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COUPLED GRIFFIN AND PRONGHORN SIMULATION OF THE MOLTEN SALT FAST REACTOR (MSFR) FOR THE VIRTUAL TEST BED

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The Virtual Test Bed (VTB) repository hosts a wide range of challenge problems to showcase modeling and simulation capabilities to support advanced reactor demonstration. An overview of a coupled multiphysics model for Molten Salt Reactors (MSR) is presented here. The analysis leverages MOOSE-based tools (notably Griffin and Pronghorn) for neutronic and thermal hydraulic simulation. Neutron precursor drifting capability is showcased, along with some initial turbulence models. Both steady-state and transient coupled multiphysics results for an MSR concept are discussed.

I. INTRODUCTION & BACKGROUND

The Nuclear Reactor Innovation Center (NRIC) was established to assist the deployment and demonstration of advanced reactors. The Virtual Test Bed (VTB) aims to support this effort by developing multiphysics challenge problems that reference state-of-the-art simulation capabilities developed by the Department of Energy (DOE) Nuclear Energy Advanced Modeling and Simulation (NEAMS) program. This NRIC-NEAMS collaboration aims to develop reference plant models that can be leveraged by external stakeholders in industry, academia, and regulation, to evaluate the performance of potential future demonstrations.[1]

Among the advanced reactors being proposed for demonstrations, Molten Salt Reactors (MSR) feature prominently. In these reactors, the fuel is dissolved in a liquid salt, typically fluoride or chloride. While only a thermal MSR has been demonstrated in the past [1], interest in fast-spectrum MSR has been increasing lately. These MSR-variants can potentially offer better fuel performance and will be prioritized as part of the analysis shown here.

In light of the tightly coupled physics involved in MSR systems, the MOOSE platform is ideally suited for the analysis of this type of reactors. In particular, two MOOSE-based codes, Griffin and Pronghorn, are leveraged. Griffin is a time-dependent reactor physics code built using the MOOSE framework with weak form formulations for diffusion, P_N, and first- and second-order S_N transport and a variety of equivalence techniques with acceleration [2,3]. Pronghorn is a multidimensional, coarse-mesh, thermal-hydraulics (TH) code for advanced reactors. It serves the intermediate fidelity realm situated between detailed computational fluid dynamics (CFD) analysis and lumped system models [4,5].

Previous work has already demonstrated the applicability of these two codes to simulate fast-MSR systems [6,7]. Basic functionalities such as species tracking, coupled multiphysics, and transient analysis were shown. This article will highlight the different features useful for fast-MSR simulation that are showcased in the VTB repository.

II. PROBLEM DESCRIPTION

II.A. Reactor Model

The VTB MSR model is based off of the Molten Salt Fast Reactor (MSFR) design created under the Euratom EVOL (Evaluation and Viability of Liquid Fuel Fast Reactor Systems) and ROSATOM MARS (Minor Actinides Recycling in Molten Salt) projects [8]. It is a fast-spectrum reactor that produces 3 GW of thermal power using fuel dissolved in a LiF carrier salt. Most parameters and material properties of the VTB MSFR are taken from Ref. 8. That reference specifies a block-style geometry with all 90-degree angles, but a geometry with curved surfaces that more closely matches "Geometry II" from Ref. 9 is used for the purposes of the VTB.

Fig. 1 illustrates the geometry of the 2-D axisymmetric model used in the VTB. The model includes a core region, a pump, and a heat exchanger. An interior reflector shields the pump and heat exchanger from the high neutron flux in the core. (Note that some models of the MSFR include a fertile blanket in this region, but that blanket is neglected here as a simplification.) The model also includes an outer reflector surrounding all of the components.

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[1] All input files and documentation developed are available via the VTB website: mooseframework.inl.gov/virtual_test_bed

