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OPEN-ACCESS NUCLEAR THERMAL HYDRAULICS FACILITY DEVELOPMENT IN NORTH WALES

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1 BACKGROUND

The Nuclear Futures Institute (NFI) of Bangor University is developing a multi-user fluid flow and materials related testing laboratory at Menai Science Park (M-SParc) in North Wales, in short referred to as NFI Loop Labs. Two-phase water experimentation will be targeted in the Thermal-Hydraulics Open-access Research (THOR) facility, which is currently undergoing commissioning. Other facilities being constructed at Bangor include a flowing, high temperature lead facility investigating the erosion/corrosion behaviour of materials being considered for the next generation of nuclear power systems as part of the BEIS funded Advanced Modular Reactor Competition (phase 2) in a consortium led by Westinghouse Electric Company.

The NFI Loop Labs are an integral prerequisite for supporting coming North Wales nuclear-related ventures at sites like Wylfa, Trawsfynydd and M-SParc itself. An explicit purpose of THOR is to underpin the potential establishment of a UK National Thermal-Hydraulics Facility [1] in the region; in advance to provide local up-skilling and research infrastructure. North Wales constitutes the southernmost portion of the so-called North West Nuclear Arc (NWNA). Other regions comprised are Liverpool and Sheffield City regions, Cheshire and Warrington, Cumbria, Greater Manchester and Lancashire. Collaboration across the area is close and continually developed, and the North Wales area is well connected per road and rail to the wider region, as well as the South of the UK.

2 THOR

THOR is supported by a number of industrial and academic partners, which have contributed advice and manpower towards its development. The main characteristics of this user-oriented and flexible facility are presented in the paper in the spirit of an open invitation to the UK Heat Transfer community to approach the NFI with new experiment configuration proposals and development collaborations, hopefully to further expand THOR's current collaboration community. The NFI was awarded a research equipment grant by the Welsh Government in March 2020 to develop THOR under the leadership of Dr Marcus Dahlfors. A first round of generic equipment was tendered and procured at the same time as the global COVID pandemic began to unfold, and due to increasing logistic challenges, a decision was taken in June 2020 to take the THOR concept into an extended re-optimisation phase. THOR is to be implemented in two stages:

1. Pressurised, subcooled operation of the loop that resemble conditions in a pressurised water reactor (PWR) and can supply two-phase flows at low void fractions; and,
2. Provision of saturated conditions with the possibility to tap off steam from the main boiler vessel to cover flow regimes up to annular flow with high void content, i.e. conditions encountered in a boiling water reactor (BWR) or potentially during transient states. Steam availability will be boosted by means of a steam compressor or an auxiliary boiler vessel.

2.1 Features and Design Development

The detailed design has seen significant evolution and optimisation since then, to make maximum use of the extended lockdown periods experienced during the year to enhance performance within

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existing frameworks. It was taken to conclusion in March 2021, when final procurement and construction of the flow loop infrastructure began. An overview THOR piping and instrumentation diagram (P&ID) is given in **Figure 1**.

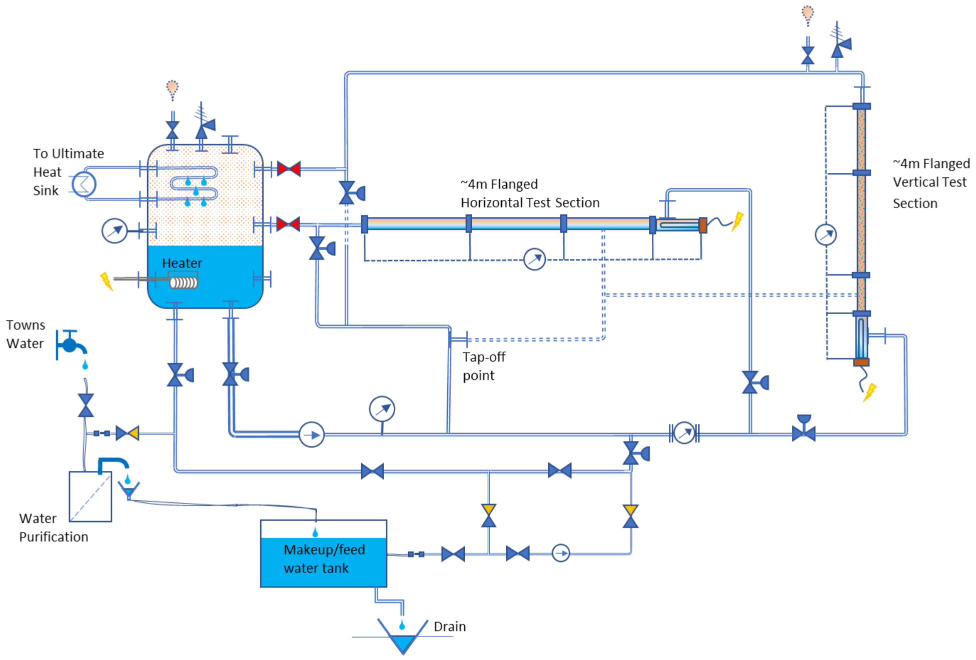


Figure 1: The Thermal-Hydraulics Open-access Research (THOR) facility: high-level P&ID.

