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REGULAR ARTICLE

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SESAME project: advancements in liquid metal thermal hydraulics experiments and simulations

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Abstract. Liquid metal cooled reactors are envisaged to play an important role in the future of nuclear energy production because of their possibility to use natural resources efficiently and to reduce the volume and lifetime of nuclear waste. Sodium and Liquid lead (-alloys) are considered the short and long term solution respectively, as coolant in GEN-IV reactor. Thermal-hydraulics of liquid metals plays a key role in the design and safety assessments of these reactors. Therefore, this is the main topic of a large European collaborative program (the Horizon 2020 SESAME) sponsored by the European Commission. This paper will present the progress in the project with respect to liquid metal cooled reactor thermal-hydraulics (liquid metal heat transfer, fuel assembly thermal-hydraulics, pool thermal-hydraulics, and system thermal-hydraulics). New reference data, both experimental and high-fidelity numerical data is being generated. And finally, when considering the system scale, the purpose is to validate and improve system thermal-hydraulics models and codes, but also to further develop and validate multi-scale approaches under development.

1 Introduction

Within the framework of the Strategic Energy Technology Plan (SET-Plan), civil nuclear power is envisaged to deliver safe, sustainable, competitive and essentially carbon-free energy to Europe's citizens.

ESNII, the European Sustainable Nuclear Industry Initiative, is an European framework of collaboration, led by the industry, but involving also research bodies and nuclear stakeholders, aiming at promoting the development of Gen-IV Fast Neutron Reactor technologies, together with the supporting research infrastructures, fuel facilities and R&D work [1].

Under the ESNII umbrella, four projects are boosted in Europe, as depicted in Figure 1.

ASTRID is the SFR industrial prototype, and it represents the shorter-term option for fast nuclear reactor in Europe being based on the proven sodium technology [2]. ALFRED is the European demonstrator of Lead cooled Fast Reactor (LFR) technology, to be constructed in Romania [3]. MYRRHA, under construction in Mol (Belgium) is a multipurpose fast neutron spectrum irradiation facility proposed to operate as a large research infrastructure [4]. MYRRHA will also demonstrate the technological feasibility of the Accelerator Driven System (ADS) operated for waste transmutation.

The last is SEALER, a small lead cooled reactor, which is currently under development by the Swedish company LeadCold. It is designed to provide reliable and safe production of power/electricity for remote sites [5]. Except for the SEALER concept, the reactors under consideration have been described in IAEA [6] and the IAEA booklet on the status of fast reactor designs and concepts [7].

For the technological development of the above mentioned projects, many efforts are devoted to the development of liquid metal technologies (lead, lead-alloys, sodium), and as consequence thermal-hydraulics of liquid metal is considered one of the key scientific subjects in the design and safety analysis. Many efforts have been spent in Europe for addressing thermal-hydraulic issues as reported in [8–16]. To address thermal-hydraulic issues, analytical and empirical correlations are proposed and verified,

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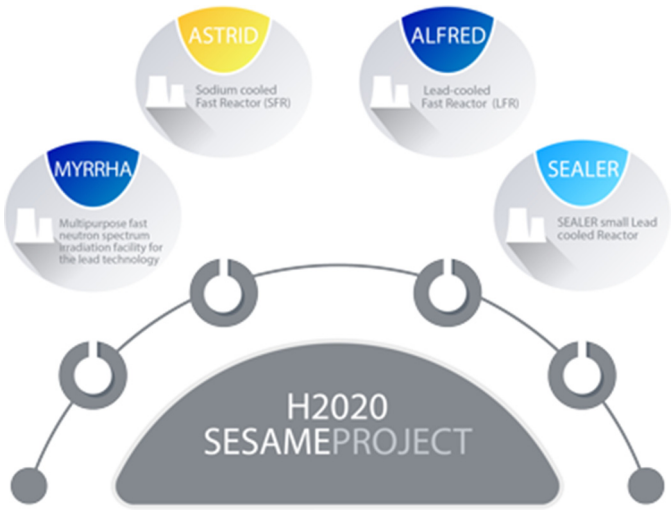


Fig. 1. European liquid metal cooled reactor demonstration projects.



