THE UK NUCLEAR INNOVATION PROGRAMME - THERMAL HYDRAULICS RESEARCH, INNOVATION AND INDUSTRIAL CAPABILITY DEVELOPMENT

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ABSTRACT

The UK Government's 2013 Nuclear Industrial Strategy described significant ambitions to grow the UK's nuclear capability. To help fulfil the strategy's objectives, a 'Nuclear Innovation Programme' (NIP) was launched, with the aim of developing the UK as a significant partner in the next generation of nuclear reactor design and deployment.

This paper summarises work undertaken between April 2017 and June 2021 within the NIP in the field of nuclear thermal hydraulics, including the main activities, the motivation behind them and outputs produced.

1 UK NUCLEAR INNOVATION PROGRAMME

The UK Government's 2013 Nuclear Industrial Strategy described significant ambitions for the UK to grow its nuclear capability. The aim was to both build an energy system delivering domestic net zero carbon targets, and develop the UK as an active partner in next generation nuclear reactor design and deployment.

To deliver this Nuclear Industrial Strategy, BEIS (Department for Business, Energy and Industrial Strategy) invested £180 million in a Nuclear Innovation Programme (NIP) from 2016 to 2021, following the recommendations in [1]. This NIP covered research and innovation across a range of technical disciplines such as advanced reactor design, advanced fuels, recycling and reprocessing, advanced manufacturing and materials.

Since reducing costs is one of the most pressing requirements for the civil nuclear industry worldwide, improvement in and demonstration of predictive techniques is key to the future of nuclear power. The importance of thermal hydraulics (both modelling and experimental investigation) in underpinning the performance and safety of all reactor designs was recognised within the NIP and a specific project was included under the 'Digital Reactor Design' area of the programme. This paper summarises work undertaken within the Thermal Hydraulics part of the NIP between April 2017 and June 2021, with a budget of £4.6 million. The project involved numerous activities, and this paper only includes some examples of the work undertaken; the outputs referred to within this paper are freely available on our project website[1] and are described in more detail in [2].

In contrast to many government funded research activities within the UK, the vision for the NIP was that it should be led by industry in order to focus the work on what could be most directly exploited in the short and medium term. However, the majority of the UK civil nuclear industry was focused on

[1]https://www.innovationfornuclear.co.uk/nuclearthermalhydraulics.html

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reactor operation, plant life extension, decommissioning and waste management. Therefore, it was clear from the outset that a project team comprising UK industry alone would not be best placed to complete a project focused on next generation reactor design. The activities were led by Frazer-Nash Consultancy and were delivered and supported by a team of organisations (co-authors to this paper) and further UK and international industrial and academic partners.

2 THERMAL HYDRAULICS NIP PHASE 1

The first phase of the project (2017-2019) focused on critical review and requirements capture activities, with the intention of determining the most effective direction for future UK R&D. The direction for reactor technology development in the UK had not yet been decided, and so these activities were comprehensive, considering all reactor technologies, including mature designs of large Light Water Reactors (LWRs), as are currently under construction in the UK, and advanced designs using alternative coolants including liquid metals or molten salts (Generation IV reactors).

2.1 What is a Nuclear Thermal Hydraulics Modelling Capability?

One of the outputs required of Phase 1 was a specification supporting the development of a UK nuclear thermal hydraulic (NTH) modelling capability. To achieve this it was necessary to explore questions such as: What capability does the UK have now and what capability will it need? Even more fundamentally, the question of what constitutes a nuclear thermal hydraulic modelling capability was raised.

A modelling capability in this context is often thought of as the specification, coding and execution of mathematical models in order to simulate plant performance or investigate fluid flow and heat transfer in a nuclear context. However, a 'nuclear thermal hydraulic modelling capability' must be broader than just the methods and tools employed - there are other aspects of capability that are equally important in delivering a complete solution that is industrially useful and acceptable to regulators. Figure 1 shows a simplified version of the concept of an NTH modelling capability developed for use within this project, where the other aspects of capability are shown as all contributing the modelling solution.