Unique features provided by THOR include reconfigurable horizontal (HTS) and vertical (VTS) test sections driven by steam and heated water supply from a main pressurisation and condensation vessel. The HTS and the fully evolved vessel configuration were implemented during the optimisation effort and particularly add to the capability and flexibility experienced by users. An upgraded pump in combination with an optimised vessel configuration cater for delivery of a minimally sub-cooled fluid being delivered to the test sections. The guiding vision is to provide a robust flow loop platform to open up a wide range of experimentation possibilities for users. Some central parameters are given in **Table 1**, note that some values are preliminary or upgradeable at the moment of writing to allow evolution of the design based on participants' needs. A more elaborate description of the design basis of THOR can be found in [2].

Table 1: THOR Stage 1 key parameters; preliminary and approximative values indicated with an asterisk (*)

Parameters	Values
Height, total*	5.6 m*
Experiment hall height	6.35 m
Vertical test section height	4.0 m
General loop piping diameter	2" (~5.1 cm)
Horizontal test section, support up to	4" (~10.2 cm)
Total power in operation*	35 kW*
Heating power, main vessel	8 kW
Heating power, each test section	20 kW
Upgradeable power total	120 kW
Pressure, max	16 bar
Temperature, saturated coolant max	202 °C
Flow rate in horizontal test section*, up to	8 kg/s*

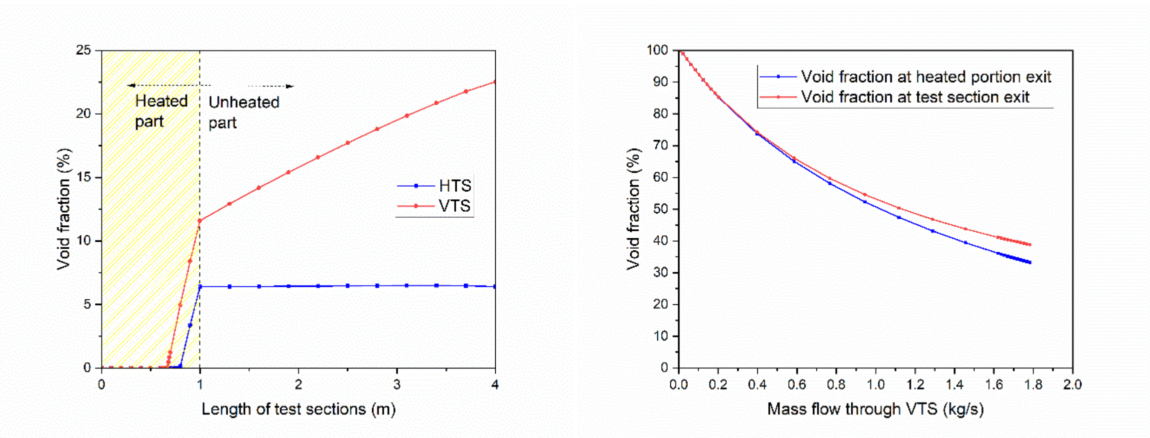
2.2 Commissioning and early experimentation

THOR will be deployed in a two-stage approach that will ensure devoted testing of the planned operation modes. Instrumentation and testing of the main vessel started in December 2021, with Stage 1 full loop commissioning to follow in March 2022. THOR Stage 1 is envisioned to provide a robust loop platform that will only need minor tweaks and adaptations to accommodate a wide range of future experiments in conditions typical to Pressurised Water Reactors. Stage 2 will add high steam content capability that will expand experimental capabilities with a view to transients, critical heat flux, pure steam line and Boiling Water Reactor conditions. Stages 1 and 2 taken together will provide a comprehensive and flexible hardware platform and thereafter continual and incremental development of the facility is foreseen to be focused on experiment sections and instrumentation.

First commissioning of THOR Stage 1 will verify basic parameters by testing the facility's operation in several temperature and pressure ranges, in steady state and eventually transient operation. Transient testing will be achieved through application of flow pulsing produced through pump rotational speed variations and bypass flow throttling. Detailed flow characterisation initially rests on Wire Mesh Sensors (WMS) technology. Future configurations will add (partial) visual access to allow for High-Speed Camera based visualisation and potentially Particle Imaging Velocimetry techniques. However, WMS are foreseen to provide the mainstay reference method, planned to be flexibly employable in positions between the interconnecting flanges of the test sections. In-house technician capability is under development so that bespoke test sections and interconnections can be configured. Differential pressure data can be derived from dedicated spacer rings allowing access at the flanging points, while the loop also has two absolute measurement points – one in the main vessel and one at the point of highest pressure right after the main pump (cf. **Figure 1**).