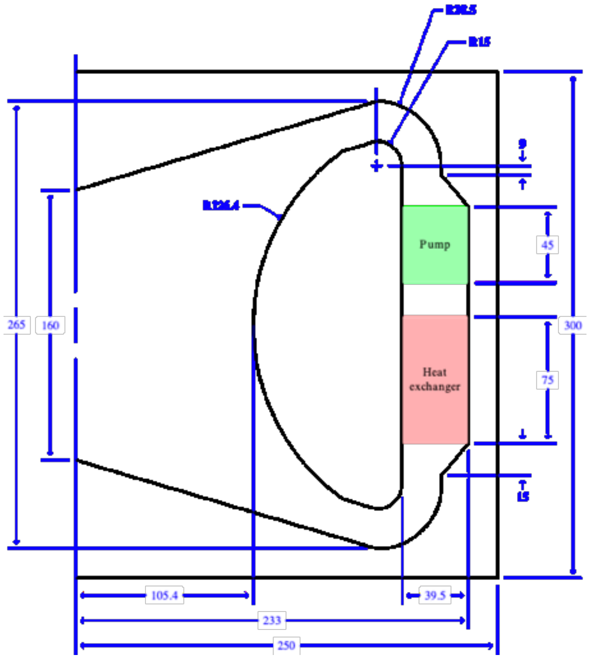

Fig. 1. VTB MSFR geometry specifications.

The composition of the fuel salt is 19.985% ThF_4, 2.515% $U^{233}F_4$, and 77.5% LiF (by mole). The nominal inlet and outlet salt temperatures are 650 and 750°C, respectively [9]. A nickel alloy is assumed is assumed for the inner and outer reflectors.

II.B. Griffin-Pronghorn Model

This works focused on the demonstration of the transient, multiphysics capabilities implemented in the Griffin and Pronghorn applications [6] to support various envisioned MSR operating scenarios. Griffin is a reactor-multiphysics code which is particularly well-suited for fast-spectrum, pool-type MSR analysis because it can be integrated with Pronghorn, allowing full coupling between precursor drift and thermal-hydraulics evolution equations. In addition, it also includes interfaces with the cross section generation code that was specifically developed for fast-spectrum reactors. Pronghorn is a multidimensional, coarse-mesh, thermal-hydraulics code [4]. It solves the multidimensional, compressible, and incompressible fluid flow equations for porous and non-porous flow configurations.

The relevant equations for MSR Multiphysics dynamics comprise a multigroup diffusion model, Boussinesq model of incompressible fluid flow, a temperature equation and a set of delayed neutron precursors. The multigroup diffusion model is given by:

(1)

(2)

(3)

(4)

The variable definitions and constants in Eqs. 1-4 are given in [7].

The neutron diffusion equation (Eq. 1) is discretized using the finite element method (FEM). Eqs. 2-4 are discretized using the finite volume method (FVM), a recently added capability in MOOSE. More details about MOOSE FVM can be obtained in [7].

Furthermore, to deal with high Reynolds number flows, MOOSE Navier-Stokes module includes simple, tunable turbulence models for RANS simulations. To model the Reynolds stresses, turbulent heat fluxes and turbulent precursor mixing terms, a Boussinesq eddy viscosity assumption is used:

(5)

(6)

(7)

where is the eddy viscosity, and are the turbulent Prandtl and Schmidt number, respectively.

III. RESULTS

III.A. Steady-State Simulation

The coupled neutronic-thermal hydraulic results are shown in Fig. 2. The temperature distribution is obtained by leveraging the fission power density estimated by Griffin, and the thermal/flow characteristics computed by Pronghorn. Iterations are performed to account for the temperature feedback effect on the fission source.

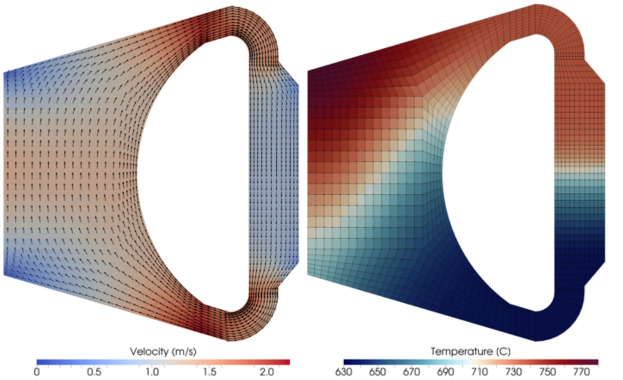

Fig. 2. Steady-state velocity (left) and temperature (right) fields in the Griffin-Pronghorn simulation of the MSFR. Taken from Ref. 7.

The uniform eddy viscosity model leads to significant diffusion throughout the reactor and, thus, relatively smooth temperature and velocity fields with no flow separation. This is not expected to be entirely representative of the MSFR behavior, and will be improved upon in future work. The highest temperature was found at the top of the core and in the low-flow region along the centerline. The salt there will be in direct contact with the core structure and may challenge the temperature limitations of the structural material.