Fig. 2. SESAME partners.

system thermal hydraulics (STH) and sub-channels codes implemented and validated. In the last fifteen years, Computational Fluid Dynamics (CFD) techniques are playing a relevant role in the design and safety assessment of liquid metal cooled fast reactors.

To advance progress in this field, the collaborative Horizon 2020 thermal hydraulic Simulations and Experiments for the Safety Assessment of MEtal cooled reactors (SESAME) project, sponsored by the European Commission, was initialized in 2015 with duration of 4 years. This project ended in 2019 [17].

One of the main deliverables of this international project was a textbook titled 'Thermal Hydraulics Aspects of Liquid Metal Cooled Nuclear Reactors', [18].

23 European institutes and US partners were involved in the project (see Fig. 1) with about 100 researchers and 916 PMs of work (Fig. 2).

2 Liquid metal heat transfer

One of the most relevant task in the safety analysis of liquid metal nuclear reactors consist of in the accurate prediction of turbulent heat transfer under forced, mixed and natural convection regimes.

Presently, the most adopted models to simulate turbulent heat transfer are based on the Reynolds analogy. While this approach is applicable successfully for forced convective flows with a Prandtl number of order of unity, in the case of nuclear systems cooled with liquid metal, for which Prandtl number is higher than the unity, this approach is not enough accurate for the aim.

This is especially true for the simulation of large pool reactors where all flow regimes may occur simultaneously. As consequence, an improved numerical modelling for the turbulent heat transfer in liquid metal is required, applicable with any flow regimes. Improvements on modelling and simulation have been proposed and tested on different simple test cases [19]. An update of the ongoing model evaluation and development is reported in [20].

The extension of the validation base for flow separation, jets, mixed convection and a rod bundle represent one of the main topics of the SESAME project. An overview of experimental and numerical activities performed, is presented in Figure 3. In [21], new reference data from open literature on a backward facing step was used. It shows encouraging results for the AHFM-NRG model for turbulent heat transport coupled to an isotropic linear model for momentum. The same authors explain in [22] that they have extended their turbulent heat flux model to the use of an anisotropic non-linear model for momentum. They tested it for different scenarios like the flow between two flat plates, impinging jet case from the project and for a bare rod bundle case for which reference data was available from other projects and open literature. In [23], an assessment of a variety of promising models is made with respect to the impinging jet case also used in [22]. Apart from the Reynolds analogy, three different advanced models have been employed: an implicit and explicit AHFM model and the so-called Kays correlation. Limitations of the Reynolds analogy are clearly demonstrated while, all advanced models show reasonable behaviour for this forced convection case. However, they are all based on an isotropic linear model for momentum, and it is concluded that expansion to an anisotropic non-linear model (as in [22]) could clearly bring added value.

Finally, [20] summarizes the latest developments with respect to advanced turbulent heat flux model developments. In the frame of the SESAME project, new reference data are assessed for a variety of advanced turbulent heat flux models, i.e. the second order TMBF-eq-ATHFM model, an implicit AHFM model and the AHFM-NRG. Three different sets of reference data are assessed covering the various flow regimes. For the natural convection flow regime a Rayleigh-Bernard Convection case has been considered from literature, for the mixed convection flow regime, new data from the SESAME project has been considered and for the forced convection flow regime, again the impinging jet case has been considered. Once again, the AHFM-NRG showed good results in all flow regimes. The implicit AHFM model showed good results in the forced convection