2.3 Design simulations

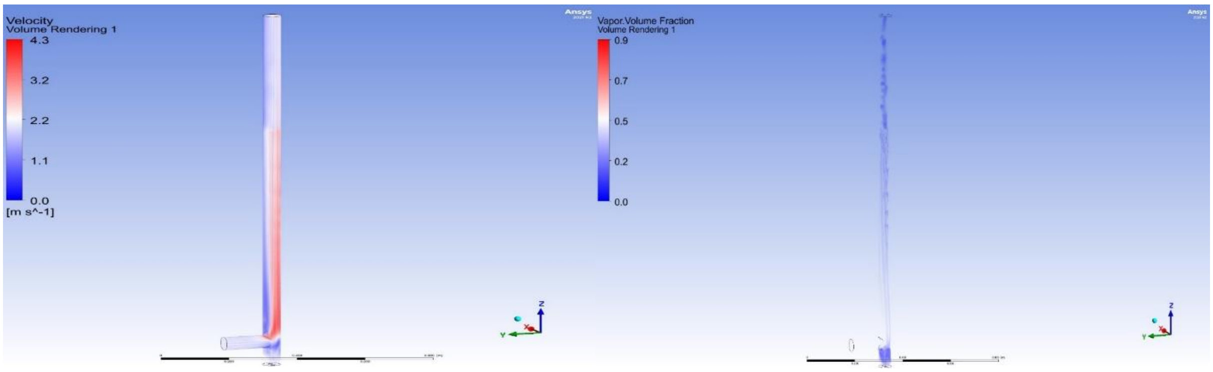
THOR design assumptions and detailed design development are on the system level been underpinned by simulations undertaken in RELAP5 [3] and Flownex® [4]. Computational Fluid Dynamics (CFD) based methods were applied and models are continually developed for the test sections to obtain detailed information pertaining to flow velocities, voiding and local pressure drop fields. CFD simulations are performed in ANSYS Fluent [5] and OpenFOAM [6]. For THOR Stage 1, a central design requirement is to provide modest steam generation capability at up to 2 kg/s mass flow in the test sections, to ensure that PWR conditions can be reached and somewhat surpassed (Stage 2 is to further add high steam content condition experimentation possibilities). **Figure 2** shows the expected void generation in THOR's HTS and VTS, as well as the void fraction dependency on mass flow.



(a) (b)

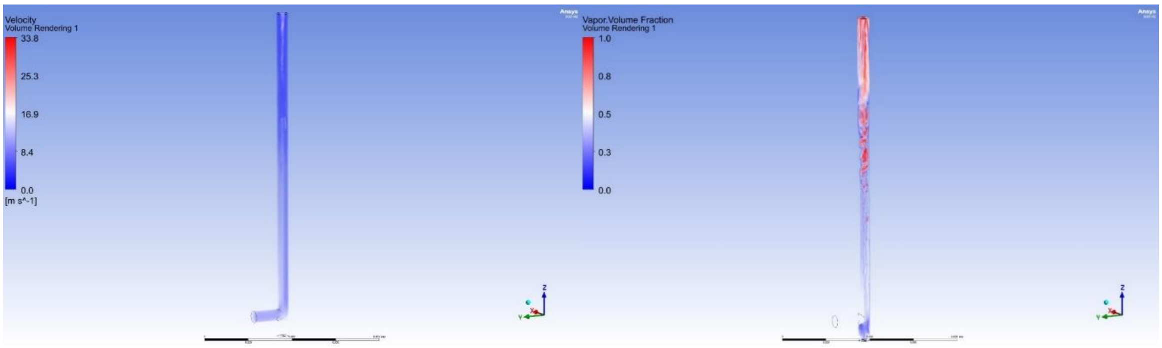
Figure 2: Steam generation capability in THOR's test horizontal and vertical test sections: (a) shows void fraction evolution over the length of each section, and (b) void fraction dependency vs mass flow in the vertical test section

The initial CFD studies have in particular focused on flow evolution after the 20 kW heaters in the T-shaped heating-mixing chamber in the inlets to the HTS and VTS. **Figure 3** displays the local velocity fields and void fractions resulting with 2 m/s inlet flow, and **Figure 4** the corresponding parameters at 1 m/s inlet flow. The resulting void fraction distribution maps at a postulated WMS position at 1250 mm height from the inlet are also shown in **Figure 5** for these two respective inlet flow values.