The Griffin-Pronghorn model also provides the steady-state distributions of the delayed neutron precursors. The distributions of 3 (of the 6) groups are shown in Fig. 3. The concentrations have been normalized so that the maximum value for each group is unity. Group 6 has the shortest half-life (240 ms), and its behavior is dominated by radioactive decay rather than advection. Consequently, its distribution closely matches the fission distribution, with a distinct peak in the middle of the core. Groups 3 and 1 have longer half-lives (6 and 52 s, respectively), and are therefore more readily advected and diffused by the fluid. Indeed, the distribution of the slowest decaying group, group 1, is nearly uniform throughout the salt.

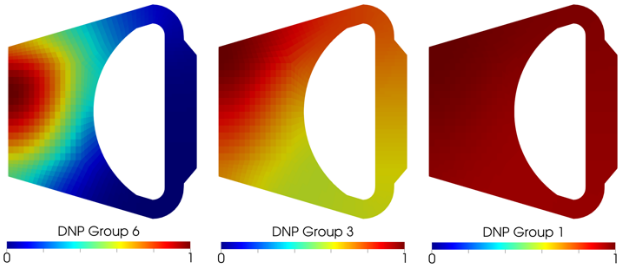

Fig. 3. Delayed neutron precursor (DNP) concentrations in different groupings. Taken from Ref. 7.

III.B. Transient Simulation

A transient simulation of an unprotected loss of flow (ULOF) is showcased in the VTB. The control rods are held in place while the pump head is reduced to zero. This is considered to be a rather extreme, beyond design-basis event. Fig. 4 shows the evolution of various informative metrics, including the power to flow ratio (PFR), defined as:

(8)

The pump trip causes a quick reduction in the salt velocity. This leads to a rise in temperature and a consequent drop in reactor power, due to the significant negative feedback. The salt temperature reaches its peak 7 s after start of the transient. The PFR reaches its peak slightly earlier, about 5 s after the pump trip. The total computational time on a 64-core AMD Ryzen Threadripper 3990X, was approximately 4.5 second/step. This is expected to be improved by future optimization/acceleration in the two, but is sufficiently fast to enable parametric transient analysis.

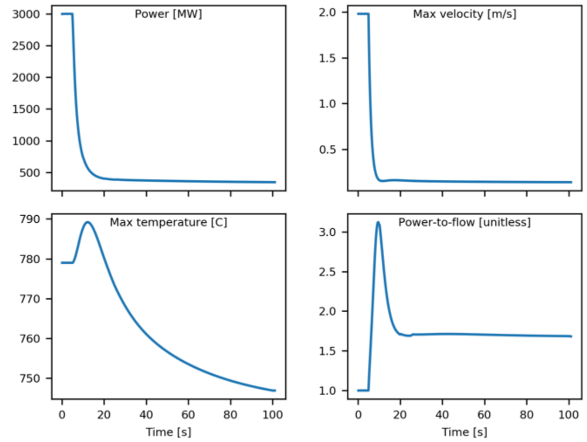

Fig. 4. Transient MSFR simulation results. Taken from Ref. 7.

IV. FUTURE IMPROVEMENTS

As discussed in Section III.A, so far, a uniform eddy viscosity has been used for the Multiphysics simulations. To enhance the turbulence modeling capabilities of MOOSE Navier Stokes module, Prandtl's mixing length model is implemented [10] to provide a zero-equation model for the eddy viscosity in Eq. (5).

where is the von Karman constant and is the distance to the wall.

The mixing length model constitutes a simple algebraic approach towards turbulence modeling. However, its applications are limited to wall bounded flows, flows without separation or adverse pressure gradient and steady state flows. Therefore, simulations using this turbulence model is going to be compared against Nek5000 [11] simulations to verify its applicability in MSFRs.

In addition to the mixing length model, standard velocity wall functions used as boundary conditions have also been developed to maintain the premise of doing coarse mesh thermal hydraulics. This boundary condition is also going to be tested against Nek5000 simulations.

V. CONCLUSION

This paper showcases MOOSE-based capability (notably Griffin and Pronghorn) to conduct steady state and transient simulations of interest in the MSFR context. Coupled feedback between neutronics and thermal models are captured. Delayed neutron precursor drifting impact can be quantified. Multiphysics transient simulations highlight the benefit of leveraging the coupled suite of tools for complex analysis of molten salt systems.

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