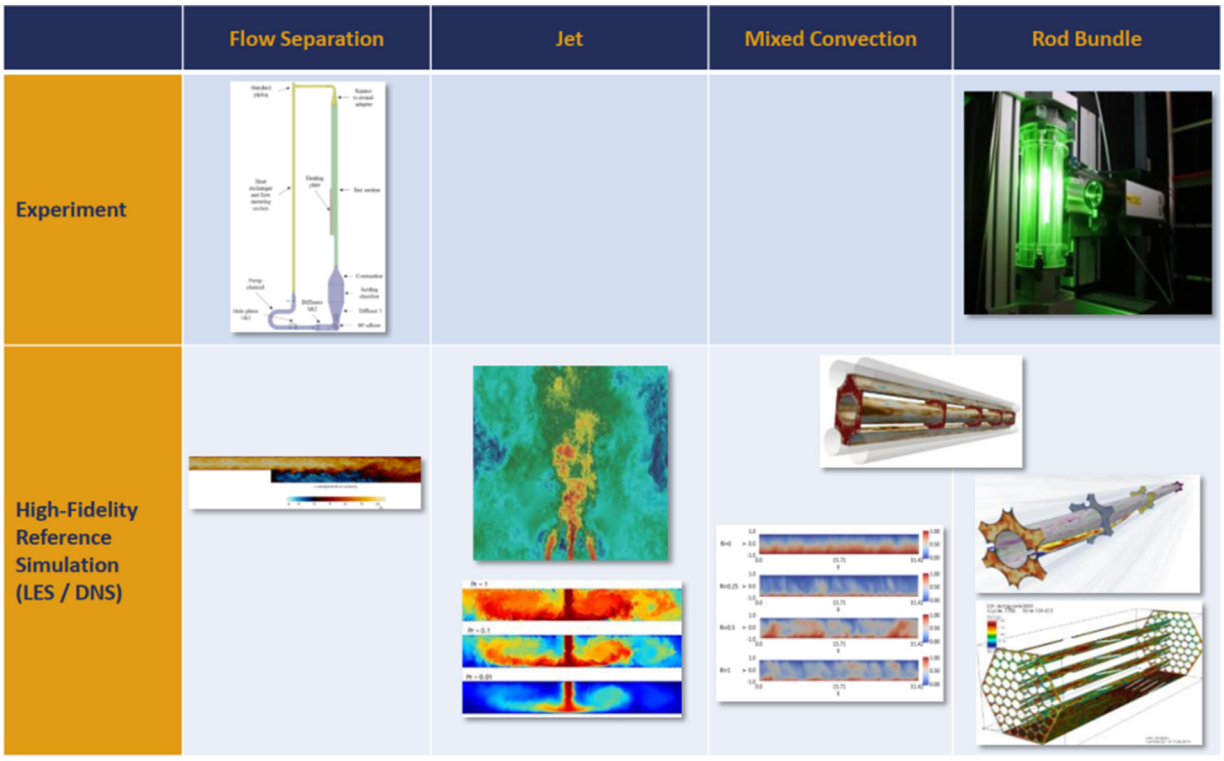


Fig. 3. Overview of reference data referred to liquid metal heat transfer.

regime, while it became clear that the promising second order TMBF-eq-ATHFM will need further calibration especially for applications involving non-negligible buoyancy effects, before definite conclusions on the performance of this model can be drawn. An extensive discussion on this work, can be found in [24].

3 Core thermal hydraulics

The core thermal hydraulics work package, within the SESAME project was focused on the development and validation of numerical models for the thermal hydraulic simulation of liquid metals fast reactor cores. The developed models include sub-channel codes, reduced resolution CFD, coarse-grid-CFD and CFD models. New reference data were generated from the considered experiments, high fidelity numerical models and DNS. Experimental data is generated for wire-wrapped bundles, a bundle with spacers, the effect of blockage, and inter wrapper flow. All intended data was prepared and applied in the model development or in the validation of the used model.

In the SESAME project, a 7-pin rod bundle experiment was performed adopting water as coolant, allowing to implement a validation database for the flow field. Moroever, quasi-DNS simulation data was generated for a rod bundle with an infinite number of pins and LES data was generated for a 61-pin bundle. In [25], the work on validating RANS CFD methods for wire-wrapped fuel assemblies is summarized. It is concluded that validation efforts up to now indicate that an accuracy within 12.5% for engineering RANS models should be feasible for all bundle sizes and all parameters checked. It is also noted that this value has to be considered as preliminary. Important steps in the validation strategy are missing, i.e. validation for large scale bundles both for the hydraulic field as well as for the thermal field. Furthermore, it is important to realize that all of the applied thermal validation simulations have used the standard Reynolds analogy with a constant turbulent Prandtl number approach and as such there is room for improvement.

