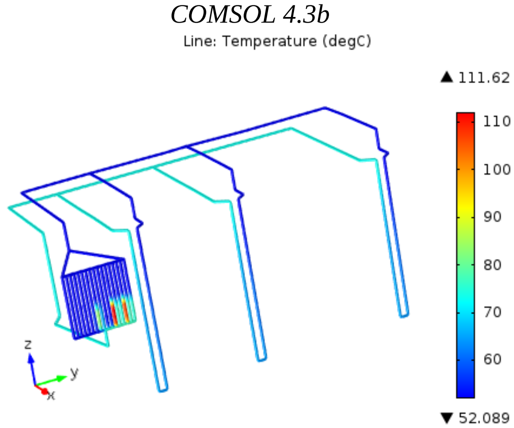
Steady-state results of the HFIR COMSOL model are summarized in Table 1, and temperature and pressure plots are shown in Figure 8. RELAP5 results are also given for comparison. It is shown that overall the COMSOL results are in good agreement with the RELAP5 results. Note that the reactor pressure vessel (RPV) pressure drop predicted by COMSOL is slightly lower than the RELAP5 prediction. This needs further investigation.

In summary, a COMSOL-based system model of HFIR could yield a fast-running production model to provide similar capabilities as the system safety analysis code RELAP5. In addition, the model could also provide improved simulation of HFIR under natural circulation conditions, particularly the transition from forced/natural convection and the velocity shift from downward to upward flow in the core. However, some improvements are needed for better use of COMSOL, for example, heat structure and pump modeling.

Table 1: COMSOL vs RELAP: steady-state results

	COMSOL	*RELAP5*
Reactor power (MW)	86.6	
Total loop flow rate (kg/s)	327.4 × 3	
RPV inlet cold leg temp. (K)	325.56	325.48
RPV exit hot leg temp. (K)	346.8	347.2
RPV inlet coolant pressure (MPa)	2.92	2.91
RPV exit coolant pressure (MPa)	2.31	2.20
Outer core hot fuel outlet coolant temperature (K)	385.08	386.2
Inner core hot fuel outlet coolant temperature (K)	380.1	381.1

COMSOL 4.3b



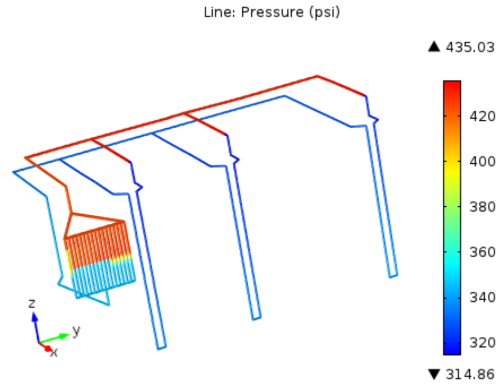


Figure 8. COMSOL model results.

4. Acknowledgements

The authors would like to acknowledge financial support provided for this work by the US Department of Energy National Nuclear Security Administration's Reduced Enrichment for Research and Test Reactors program and ORNL's Laboratory Directed Research and Development program.

5. References

1. D. G. Morris and M. W. Wendel, *High Flux Isotope Reactor System RELAP5 Input Model*, ORNL/TM-11647, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1993.
2. *COMSOL 4.3b* www.comsol.com (2013).