Multiphysics Modeling of Fusion Machines Liquid-Breeder Blankets

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Summary

In this thesis, different methods and codes for the multiphysics modeling of fusion machines liquid-breeder blankets are discussed and developed. The use of fluids can be particularly advantageous in fusion breeding blankets thanks to the fact that they can simultaneously carry out different tasks (tritium breeding, cooling, tritium transport and neutron shielding). Different initiatives, all over the world, are working on the development of such systems. Some of the most promising ones are the Water Cooled Lithium Lead (WCLL) EU-DEMO breeding blanket in Europe and the Affordable, Robust, Compact (ARC) reactor proposed by MIT in the United States, which will employ the FLiBe molten salt. These two designs, with a particular focus on ARC, are the two liquid-breeding blanket systems analyzed in this work. Due to the complex nature of these types of systems, where one single fluid has different functions and where different types of physics coexist and influence each other, a multiphysics approach is required.

The first part of this thesis deals with the development of a Serpent neutronic model of the ARC reactor. Here, also an uncertainty propagation study on the nuclear data of interest for ARC exploiting different techniques (i.e., fast Total Monte Carlo, fast GRS, Unscented Transform, Polynomial Chaos Expansion and Generalized Perturbation Theory) is presented, with a particular focus on output quantities like the neutron power deposition and the Tritium Breeding Ratio (TBR).

In the following chapter, the nemoFoam code is presented. nemoFoam is a multiphysics deterministic code developed in the OpenFOAM environment at Politecnico di Torino, with the specific aim of modeling and coupling neutronics and thermal-hydraulics in fusion systems and thus reducing the computational cost of the analysis. All the modules composing nemoFoam (namely, the multigroup diffusion, SP_3 and adjoint diffusion for neutrons, the one-group diffusion for photons and the thermal-hydraulic modules) are discussed. Particular attention has been devoted to the development of the photon module, in order to simulate also the secondary photons that are generated by electrically charged particles, which has been shown to have a non-negligible impact in fusion systems like ARC. The ARC reactor has been chosen to perform a code-to-code benchmark of nemoFoam against Serpent and to demonstrate the performance of nemoFoam. Moreover, the propagation of the nuclear data and of the thermo-physical properties uncertainties in ARC has been performed with nemoFoam and a Genetic Algorithm has been exploited to find the optimal energy grid structure to be used to model ARC with nemoFoam.

Finally, in the general framework of new model development for fusion applications, a module for the assessment of the Activated Corrosion Products (ACPs) has been implemented in the General Tokamak Thermal-hydraulic Modeling (GETTHEM) code, developed at Politecnico di Torino. The ACPs has been modeled using the Bateman equation, requiring simply the knowledge of neutron fluxes and nuclear properties (transmutation cross sections and half-life times) in each of the components of the fusion system modeled in GETTHEM. Here, the lithium-lead (PbLi) loop of the WCLL EU-DEMO breeding blanket has been chosen as a test case, also because there are currently no works available in the literature that have assessed the impact of ACPs in the PbLi loop of the WCLL.

Results for the neutronic analysis of ARC with the Serpent code have shown a good agreement between Serpent and other Monte Carlo codes and the important contribution of photons to the nuclear power deposition in fusion systems. The use of different techniques for the uncertainty propagation analysis has highlighted that the tested techniques are particularly interesting from the point of view of the computational time. The impact of the nuclear data uncertainties on the

power deposition is almost negligible, while it can represent a source of concerns for the TBR. The choice of the nuclear data libraries and of the energy grid for the collapsing of the covariance matrices has also a significant impact on the final results of the analysis.

The nemoFoam code provides good results when compared to Serpent, both when the diffusion and, in particular, the SP_3 approximations are used. The coupling between neutronics and thermal-hydraulics has shown that, at least in the ARC configuration considered for the analysis, the effect of the thermal feedback on the nuclear results is much less important if compared to what happens, for example, in nuclear fission systems. Exploiting nemoFoam for the propagation of nuclear data thermo-physical properties, it has been possible to conclude that the latter have a much stronger impact on thermal-hydraulic responses, as the temperature and pressure drop in ARC. Finally, the application of a Genetic Algorithm for the optimization of the energy grid to be used for the ARC modeling has shown that it is challenging to find a unique grid able to optimize the results of nemoFoam with respect to Serpent both in terms of neutron fluxes, neutron power deposition and TBR, but that different energy grids should be used according to the response that is really of interest in the specific case.

Finally, the module implemented in GETTHEM for the modeling of ACPs has provided good, yet preliminary, results for the PbLi loop of the WCLL, with an extremely limited computational time.

Being side projects, the nuclear data uncertainty propagation in the TAPIRO fast neutron source and the the modeling of a D_α camera for the plasma diagnostic of the ST40 fusion device are presented in the two appendices.