Concerning grid spaced fuel assemblies, new data to support the ALFRED reactor fuel assembly design has been produced by performing experiments in a liquid metal rod bundle with and without blockages (Fig. 4). These experiments have been described in detail by [26]. Simulations have been performed for these experiments also. The simulations for the unblocked bundle show a good comparison with the experimental data with differences less than 10%. The simulations for the blocked bundle also show a reasonable comparison (on average in the order of 15%), except for the prediction of the wake region behind the blockage [27]. Simulations were performed using a reduced resolution RANS approach to allow scaling up to a complete ALFRED fuel assembly at reasonable computational costs. The errors involved in using a reduced resolution technique were a priori determined by comparison to RANS results and by comparing to experiments.

The interaction of turbulent flow with the fuel pins (flow induced vibrations in a fuel assembly) was experimentally investigated in a seven pin bare rod bundle using water as coolant (SEEDS-1 experimental facility). Obtained data were used to support the development and validation of numerical approaches. Simulations were

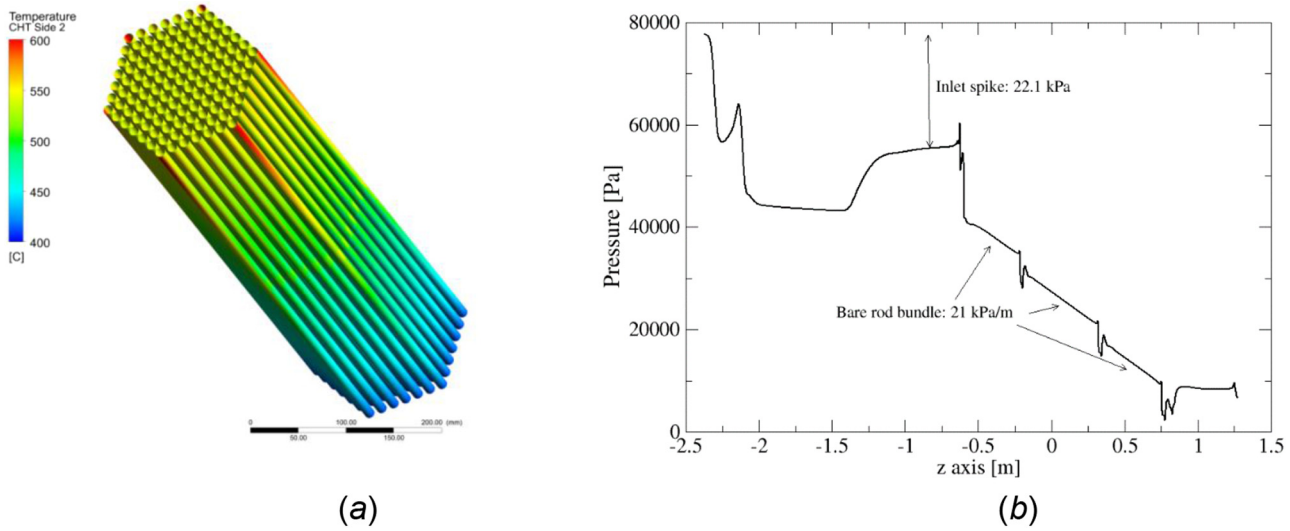


Fig. 4. Clad temperature distribution (a) and cross-section averaged pressure distribution along the streamwise direction (b): unperturbed case (ALFRED fuel assembly).

