Doctoral Dissertation
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Multiphysics modeling in ARC-class reactors

Tritium transport modeling in the Liquid Immersion Blanket and in the Outer Fuel Cycle, and Vacuum Vessel Disruption Force analysis

By

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Abstract

The commercialization of fusion power plants (FPPs) involves many technological, engineering, and physics challenges. Fusion energy must be cheap, sustainable, and safe to have a tangible impact on the global energy mix and reduce the carbon footprint of electricity production. Computational analysis is a fundamental tool to assess the design of future fusion power plants. This thesis focuses on the development of multiphysics models to support the design of crucial components of the FPP. In particular, the Liquid Immersion Blanket proposed by ARC-class reactors [1] is an advanced design characterized by innovative solutions, such as the merging of the vacuum vessel and the breeding blanket in one complex component. The liquid breeder FLiBe carries out multiple roles at the same time: coolant, neutron shield, tritium breeder, and tritium carrier. The design of these complex components and the reliability of operation of each function of the molten salt require several design iterations due to competing boundaries. Moreover, the wide range of operational conditions required by the multipurpose role of the molten salt makes it necessary to account for the influence of other physical phenomena, such as heat transfer and CFD effects on tritium transport. In this framework, many examples of breeding blanket modeling showcase a multiphysics approach, and the development of a high-fidelity multiphysics software for reactor design [2, 3] . Therefore, the thesis focuses on CFD, heat transfer, tritium transport and trapping, and electromagnetic models with the COMSOL Multiphysics® software and dedicated open-source tools.

In Chapter 2, the Liquid Immersion blanket design is analyzed. The model addresses the CFD behavior in the external tank region, a thick layer of FLiBe between the vacuum vessel, which keeps vacuum for the plasma formation, and the tank wall. This thick layer, designed to shield neutrons and maximize tritium breeding, is characterized by relatively low fluid velocities and complex recirculation flows. The analysis requires the characterization of turbulent flow CFD analysis with conjugate heat transfer, radiative heat transfer (RHT) mechanisms in molten salts at

high temperatures [4], and the evaluation of the tritium inventory and losses in the blanket [5]. Both tritium inventories and losses are of fundamental importance for safety analysis and the evaluation of tritium-self sufficiency, which is fundamental to operate a FPP.

Chapter 3 focuses on the characterization of vessel cooling channels. This analysis involves the inclusion of turbulence promoters to face extreme heat loads of plasma-facing components [6]. In addition, the tritium transport in the vacuum vessel is explored in depth: a comparison of COMSOL® with the dedicated tritium transport code FESTIM is carried out for benchmark cases and ITER plasma-facing components [7]. Solid structures can act as sink of tritium, especially when considering traps, and may pose a risk at the tritium self-sufficiency.

Chapter 4 focuses on the development of the open-source TRIOMA for outer fuel cycle design. The OFC consists of the FLiBe circuit outside the breeding blanket: the tritium extractor, which is needed to retrieve the bred tritium, and the heat exchanger, which is needed in ARC-class design due to the dual-purpose of FLiBe as a tritium and energy carrier. The code characterizes tritium transport in Permeation Against Vacuum (PAV) extractors, heat exchangers, and Gas-Liquid Contactor extractors efficiently by employing analytical tools, such as those employed in [8–10]. Extraction efficiencies, tritium losses, and tritium inventories evaluated with TRIOMA are compared against COMSOL® results. Then, TRIOMA is employed to carry out a preliminary design of ARC-class OFC and uncertainty quantification. With the analysis of the OFC, the cooling of plasma-facing components and the tank region, the entire FLiBe circuit is described.

Chapter 5 focuses on the electromagnetic characterization of the ARC-class LIB and VV with plasma during operations and during a vertical displacement event of the plasma. In particular, the innovative design of LSVV is explored. This project, in development at the PSFC, starts from the ARC LIB concept and proposes a disruption-force resistant vacuum vessel design with an insulating structure and helical conductive channels. A COMSOL® model to study disruption forces is verified for the helical-shaped configuration. Then, the vertical plasma stability is assessed with the evaluation of eigenmodes of passive conducting structures [11, 12]. The analysis is carried out with COMSOL®, which is compared against the dedicated open-source ThinCurr code [13, 14] for a toroidal and an ARC-shaped fully-metallic vacuum vessel.

The application of the same multiphysics suite applied to multiple aspects of VV and LIB analysis, such as heat transfer, tritium transport and electromagnetic forces, opens the possibility of a complete characterization of breeding blankets within the same computational environment and software, with the accountancy of multiphysics aspects and connections, and the possibility of an iterable design process which accounts for all the tradeoffs in the design of the LIB.

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