Development of a high-fidelity multi-physics simulation tool for liquid-fuel fast nuclear reactors

Ph.D. Thesis - Extended summary

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The Molten Salt Reactor (MSR) is one of the six Generation-IV nuclear reactor designs. It presents very promising characteristics in terms of safety, sustainability, reliability, and proliferation resistance. Numerous research projects are currently carried out worldwide to bring this future reactor technology to a higher maturity. In Europe, efforts are focused on developing a fast-spectrum design, named Molten Salt Fast Reactor (MSFR).

Numerical simulations are essential to develop MSR designs, given the scarce operational experience gained with this technology and the current unavailability of experimental reactors. However, modeling a molten salt reactor is a challenging task, due to the unique physics phenomena induced by the adoption of a liquid fuel that is also the coolant: transport of delayed neutron precursors, strong negative temperature feedback coefficient, distributed generation of heat directly in the coolant. Moreover, the geometry of the core cavity of fast-spectrum designs often induces complex three-dimensional flow effects. For these reasons, legacy codes traditionally used in the nuclear community often prove unsuitable to accurately model MSRs, in particular fast-spectrum designs, and must be replaced by dedicated tools.

This thesis presents the development of one of these multi-physics codes, which aims at accurately modeling the three-dimensional neutron transport, fluid flow, and heat transfer physics phenomena characterizing a fast-spectrum liquid-fuel nuclear reactor. As the research was carried out in the context of the Euratom SAMOFAR project, the MSFR is taken as reference case study, analyzing its behavior at steady-state and during several transient scenarios to assess the safety of the current design.

We first describe the newly developed CFD code. It consists of a discontinuous-Galerkin Finite Element (DG-FEM) solver for the incompressible Reynolds-Averaged Navier-Stokes equations (RANS) coupled to the classic $k-\epsilon$ high-Reynolds turbulence model. We solve for the logarithm of the turbulence quantities to guarantee their positivity. The chosen DG-FEM space discretization combines the local conservation property of Finite Volume schemes with the high-order discretization and geometric flexibility typical of FEM, necessary to handle the complex geometry of the MSFR core. All governing equations are discretized in time with implicit backward differentiation formulae (BDF). This, combined to a pressure-correction scheme, guarantees global second-order time accuracy. We verify the correctness of the space-time discretization with the method of manufactured solutions. Results of the simulation of a backward-facing step and of a Von Kármán vortex street in the wake of a square cylinder show good agreement with those reported in literature and validate our approach.

Then, we describe the neutronics code and the coupling between the two tools. An existing DG-FEM discrete ordinates transport solver is extended to model the movement of delayed neutron precursors, as well as the decay-heat distribution. Time-dependent problems are handled with the adoption of a second-order accurate BDF scheme for all equations. Attention is paid to increase the efficiency of the preconditioner for the coupled flux-precursors equations in this class of problems. The coupling between the codes is realized by exchanging data and iterating when necessary. To optimize the computational cost, neutronics and thermal-hydraulics meshes can be different, with the latter typically more refined in regions of low neutron importance but large flow gradients (e.g, close to the wall boundaries of the reactor). The hierarchy of the mesh refinement makes the exchange of data easy through Galerkin projection. For steady-state calculations, codes are iterated until convergence, while in transient calculations a loose-coupling strategy is adopted. Proper time-extrapolation of the fields exchanged ensures global second-order time convergence. Preliminary simulations of the MSFR show the capabilities of our multi-physics solver.

Next, we benchmark the multi-physics tool with a test case specifically designed to properly assess the correctness of the coupling scheme and its capability to model the complex physics phenomena characterizing fast-spectrum MSRs. We present the results of a collaboration between TU Delft and several partners of the SAMOFAR project. The characteristics of the nuclear system under investigation make it a simple representation of the MSFR. The benchmark is structured into several steps in which steady-state or transient problems are solved, gradually coupling the various physics phenomena to easily identify sources of error. By comparing our results with those obtained by the other partners, we prove our code is able to correctly model the physics phenomena characterizing a liquid-fueled fast reactor.

In the final part of the thesis, we employ our novel multi-physics tool to extensively analyze the MSFR behavior at steady-state and during several accidental transient scenarios: loss of heat sink, loss of fuel flow, total loss of power, pump over-speed, and salt over-cooling. Steady-state calculations show that previous interventions on the MSFR core geometry were effective in removing unwanted hot spots at the entrance of the core cavity. However, a large recirculation region is still present and should be eliminated in the future, as it induces localized pressure drops. Moreover, the concentration of fissile material in the fuel salt should be reduced, as the reactor turns out to be supercritical at the intended salt average operating temperature. No threats for the reactor safety could be detected during the simulated transients. The salt temperature always keeps a considerable margin both from the freezing point and the critical temperature causing damages to structural materials, thanks to the large salt heat capacity and the strong negative reactivity feedback coefficient. However, natural circulation is very limited so further optimization of the design should focus on reducing pressure losses in the fuel circuit.

In conclusion, the solver described in this thesis, which is the first multi-physics code dedicated to liquid-fuel fast reactors based on a full-transport neutronics model and on high-order DG-FEM space discretization, proved capable of accurately modeling the complex physics phenomena characterizing this reactor technology. It was employed to derive useful information on the current status of the MSFR design. This research constitutes a solid base for possible follow-up studies, which we discuss.