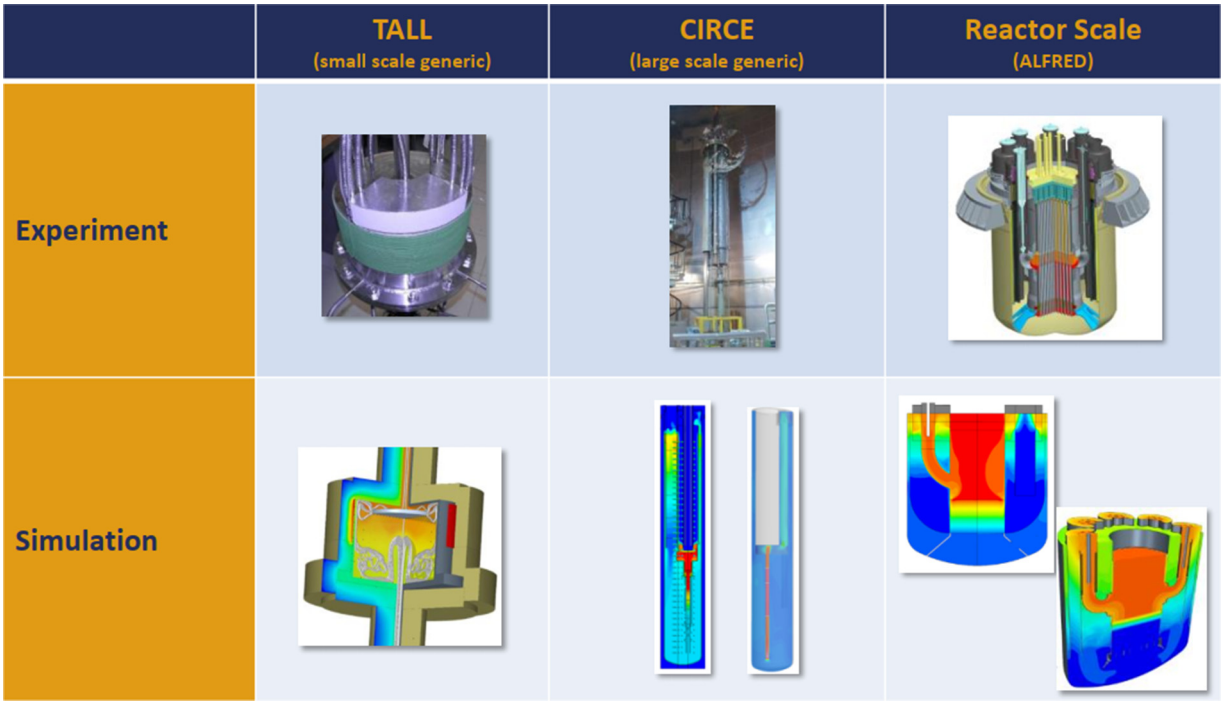


Fig. 5. Overview of experimental and numerical pool thermal hydraulic activities.

based on a URANS approach with an SST k-ω turbulence model and strongly coupled algorithms to account for the fluid-structure interaction. The frequency of the flow pulsations was reasonably well predicted. However, the results of the Fluid Structure Interaction (FSI) calculations deviated from the experiments in that they under-predicted the amplitude of the flow-induced vibrations and in that they over-predicted the respective frequency. Several possible reasons for the mismatch were identified, but will need future investigations to draw conclusion. In particular, the fixation and/or material properties of the transparent material, the stiffness of the rods, the modeling of the water filling of the rods, and dimensional tolerances of the components of the experimental set-up might play a role [28].