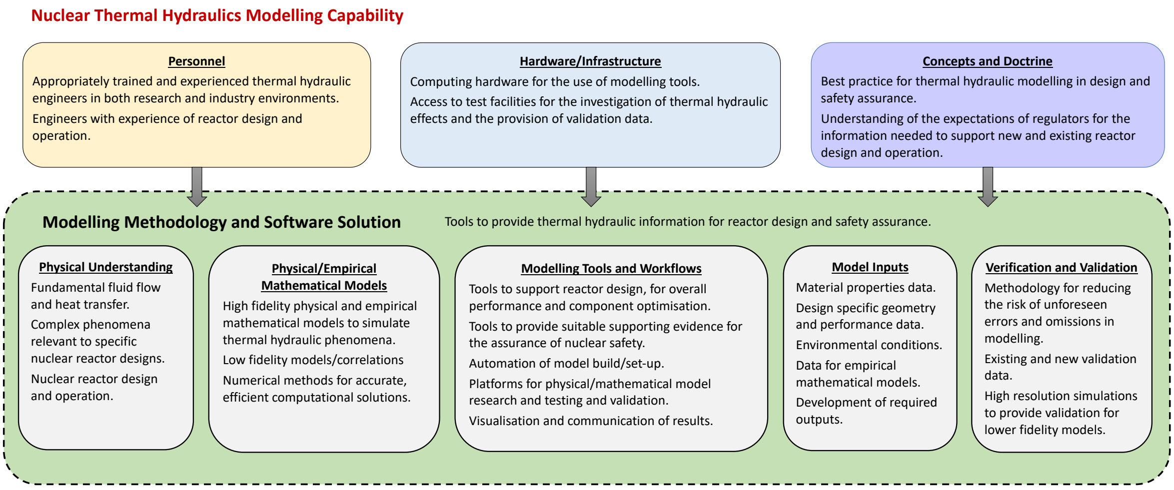

Figure 1: The elements required for a nuclear thermal hydraulics capability.

2.2 Specification of UK Capability Development

Having defined what an NTH capability is in general, it was then necessary to consider what future capability the UK might need. The first activity was a critical review of current UK and world capability in both thermal hydraulic modelling and testing [3, 4].

The second activity was to look at the requirements for thermal hydraulic testing and modelling in current and prospective nuclear power plant designs. Around 60 organisations throughout the world, covering a range of reactor developers, academic and national institutions and service providers, participated in this assessment via questionnaires, phone calls and meetings [5]. A number of common themes became apparent within the requirements set. For example:

- An overriding concern for many stakeholders and across all technologies was related to 'trust' in the results of thermal hydraulic modelling. The input, from reactor developers in particular, suggests that increased confidence in current methods is a higher priority than increases in tool functionality. Requirements under this theme included improved best practice guidance, better quantification and bounding of uncertainty in CFD and the need for high quality validation data.

- The innovative combination of different modelling tools and techniques to enable a more complete picture of the physics and/or to gain results in practical timescales was identified as an under-exploited approach.

- Better predictive methods for thermal hydraulic phenomena relating to one or two-phase natural circulation/convection were of interest across a range of reactor technologies to support the adoption of passive cooling features in reactor design.

To develop the requirements into a specification for a UK modelling capability development, a workshop involving the UK thermal hydraulics community was held in 2018 that created 34 research and development proposals to address the modelling challenges identified [6]. Two proposed activities were universally considered to be of value regardless of future reactor technology decisions and formed a significant part of the scope for Phase 2:

- *Maximising UK Collaboration and Collective Learning* to establish a framework for collaborative working in NTH modelling, developing and sharing good practice and lessons learned.

- *Increased Participation in Benchmarking* to re-engage the UK in international benchmarking activities thereby promoting international collaboration and enabling improved confidence in, and understanding of, NTH modelling tools.

2.3 Phase 1 Modelling Innovation

In parallel with the critical review and requirements activities, initial research was performed encompassing a range of promising thermal hydraulic modelling innovations. These chosen activities supported one or more of the areas of capability shown in Figure 1, and were able to exploit the UK's existing strengths. In addition, previously unpublished experimental work carried out at the University of Manchester from 1980 to 1993 on sodium surface emissivity and the heat transfer across a sodium aerosol-laden cover gas was identified.

3 THERMAL HYDRAULICS NIP PHASE 2

Consideration of the UK thermal hydraulics capability, in the context of the NIP objectives, concluded that R&D to build on, expand and improve existing thermal hydraulics toolsets (rather than 'from scratch' development) was the most effective way forward. Phase 2 work focused on single-phase heat transfer, especially aspects relating to passive cooling (as these had the widest applicability across advanced reactor technologies).

3.1 UK Industry Skills Development

A primary aim of Phase 2 was addressing the challenge of up-skilling current and new industrial engineers in NTH modelling to anticipate the capacity and capability needed to accelerate reactor development and deployment.

Because regular and smooth interactions between reactor developers, technical support and supply chain organisations and nuclear regulators will be needed, one of the objectives was to produce a set of materials that represented a common and agreed view on what 'good' looked like for those performing, procuring and assessing analysis. To achieve this, six 'Technical Volumes' covering a range of aspects of NTH modelling intended for industry use were prepared. These technical volumes are supported by a set of four 'Case Studies', demonstrating worked examples of the application of their contents in a range of typical industry scenarios. This set of documents is now freely available[2].

Technical Volumes

The purpose of the volumes is to provide clear, concise guidance in a usable form for industry. The target audience for the technical volumes is envisaged to be engineers and managers with some prior knowledge of nuclear thermal hydraulics who wish to know more about state-of-the-art analysis methods and how they can be applied.

1. *Introduction to the Technical Volumes and Case Studies:* Introduction to thermal hydraulic analysis and description of current NTH analysis methods.

2. *Convection, Radiation and Conjugate Heat Transfer:* The fundamentals of heat transfer via conduction, convection and thermal radiation.

