Proceedings of the 18th UK Heat Transfer Conference

9-11 September 2024, Birmingham

UKHTC2024-043

Current state and advances in Nuclear Engineering

VALIDATION OF UNSTEADY RANS AGAINST LES CALCULATIONS FOR PREDICTING NATURAL CIRCULATION STALL PHENOMENA WITHIN A TEST FACILITY LOOP

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1. ABSTRACT

Unsteady Reynolds-Averaged Navier-Stokes (URANS) computations have been validated against analogous Large Eddy Simulation (LES) benchmark cases concerning a Natural Circulation (NC) loop. Simulations were run to achieve a statistically steady state before transient events were introduced to the loop flow. Both cold flow injection with varying mass flow rates, and zero heater power transients were considered. For the first injection case, presented within this abstract, both models observed a decrease in mass flow and temperature within the loop, with recovery occurring shortly after the injection was stopped. The URANS data exhibits a temperature offset at both the heater and cooler outlets, approximately 2.5% below the LES throughout the transient. The mass flow comparison also demonstrates how the URANS results follow the general flow behaviour of the LES, indicating URANS is capable of predicting whether the perturbation will stall the loop.

2. INTRODUCTION

Flow within an NC-driven loop is of interest in the study of hydraulic phenomena as it exhibits different behaviour to pumped flow, and perturbations could stall the loop altogether. One-dimensional systems codes are widely used to model such systems, but have limitations in their ability to accurately predict prevailing system behaviour during scenarios that involve 3D flow fields. This limitation raises the requirement for a modelling approach capable of sufficiently capturing 3D phenomena associated with perturbed loop NC, subsequently providing insight into stall mechanisms.

This drives towards a three-dimensional (3D) modelling approach, such as Computational Fluid Dynamics (CFD), but with the aspiration of limiting the associated computational cost. This means lower fidelity CFD methods, such as URANS, are favoured over higher fidelity LES approaches. URANS solves for the Reynolds-average of the Navier-Stokes (NS) equations whilst modelling turbulence, whereas LES predicts the instantaneous flow field and uses a spatial filter to resolve large eddies whilst modelling smaller ones. Due to the increased computational burden associated with LES modelling, it is deemed appropriate for benchmarking only in this case. To build confidence that URANS CFD is capable of accurately predicting flow within an NC driven loop, results have been validated against LES data for multiple transient types exhibiting different stall mechanisms.

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3. METHDOLOGY

Results were obtained from URANS simulations performed in STAR-CCM+ using a Standard K-Epsilon Two Layer (SKE2L) turbulence model. The loop consists of a heater, primary cooler, secondary cooler, Injection Points (IP), and a surge connection as shown in ***Figure 1***. A polyhedral meshing approach with prism layers was used, with prism layers being included on the walls of the pipes. A mesh sensitivity study has been carried out using the base size factor to vary the mesh.

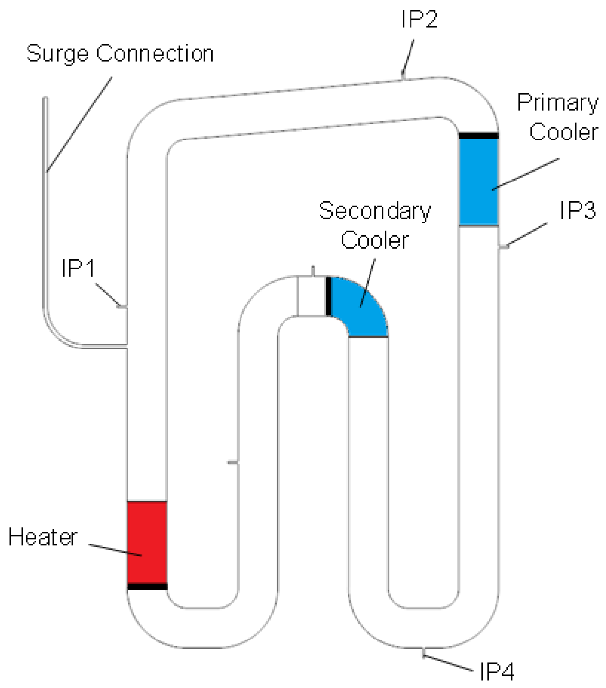

Figure 1 – Loop Geometry

Orifice plate locations throughout the loop, denoted with thick black lines in ***Figure 1***, have been modelled as porous regions to simulate the pressure drop across a few cells. These were found to be more stable to model than porous baffles, which would only allow the pressure to drop over a surface. Polynomial fluid properties have been used, and body forces due to gravity have been included to simulate buoyancy to drive the NC flow. During the transient state of the simulation adaptive time stepping has been used. This is controlled by the maximum timestep size, maximum Courant number, and target mean Courant numbers set by the user.