4 Pool thermal hydraulics

SESAME work package number three, deals with HLM flows in a pool configuration at different scales (Fig. 5). Thermal stratification and mixing phenomena were

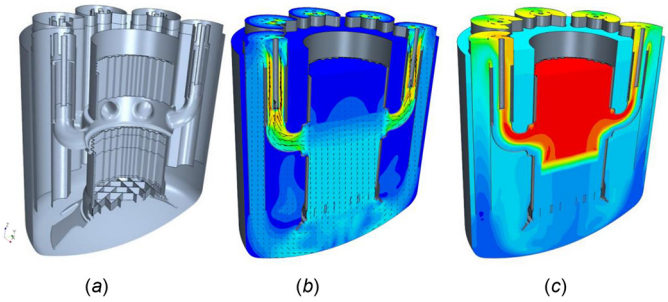


Fig. 6. ALFRED according to LEADER project. Geometry (a), velocity field (b) and temperature field (c).

investigated in small scale apparatus like the TALL-3D facility [29] (Thermal-hydraulic Lead-bismuth Loop with 3D flow test section) developed at KTH (Royal Institute of Technology, Stockholm, Sweden). Solidification/remelting in buoyancy driven lead flow was performed in the SESAME-stand experimental facility by CVR (Research Centre Rez, Czech Republic). Large scale experiments were performed at ENEA Brasimone R.C. in the CIRCE (Circolazione Eutettico) refurbished with the Integral Circulation Experiment (ICE) test section and thermal stratification and flow patterns were experimentally investigated.

Experimental data were used to validate numerical approaches developed in parallel for these facilities using CFD software. These comparisons, reported in [30,31] show reasonable performance of the CFD models. In [30] validation of CFD was performed for the TALL facility including an elaborate sensitivity analysis. This analysis indicates that the boundary conditions (e.g. LBE mass flow rate, inlet temperature, heater power) followed by the turbulent Prandtl number and material properties (e.g. density and heat capacity of LBE) constitute the major sources of modelling uncertainty. Once the radiative heat transfer was taken into consideration, the CFD simulations reported in [32] could reproduce with good accuracy the solidification/remelting experiments performed in the SESAME-Stand facility. The CFD models of CIRCE-ICE reported in [31] reproduce the general flow and temperature patterns of the facility operating under nominal and transient conditions reasonably well. It was found that prediction of the stratification in the CIRCE-ICE pool is sensitive to the modelling of the conjugate heat transfer from the inner loop to the pool. Overall, modelling results of CIRCE-ICE served as valuable feedback to the experimentalists, resulting in changes made to the facility and a better data acquisition in follow-up experiments.

Finally, full CFD approaches are applied to the full scale ALFRED design [3], profiting from the validation efforts on the TALL and CIRCE-ICE facilities. These simulations for a full scale reactor provide designers a priori detailed insight in 3 dimensions concerning the behaviour of flow and heat transport in their design (Fig. 6).

4.1 System thermal hydraulics

In the frame of safety assessment and design of nuclear reactors, the use of system thermal-hydraulics codes is widely adopted to simulate the transient behaviour of the whole systems, i.e. primary and secondary system, including the balance of plant.

Such STH-codes have been developed mainly for PWRs and BWRs (e.g. RELAP5, CATHARE, etc..), and validated using integral test facility design specific or experimental data coming from the operation of nuclear reactors and prototypes [33].

For the application to liquid metal fast reactor, these STH-codes need to be updated with state-of-the-art algorithms, models and correlations, and their validation extended with suitable experimental database aiming at confirming their applicability for safety analysis.

Moreover, in the case of multi-scale approaches, in which STH-codes are coupled with CFD codes to catch relevant 3D phenomena in the system simulation, the validation process has to be further extended considering the code coupling. The multi-scale approach is going to be developed both for light water [34] and liquid metal cooled reactors [35].

For liquid metal systems very few data set are available for the validation process, as for example the data coming from the experiments performed on TALL-3D loop.

Apart from this small scale basic experiment, validation of such multi-scale approaches has also been performed by comparing to reactor scale data from the EBR-II [36] and Phénix natural circulation tests [37]. As these data relate to real operating reactor, the possibilities for instrumentation were limited.

One of the main goal of SESAME project was to extend the validation base of STH-codes or multi-scale approaches, providing suitable experiments for the aim (see Fig. 7).

The first level of validation data was provided by experiments performed by TALL-3D (KTH, Sweden) and NACIE-UP (ENEA, Italy) loop facilities. For scaled-up multi-scale approach, experiments on CIRCE-HERO (ENEA, Italy) have been implemented and run in the frame of the project [38].

