# Modelling liquid metals for fusion and fission nuclear reactors

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## Summary

**Liquid metals (LMs)** are used in both fusion and fission nuclear systems: in advanced divertor solutions and in breeding blankets for fusion reactors, and as coolants for fission fast reactors. The present thesis reports the research work carried out by the candidate along two main lines:

I. the modelling of **Liquid Metal Divertors (LMDs)** for future nuclear fusion reactors, including the interactions of the LM with the Scrape-Off Layer (SOL) plasma;
II. the multi-physics (neutronics and thermal-hydraulic) modelling of the full core of **Liquid Metal-cooled Fast Reactors (LMFRs)**.

## I. Liquid metal divertors

LMDs are currently being considered as an alternative solution to the power exhaust problem in future fusion reactors, because of their self-healing features, among others. In the first part of the thesis, the development and application of computational tools to model LMDs, with specific focus on the interactions of the LM with the SOL plasma, are reported. Two different LMD designs are considered: the first, having an ITER-like shape of the plasma-facing components, is based on the Capillary-Porous Structure (CPS) concept, while the second is based on the "vapor-box" divertor concept.

First, the results of simulations aimed at assessing the effect of installing **a CPS-based, ITER-like LMD** in the EU DEMO tokamak, within the same envelope of the reference solid divertor, are presented. The SOLPS-ITER code was used to model the SOL plasma and neutral species (both fuel neutrals and metal eroded from the target), with the latter treated by means of a fluid model, for the sake of simplicity. SOLPS-ITER was coupled to an ad-hoc developed model for the target temperature distribution, to allow for the self-consistent evaluation of temperature-dependent erosion phenomena such as evaporation. In this way, a fair comparison between Li and Sn as materials for an LMD target could be performed. First simulations considering only D and Li (or Sn) suggested that the margin for operating an ITER-like LMD in the EU DEMO without any additional impurity seeding could be narrow, if existing. For this reason, further simulations assessing the effect of seeding Ar in the SOL to further reduce the target heat load, and thus the metal erosion rate, were performed. Results show a noticeable and promising widening of the operational window in terms of both core plasma compatibility and tolerable target heat flux.

Second, a simplified but self-consistent model for **an LM vapor-box divertor** is presented, together with its application to the Divertor Tokamak Test (DTT) facility, which is under construction in Italy. Given the upstream plasma conditions, the model evaluates the plasma heat and particle flux on the LM surface, the thermodynamic state of the metal (liquid and vapor) in the

divertor boxes and the temperature distribution in the solid walls. Also for this design, the model is used to compare Li and Sn as possible LMs, in terms of operating temperatures and of metal vapor flux from the divertor box system towards the main plasma chamber. The results indicate that, for both Li and Sn, this design allows to reduce the impurity flux towards the main plasma by ~2 orders of magnitude. However, only for Li the evaporation and radiation cooling are effective in reducing the target heat load, thanks to the relatively large Li concentration inside the boxes.

## II. Liquid Metal-cooled Fast Reactors

The development of LMFRs is currently under way within the Generation-IV program. In particular, Italy is involved in the development of the design of the Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED). In the second part of the thesis, the development, validation and application of computational tools to model the full-core, coupled neutronic and thermal-hydraulic behavior of LFRs is reported.

First, the design, development and preliminary validation of **a Design-Oriented Code, TIFONE**, aimed at evaluating the effect of the inter-subassembly heat transfer in the core of an LMFR, is presented. The code is based on the sub-channel method and the development was carried out in compliance with the ENEA software quality assurance requirements. TIFONE computes the axial and perimetrical coolant temperature profiles in the inter-subassembly gaps throughout the whole core, as well as the axial and perimetrical wrapper temperature profiles, and notably the (possibly) different values of each side of the wrapper itself. The code results allow the core designers to assess the presence of cold by-passes and of excessive thermal gradients among opposite faces of the wrapper of each sub-assembly, as well as the effectiveness of possible gagging schemes in mitigating these undesired phenomena. The code was compared with experimental data from the KALLA inter-wrapper flow and heat transfer experiment, confirming its ability in reproducing the measured data in its anticipated validity domain.

Second, the application of **FRENETIC, a multiphysics (neutronic/thermal-hydraulic) code** recently developed at Politecnico di Torino, to the full-core analysis of the ALFRED design is presented, together with results of the benchmarking activity against high-fidelity single-physics codes (Serpent for Monte Carlo neutron transport and OpenFOAM for CFD). The satisfactory results obtained for these benchmarks confirm the suitability of FRENETIC for the characterization of the ALFRED core in both steady-state and time-dependent conditions.