CONJUGATE HEAT TRANSFER LARGE EDDY SIMULATION OF A HYPERVAPOTRON: FROM INCIPIENT NUCLEATE BOILING TO CRITICAL HEAT FLUX

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Efficient management of high heat fluxes in tokamak reactors presents a significant challenge crucial to their sustained operation. One key solution is the utilisation of specialised high-heat-flux devices, such as the HyperVapotron, which play a vital role in several components of a tokamak, including the first wall, neutral beam injectors, and divertor systems [1].

Despite their extensive application, past simulation studies of the HyperVapotron have primarily employed Reynolds-Averaged Navier-Stokes (RANS) turbulence models, as noted from a recent review published in [2]. A notable limitation of these RANS models is their ability to accurately capture the complex thermophysical phenomena of a HyperVapotron. For instance, research presented in [3] demonstrated that different RANS turbulence models can yield significantly divergent flow patterns within a HyperVapotron-like cavity, underscoring the model's sensitivity to the chosen parameters. Furthermore, many of these past studies employed computational models which focused on investigating specific heat transfer regimes: convective heat transfer, nucleate boiling, and critical heat flux (CHF). These models require manual intervention when transitioning between different heat transfer regimes. This limitation may hinder their ability to be used in efficient design work flows, particularly those employing automated design optimisation, such as the approach developed in [4].

In contrast, Large Eddy Simulation (LES) represents a high-fidelity turbulence modelling approach that may enhance our understanding of the validity and applicability of RANS models in the context of HyperVapotrons. Preliminary studies utilising LES have primarily centered on the convective regime, as outlined in [5]. However, there remains a considerable gap in the application of LES to the nucleate boiling and CHF regimes. The ability to resolve intricate turbulence structures and multiphase interactions in these regimes could be critical for the effective design and operation of HyperVapotrons.

This research aims to bridge that gap by developing a comprehensive Conjugate Heat Transfer (CHT) LES modelling capability. Our objective is to simulate HyperVapotron performance across all heat transfer regimes without the need for manual regime-switching. Building upon our previous work validating a HyperVapotron operating in the convective regime with the Cardinal multiphysics solver (see Fig. 1), we intend to extend our analysis to encompass nucleate boiling and CHF regimes. Cardinal (https://github.com/neams-th-coe/cardinal) is an open-source tool that couples the heat transfer module from the MOOSE framework (https://github.com/idaholab/moose) with the NekRS (https://github.com/Nek5000/nekRS) LES computational fluid dynamics (CFD) solver, a combination employed extensively within the nuclear fission industry for conducting thermal-hydraulic analyses.

As part of our initiative, we plan to enhance NekRS to incorporate models for multiphase flow and film boiling. This advancement will facilitate high-fidelity simulations capable of accurately capturing the full thermophysical complexities associated with HyperVapotron operation. A rigorous verification and validation process will be undertaken to ensure the accuracy of the implemented solver, with particular emphasis on its application to the operational conditions of HyperVaportrons. The outcomes of this research hold the potential to significantly enhance modelling techniques and the design of thermal management systems in fusion reactors.

The anticipated benefits of this work to the wider fusion community are:

1. **Enhanced understanding of heat transfer and turbulence dynamics:** A thorough exploration of the physical processes involved in HyperVapotrons will lead to a deeper understanding of the heat transfer and turbulence dynamics. This knowledge is essential for optimising their performance and increasing the efficiency of thermal management systems.

2. **Comparison of LES and RANS capabilities:** By establishing a rigorous framework for comparing LES results with traditional RANS models, we will be able to identify and quantify the limitations of existing modelling approaches. This comparison is crucial, as it will pave the way for improvements and refinements in turbulence modelling methodologies.

3. **Improved RANS model development:** Insights gained from our LES simulations can be leveraged to enhance the current state of RANS models. Such improvements will be critical for refining the design and optimisation processes for high-heat-flux devices, ultimately contributing to better performance and reliability of RANS models in high-heat-flux devices.

In summary, the integration of Large Eddy Simulation within the context of HyperVapotron operation signifies an advancement in thermal-hydraulic modelling for high-heat-flux devices. By addressing existing gaps in current computational capabilities and providing a more comprehensive simulation approach, this research promises to facilitate progress in the design and management of thermal systems in fusion reactors. We are optimistic that the findings will assist in the design and analysis of high-heat-flux devices both locally at the UKAEA and for the wider fusion community.

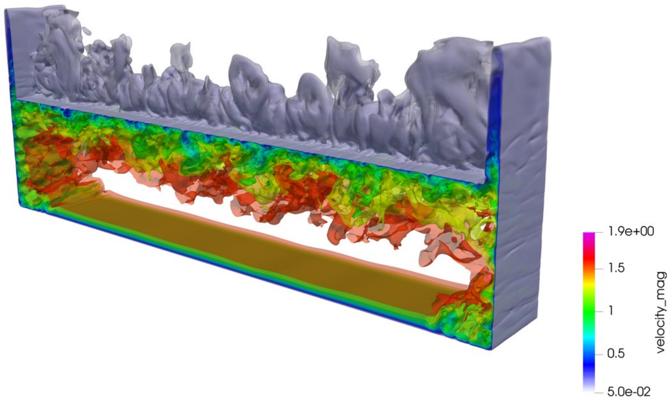

Figure 1: NekRS LES simulation of a HyperVapotron operating in the convective regime.

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