A further added value coming from the SESAME Project is the availability of experimental data (i.e. dissymmetric tests) coming from the Phénix reactor end of life tests. This data will support the validation process of multi-scale codes to a much larger extent than the natural circulation test data which were previously used [37].

A large amount of experimental tests was performed in the TALL-3D facility [39]. Specific tests were selected for blind and open benchmark with system codes or coupled multi-scale numerical approaches. The open benchmarked results from, all available simulations compared well with the experiment. The blind benchmark demonstrated a spread of the results. In fact, all possible types of transients were obtained in the simulations. An uncertainty propagation analysis was performed which provided a lot of insight. The results suggest that the current models are not capable of capturing the experimental data (even taking into account experimental uncertainties).

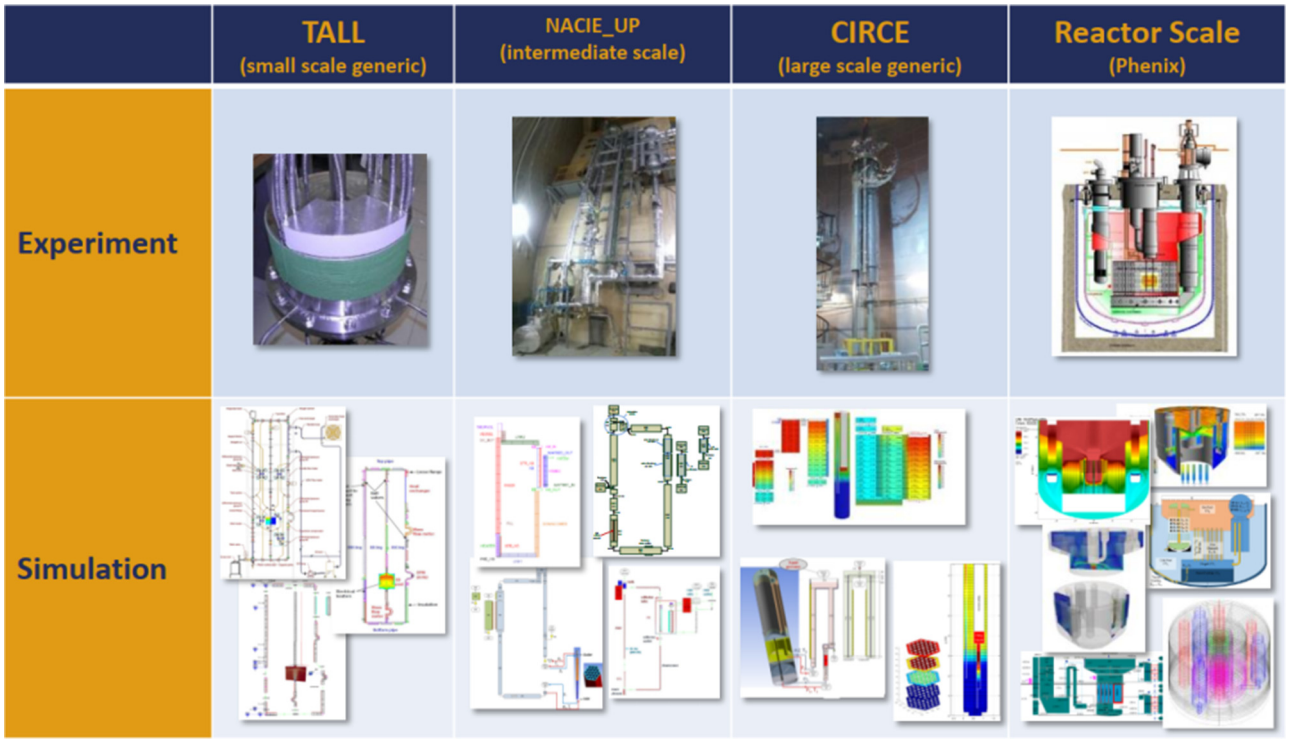


Fig. 7. Overview of system scale experiments and simulations.

