Development of Explainable Multiphysics-Informed Machine Learning for the Prediction of Critical Parameters in Water-cooled Nuclear Reactors

In collaboration with TRACTEBEL (ENGIE) – Engie Tower – Bruxelles, Belgium

- ## Context of the research

Tractebel, a subsidiary of the Engie Group, has over 150 years of experience and is one of the world's largest engineering companies. Tractebel provides its customers with multidisciplinary solutions in the fields of energy, nuclear engineering, hydraulics and infrastructures. The company is responsible for conducting the safety analyses of Belgian nuclear power plants (NPPs).

One of the objectives of Generation IV and small modular reactor (SMR) technologies is to restore public trust in nuclear safety. To optimize new reactor designs, safety analysis (particularly reactor core thermohydraulic analysis) is integrated at early stages into the design process. This analysis aims to estimate critical parameters and thermal limits to prevent core damage. One such parameter is critical heat flux (CHF), a thermal limit in boiling heat transfer beyond which there is a drastic reduction in heat transfer efficiency, leading to a significant increase in surface temperature. CHF is the heat flux at which a transition from nucleate boiling to film boiling (commonly known as the "boiling crisis") occurs. This phenomenon results in a sharp deterioration in the heat transfer coefficient, causing system overheating, potential failure and phase changes that can lead to unpredictable behavior. For this reason, accurate prediction of CHF is considered a critical factor in the safety analysis and technical design of efficient thermal systems, such as water-cooled NPPs, steam generators and cooling devices. As a key parameter in thermal engineering design, CHF has been extensively studied over the past several decades. However, the lack of a deterministic theory for CHF prediction remains a significant challenge in thermal engineering, and numerous prediction models have been developed, ranging from mechanistic and empirical correlation models to artificial intelligence (AI) and machine learning (ML) techniques, each performing differently under specific flow conditions. Recent advancements in CHF prediction have relied on data-driven approaches based on AI/ML techniques. Nevertheless, purely data-driven models often lack intrinsic physical insights and interpretability, limiting their broader acceptance for practical applications in safety-critical systems like water-cooled NPPs.

- ## Objective of the research

The objective of this thesis project is to develop and implement an interpretable Multiphysics-informed ML method for CHF prediction in NPPs by integrating multiple empirical correlations into the learning process to enhance the accuracy, generalization and interpretability of CHF predictions. The methodology will be applied to a benchmark experimental CHF dataset provided by OECD/NEA projects and other relevant case studies proposed by Tractebel.

The research activities will include:

- familiarization with the thermohydraulic critical parameters, including CHF, relevant datasets and case studies;
- review and analysis of the empirical correlation models and AI/ML methods for CHF prediction;
- examination of explainable AI (XAI) approaches;
- selection of the most promising correlation models for integration into AI/ML frameworks;
- formulation of the Multiphysics-informed ML approach based on the selected correlation models;
- development and evaluation of the proposed Multiphysics-informed ML model;
- selection and implementation of the suitable XAI techniques to enhance the interpretability of the developed model;
- analysis and interpretation of the obtained results.

Collaborations

The work will be performed in the Laboratory of Analysis of Systems for the Assessment of Reliability, Risk and Resilience (LASAR^3) in tight collaboration with TRACTEBEL in Bruxelles (Belgium), where an internship is foreseen.

Required skills

- Good knowledge of computer vision and AI/ML technologies and techniques;
- Interest in developing innovative algorithms to address real-world applications;
- Good knowledge of Python and/or R programming languages, with a focus on deep leaning (DL) and ML libraries.

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