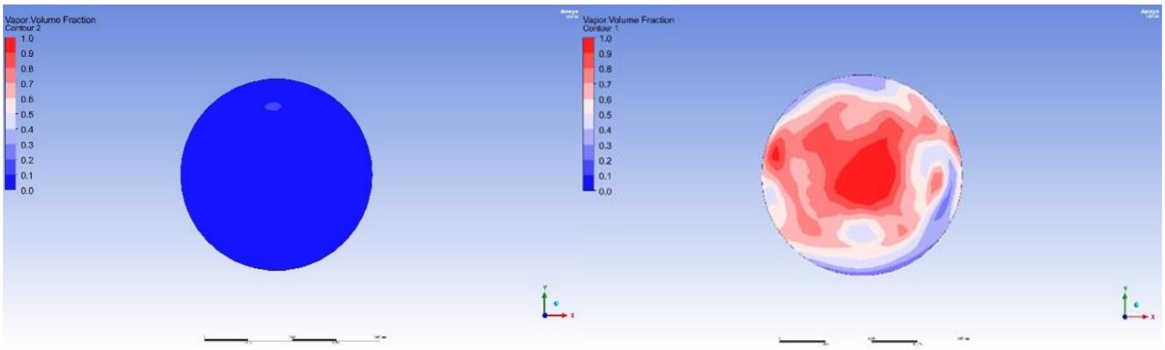
(a) (b)

Figure 3: Local velocity (a) and void fractions (b) at 2 m/s inlet flow



(a) (b)

Figure 4: Local velocity (a) and void fractions (b) at 1 m/s inlet flow



(a) (b)

Figure 5: Void fractions in WMS position at 2 m/s (a) and 1 m/s (b) inlet flow.

The above presented fundamental simulations aim to provide an understanding of flow velocities and void contents throughout the test sections to achieve optimal placement of WMS – and to produce the basis for initial WMS flow imaging validation measurements during THOR commissioning. Aspects taken into account when optimising the location of the currently employed WMS type are that the sensors must be operated in mass flow not exceeding 8 kg/s (which corresponds to max local velocities of 4 m/s in the present geometry), that measurable amounts of local void exist and in cases with multiple WMS that the flow image in a downstream measurement location is not significantly disturbed by the preceding WMS. As can be concluded from

3 BULLET

The Bangor University Lead Loop for Erosion/corrosion Testing (BULLET) apparatus is being designed with SRS in Italy within the BEIS AMR competition supporting the lead-cooled fast reactor development lead by Westinghouse Electric Company and will be commissioned in late 2021 under the leadership of Dr Simon Middleburgh. Additional capability within the facility is being supported through the NNL's Advanced Fuel Cycle Programme (AFCP) enabling the testing of the next generation of nuclear fuel materials within the flowing lead environment. Flowing lead sections will test samples at temperatures of ~450 °C with Pb velocities of up to 6 m.sec^{-1}. Oxygen control within the system will be controllable between 10^{-8}-10^{-6} %.

Initially Middleburgh will use BULLET to focus on corrosion/erosion relevant experimentation supported by thermal-hydraulics studies. Material selection is being supported by the existing MERLIN active laboratories at Bangor University (see https://nubu.nu/materials/merlin/). Future applications include TH experiments and experiments relevant to other advanced nuclear systems including fusion.

4 INDUSTRIAL HYDRODYNAMIC FLOW TESTING RIG

The hydrodynamic flow rig is a low-cost reconfigurable rig comprising of commonly available components. Its key characteristics include the ability to run a range of fluids through the flow loop. Examples include water, saline water and hydraulic fluids with an ability to maintain and adjust the temperature of the fluids. The nature of the two-loop control system allows for adjustable speed and pressure allowing for both laminar and turbulent flow conditions to be replicated. This is furthered by removable sections of this rig that allow for added flow replication per flow adjusting structures at a range of points throughout the structure. The removable test section also allows for measurement and visualisation of flow, along with the ability for both pipe radius and internal coatings to be altered to suit experimental needs. The rig is being used by Bangor University to study drag reduction coatings for hydraulic systems and allows them to be tested. Additionally, extended uses of this rig include the testing and development of equipment such as flow characteristic measurement instrumentation and hot wire sensors before they are integrated in the larger THOR facility.

5 CONCLUSIONS

Bangor University is developing the NFI Loop Labs at M-SParc in North Wales for fluid flow and materials related testing. The THOR facility accommodates a variety of setups that will allow flexible multi-user water thermal-hydraulics experimentation and testing possibilities for industry and academia. A variety of measurement configurations are offered at conditions of about 16 bar and 200 °C at THOR. The lead testing apparatus BULLET is also being deployed in 2022 to support the fast-paced advanced modular reactor programme within the UK. We welcome proposals for novel experiments as well as industrially relevant testing that take maximum advantage of facilities and will generate fruitful collaborations.

ACKNOWLEDGEMENTS

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