However, the predictions are close to experimental data and do capture the character of the natural circulation instability.

The blind benchmark results on the NACIE_UP tests are reported in [40]. The simulations showed a sufficiently good agreement among the participants regarding the general behaviour of the loop in both steady state and transient conditions. The observed discrepancies in the LBE mass flow rate were mainly related to the specific parameters adopted to set the numerical model, as the pressure loss coefficients or the gas circulation model.

With respect to CIRCE-HERO, [41] reports that an interesting observation is that the two multiscale coupled models show similar overshoots in the outlet temperature of the heat exchanger. This may indicate that a particular 3D phenomenon is not captured by the STH part of the coupled model or that particular input from the experiments is missing. It is advised to investigate this further in the future. Despite the observed differences between multi-scale simulations and experiments, it is concluded that multi-scale coupled techniques provide a promising methodology that deserves further investigation and qualification to be used as a tool in the design of nuclear power plants. Because of the complexity of the phenomena involved and of the size of the physical domain, the modelling of the Phénix reactor proved to be a challenging task [42]. The best compromise has to be found between the accuracy and the computational cost. The results reported in [42] show two main issues: (i) correctly computing the thermal hydraulics of the first three minutes of the dissymmetric transient and (ii) finding the correct parameters to accurately compute the remaining 27 minutes. For the first 3 minutes of the transient, it is concluded that the intermediate heat exchangers should be included in the CFD model in order to correctly compute the momentum and stratification of the sodium leaving the intermediate heat exchangers. For the remaining 27 minutes, most participants underestimate the cooling rate. A deeper investigation of the heat losses from and the thermal inertia in the Phénix reactor is therefore recommended.

5 Conclusions

The activities and progress in support of liquid metal cooled reactor design and safety analyses performed within the European collaborative H2020 SESAME project are described in this paper. The major outcomes are:

– Turbulent heat transport in liquid metal:
  - Enlargement of the reference database with new experimental and high fidelity numerical data with a focus on flow separation, jets, and rod bundle flow phenomena.
  - Further development and assessment of promising models like a second order heat flux model, implicit and explicit algebraic heat flux models and the application of the Kays correlation.

– Core thermal hydraulics:
  - Creation of new experimental and high fidelity numerical data for validation of RANS models with respect to the hydraulics of the flow in wire wrapped fuel assemblies.

- New experimental data is created for the assessment of liquid metal fuel assemblies employing grid spacers including the effects of blockages. RANS modelling approaches have been validated using these data, and subsequently these validated modelling approaches have been applied to a full scale ALFRED fuel assembly.
- Assessment of the influence of the inter-wrapper flow through experiments and numerical analyses which have been validated using the experimental data.
- Creation of new experimental data and parallel model development for validation of numerical models concerning flow induced vibrations in liquid metal reactor fuel assemblies.

– Pool thermal hydraulics:
- Enlargement of the validation base for pool thermal hydraulics by creation of new experimental data using two important LBE facilities, i.e. TALL-3D and CIRCE.
- Further development and validation of CFD tools for pool modelling.
- Design (TALL-STS) and construction (SESAME-Stand) of new experimental facilities supporting development and validation of CFD models for solidification phenomena.
- CFD was applied to a full scale ALFRED pool revealing some potential design improvements.

– System thermal hydraulics:
- The validation base for liquid metal system thermal hydraulics has been enlarged with new experimental data ranging from a small generic scale, to intermediate scale and large scale experiments, and finally to real reactor scale.
- Results of system thermal hydraulic codes and multi-scale coupled simulation tools have been compared with experimental results and in general contribute to the increase in validation of the numerical tools while at the same time highlighting shortcomings on modelling as well as measurements.

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Author contribution statement

The corresponding author, as SESAME Project coordinator, provided for the paper writing and final review. Other authors, as work package leader of the project, provided a contribution about their own work package. They also revised the final draft before submission.

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