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Multiscale approach for the thermal-hydraulic analysis of heavy liquid metal pool systems

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Summary

This thesis describes the research work carried out within the framework of Generation IV Lead-cooled Fast Reactors (LFRs) development. Specifically, it presents an advancement in the modelling of LFR thermal-hydraulics (TH), achieved by coupling computer codes featuring different resolution and modelling scale, to improve design and analysis effectiveness of next-generation nuclear reactors.

The work benefits from the collaboration between Politecnico di Torino and the ENEA Brasimone research centre, combining an academic approach with practical, hands-on experience in the Heavy Liquid Metal (HLM) field. This partnership has facilitated access to state-of-the-art experimental facilities and data, promoting a research environment in which the development, verification, and validation of computational tools are tightly coupled with industrial and international project needs.

Firstly, an overview of the current status of TH) R&D is presented, setting the context for the TH modelling challenges that Generation IV LFRs face. Chapter 2 provides a literature review of existing TH tools applicable for the analysis of LFR systems. Traditional System Thermal-Hydraulics (STH) codes, initially developed for water reactors, have been foundational in the nuclear industry since the 1970s. However, these codes need to be further developed to effectively simulate LFR systems, especially due to the properties of lead coolant, analysing TH phenomena specific to the LFRs innovative pool reactor. This development involves incorporating advanced algorithms, models, and correlations specific to HLM, as well as expanding validation database of relevant experiments. Computational Fluid Dynamic (CFD) codes are becoming a valuable tool for component analysis, leveraging the increasing computational power available and adopting a three dimensional representation of the investigated domain. In recent decades, coupled CFD-STH tool are gaining attention as they allow to exploit the advantages of both families of codes, with a multiscale approach for system TH analysis of transient events. The motivations, current status, and classification of coupled CFD-STH tools are discussed in Chapter 2, highlighting efforts made within international projects on the topic and reference applications available in the literature.

Chapter 3 describes a novel computational tool, focus of this thesis work, based of the coupling between the commercial CFD code Ansys CFX and the STH code RELAP5 Mod3.3. Furthermore, the chapter outlines the reasoning behind key design choices and the range of options available to users in terms of numerical schemes and domain discretization. The tool's integrates new developed software tools, such as Ansys CFX FORTRAN subroutine and in-house developed Python executables.

Chapter 4 presents the tool's verification and validation across multiple case studies with increasing complexity. Initial verification is conducted using a simple isothermal single-pipe model to test the tool's coupling strategy, ensuring that the Ansys CFX and RELAP5 components communicate and operate as intended. Subsequent validation is performed using experimental data from loop-type facilities, including the NACIE and NACIE-UP facilities at the ENEA Brasimone research centre and the TALL-3D facility at the Royal Institute of Technology in Sweden. Lessons learned are summarized at the end of the chapter, focusing on evaluating cases where the coupled approach proves valuable and assessing the impact of different coupling methodologies available within the tool.

The final section of Chapter 4 presents the application of the tool to ATHENA, a pool-type experimental facility designed to test full-scale ALFRED (Advanced Lead-cooled Fast Reactor European Demonstrator) components. The application of the developed tool to the ATHENA facility highlights the differences achieved by adopting a multiscale approach, where system analysis is enhanced through CFD component simulations. A code-to-code comparison is conducted, exploring the impact of using CFD models for three different ATHENA components: the Fitting Volume, the Main Pool, and the Core Simulator.

The thesis concludes with a summary of the achievements and limitations encountered throughout the development and validation process. The insights gained from this work address the field of CFD-STH coupled tool applications, highlighting their value and emphasizing the importance of expanding the experimental database, particularly from pool-type facilities designed for integral testing of reactor accident scenarios. Finally, further numerical optimizations of the presented tool are proposed.