4. RESULTS

Comparisons have been drawn to LES data for a suite of cases provided by the University of Manchester (UoM), which have been obtained via the methods described in [1]. An exhaustive list of comparison cases has been outlined in ***Table 1***, summarising cold flow injection transients at IP2 and IP4 with varying mass flow rates as well as various zero heater power transient cases. Note that the heater powers (Low/High Q) stated in ***Table 1*** refer to the heater power used to achieve the steady state initial conditions, prior to switching off the heater.

Table 1 - Summary of LES Comparison Cases Replicated using URANS

Case Description	Injection MFR (kg.s^{-1})	Injection T (°C)	Heater Q (kW)	2nd Cooler Wall T (°C)
Injection at IP4	(0.05), (0.1), (0.2)	5	25	-
Injection at IP2	(0.05), (0.1), (0.2), (0.5)	5	25	-
Heater Off (Low Q)	-	-	0.5	-
2nd Cooler On	-	-	0.5	10
Heater Off, 2nd Cooler On	-	-	0.5	10
Heater Off (High Q)	-	-	25	-

For each case, monitors of mass flow rate and temperature, at the heater and primary cooler outlets, have been compared. Here, the results for the first case are presented and discussed (***Figure 2***) with the remaining cases being presented during the conference. The URANS simulation was run for 100 seconds (s) with fixed boundary conditions to achieve a statistically steady state with the initial conditions required, ensuring that NC had been established prior to initiating the injection at IP4.

In figures ***2a***, ***2b*** and ***2c*** the initial 100 s have been removed for clarity, as comparisons have been drawn between the URANS and LES data from the start of the transient. Injection was initiated for 2000 s so that the resultant impact on the flow could be monitored to assess whether this causes the loop NC to stall. Once injection at IP4 had ceased, the flow was monitored for a further 1000 s to determine whether the flow behaviour exhibited a recovery from stall and re-established NC.

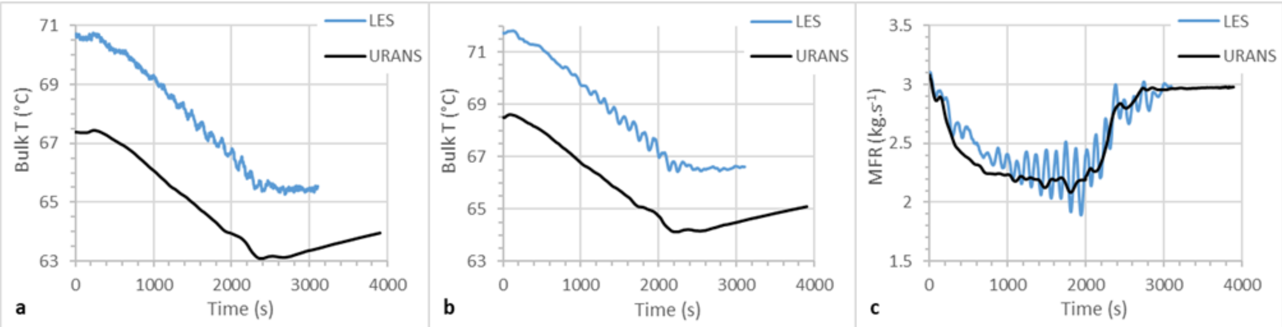

Figure 2 - a) Cooler Outlet T/t, b) Heater Outlet T/t, c) Heater Outlet MFR/t

5. CONCLUSIONS

The URANS results show general agreement with the benchmark LES data, implied by the models seeing a decrease in both bulk temperature (***2a***, ***2b***) and mass flow rate (***2c***) upon initiating the injection transient. There is an evident temperature offset between the URANS and LES data of approximately 3°C, however, the data trend conforms to that of the higher fidelity LES by exhibiting recovery around the 2000 s mark following a decrease in temperature at both the heater and cooler outlets. The comparisons drawn between the LES and URANS data imply that URANS is a promising candidate 3D modelling approach for simulating NC driven flow, whilst mitigating the associated computational cost that higher fidelity approaches would exhibit.

REFERENCES

[1] A. Skillen, R. Tunstall, S. Parry, S. Hind, S. Treasure, NATURAL CONVECTION WITHIN A LOOP WITH COLD-FLOW INJECTION, UK Heat Transfer Conference, 4-6 April 2022, Manchester, UK.