3. *Natural Convection and Passive Cooling:* Focusing on buoyancy influenced flows and heat transfer within loops, channels, pools and plena.

4. *Confidence and Uncertainty:* Understanding and quantifying the sources and magnitudes of uncertainty, and establishing the level of confidence in the results.

5. *Liquid Metal Thermal Hydraulics:* Thermal hydraulics that occur in liquid metal cooled reactors as a result of the reactor design or characteristics of the primary circuit fluid.

6. *Molten Salt Thermal Hydraulics:* Heat transfer in molten salts, describing the physics and chemistry of typical salts, including partial transparency to thermal radiation.

The volumes do not cover only modelling guidance – they also describe how analysis fits into the graded approach of a regulatory framework, such as the use of conservative vs Best Estimate Plus Uncertainty (BEPU) models.

Case Studies

The technical volumes are supported by four case studies. They provide illustrative reactor-specific 'worked examples' of thermal hydraulic analyses, with an emphasis on passive cooling applications and practical guidance showing how the methods outlined in several technical volumes can be combined and applied.

[2] https://www.imeche.org/digital-thermal-hydraulics

A. *Liquid Metal CFD Modelling of the TALL-3D Test Facility:* Using CFD to model forced and natural circulation in liquid metals in TALL-3D. A range of fidelities were used from Large Eddy Simulation (LES) to 2D steady-state models, which were compared to the experimental data.

B. *Fuel Assembly CFD and UQ for a Molten Salt Reactor:* Flow through a fuel assembly under forced and natural circulation is analysed to demonstrate CFD of molten salts, the derivation of a porous model representation of the fuel, and the application of Uncertainty Quantification (UQ) and Sensitivity Analysis to the salt thermophysical properties.

C. *Reactor Scale CFD for Decay Heat Removal in a Lead-cooled Fast Reactor:* Natural circulation modelling of the whole primary circuit of a lead-cooled fast reactor to analyse flow paths and associated heat transfer for decay heat removal.

D. *System Code and CFD Analysis for a Light Water Small Modular Reactor:* Emergency cooling injection into the LSTF test facility is modelled and compared to the OECD/NEA ROSA test data. Conjugate heat transfer prediction of the reactor vessel and pipework temperatures from CFD is shown with its relation to Pressurized Thermal Shock (PTS) stress prediction.

These case studies describe the process of starting from a state-of-knowledge representative of a concept design or early reactor design, and demonstrate how CFD analysis can be used to provide more detailed insight into reactor and component behaviour [7].

3.2 International Collaboration

Over the past 20 years, UK involvement in international collaborative activities in the area of nuclear thermal hydraulics has become sporadic and largely undertaken by academic institutions. However, the thermal hydraulics NIP project has provided an opportunity for UK industry to re-engage actively with international organisations. This has included:

- Frazer-Nash Consultancy have become active members of the OCED/NEA WGAMA CFD task group, and have supported the current update to the best practice guidelines for the use of CFD in nuclear reactor safety applications [8] using the research and information that has been developed for the technical volumes.
- Frazer-Nash Consultancy also participated in the 6th WGAMA CFD for nuclear reactor safety benchmark, assessing the prediction of Fluid-Structure Interaction.
- BEIS and the US Department of Energy agreed a Civil Nuclear Energy Research and Development (R&D) Action Plan in 2018 to facilitate cooperation in R&D. Advanced modelling and simulation is one of six areas of focus for the Action Plan, and the NTH NIP programme has been active in building collaborative relationships, including performing the WGAMA CFD benchmark as a joint endeavour.

3.3 Phase 2 Modelling R&D

Three specific research projects were selected in Phase 2 for further study, based on interest from industry and international researchers, potential for near-term industrial exploitation and applicability to a range of reactor technologies:

- *Natural circulation loops:* Exploring the limits of modelling of stable and unstable buoyancy driven loop configurations, using several different modelling tools and turbulence modelling strategies. Led by the University of Manchester, the aim was to better understand the modelling of the thermal hydraulic flow phenomena present in natural circulation loop systems and further validate the recent advances in CFD modelling methods [9].

- *Coarse-grid CFD:* Further development, demonstration and validation of Sub-Channel CFD (SubChCFD) as a modelling tool. The University of Sheffield has led the development of the SubChCFD method, intended to fill the gap between CFD and lower fidelity tools [10].

- *Liquid metal modelling:* Examining the modelling of low Prandtl number fluids with CFD and generation of high-fidelity benchmark results. This University of Sheffield led research included LES models of forced and mixed convection in the TALL-3D facility [11].

4 OUTCOMES

This NIP Thermal Hydraulics programme, funded by the UK Government, has brought the UK thermal hydraulics community together into more regular contact, and provided an impetus for model development and experimentation in this field. The UK has committed to develop a Small Modular Reactor (SMR) design and to build an Advanced Modular Reactor (AMR) demonstrator by the early 2030s [12]. The technical volumes, case studies and research developed by this programme are expected to increase the UK's thermal hydraulics capability to support these reactor development programmes, and to be adopted as a useful resource internationally.

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