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BLIND SIMULATIONS OF NACIE-UP EXPERIMENTAL TESTS BY STH CODES

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ABSTRACT

In the frame of the SESAME project, a benchmarking activity was proposed to validate the existing system thermal-hydraulics codes for Heavy Liquid Metal reactors. More specifically, blind simulations on three well-defined experiments were carried out on the NACIE-UP facility, using CATHARE by ENEA, ATHLET by GRS, RELAP5-3D by University of Roma and RELAP5/Mod3.3 by University of Pisa. The numerical models were calibrated in terms of system thermal losses and gas enhanced circulation by means of the outcomes from specific experimental preliminary tests.

The present discussion expose, compare and analyze the numerical results of some representative parameters (primary lead-bismuth eutectic (LBE) mass flow rate, temperatures and pressure) charaterizing the system behaviour in transiet scenarios in a "pre-test" blind numerical assessment.

INTRODUCTION

The European HORIZON2020 project SESAME coordinates a series of thermal hydraulics Simulations and Experiments for the Safety Assessment of Metal cooled reactors, in order to support the development of the European liquid metal fast reactors (LMFRs) - ASTRID, MYRRHA, ALFRED, and SEALER. A specific activity has been assigned to the benchmarking of system code alone and coupled CFD-STH codes, in support of the improvement, development and validation of existing thermal hydraulic codes for Heavy Liquid Metal (HLM) systems (reference for SESAME).

In particular, the selected blind benchmark exercise, proposed by the University of Pisa in collaboration with ENEA, was based on the experimental campaign performed in the NACIE-UP facility, which is a 7.7 m high, LBE loop that allows to investigate the heat removal by natural convection from a fuel subassembly representative of a lead-cooled fast reactor (LFR) core. The experimental campaign focused on two preliminary tests and three fundamental tests. The two preliminary tests (Pre-Test-1 and Pre-Test-2) were necessary to characterize respectively, the system heat losses, and the relationship between the injected gas flow rate in the riser and the corresponding LBE mass flow in the primary loop. The three fundamental tests (Test-1, Test-2 and Test-3), taken as reference for the benckmark exercise, reproduced three different transients corresponding to, respectively, a gas lift reduction, a power reduction and a Protected Loss of Flow Accident (PLOFA) scenario. The four participants executed blind simulations on the reference tests, using the following STH codes:

- CATHARE for ENEA;
- ATHLET for GRS;
- RELAP5-3D for the University of Roma "Sapienza";
- RELAP5/Mod3.3(modified) for the University of Pisa.

The preliminary experimental tests provided a calibration of the numerical models to better execute the subsequent blind simulation. The main results (flow rate, loop temperature and pressure) are illustrated and analyzed for each fundamental test.

THE NACIE-UP FACILITY

NACIE-UP [1] is a LBE loop facility designed at ENEA Brasimone Research Centre, to qualify and characterize components, systems and procedures relevant for heavy liquid metal (HLM) nuclear technologies (Figure 1). It is possible to carry out natural circulation and mixed convection experimental tests in the field of thermal-hydraulics, fluid dynamics, chemistry control, corrosion and liquid metal heat exchange, allowing the investigation of essential correlations for the design and development of new generation nuclear facilities. NACIE-UP is a rectangular loop (7.7 m height) that basically consists of two vertical pipes (O.D. 2.5", S40), namely the downcomer and the riser, connected with two horizontal pipes (O.D. 2.5", S40). In the lower part of the riser a prototypical wire-spaced fuel pin bundle simulator (FPS) is installed, whereas a heat exchanger (HX) is placed in the upper part of the downcomer.

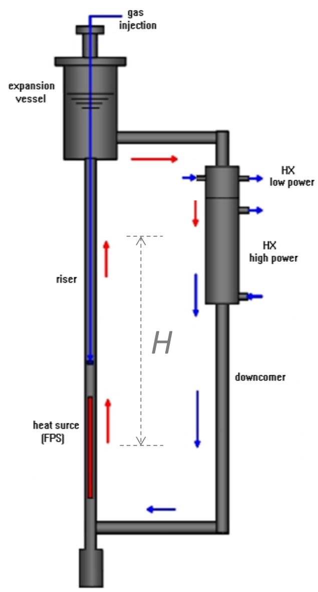

Figure 1. Schematic representation of the NACIE-UP primary loop.

The difference in height, *H*, between the centre of the FPS and the centre of the HX is about 5.5 m ensuring the driving force to sustain natural circulation inside the loop. NACIE-UP loop is entirely made of austenitic stainless steel, AISI 304, and can operate with both LBE and lead as working fluid. The experimental tests analysed here were carried out using LBE. An argon gas injection device is placed inside the riser to promote the circulation inside the loop. An expansion vessel is installed, coaxially with the riser (on the top part), enabling the thermal expansion of the LBE during operational transient and allowing the separation of the argon from the LBE.

The heat exchanger is shell and tube type and was designed to exchange heat up to 250 kW. It consists of 7 tubes arranged in a hexagonal lattice (one central and six surrounding tubes). The tubes are double-wall type to mitigate the axial thermal stresses caused by the differential thermal expansion and to avoid accidental contact of the liquid metal with water. The gap between the two walls is filled by steel powder to guarantee the thermal flux towards secondary water. The HX is composed by two separated shell sections: a cross-flow low power section (0-30 kW) and a counter-current high-power section (30-250 kW), both connected to the pressurized water secondary side. The secondary side is a 16 bar pressurized water loop with a circulation pump, a pre-heater, the HX shell side, an air-cooler and a pressurizer.

The FPS consists of 19 wire-spaced electrical pins, arranged in a triangular lattice by a suitable hexagonal wrapper. The pin has a diameter *D*=6.55 mm and the pitch to diameter ratio (*P/D)* is 1.28. The maximum power of the bundle is about 235 kW, corresponding to a maximum wall heat flux close to 1 MW/m^2. The overall layout of the FPS with its main dimensions is depicted in Figure 2. On the pin foot, a bottom grid is positioned to keep the bundle.

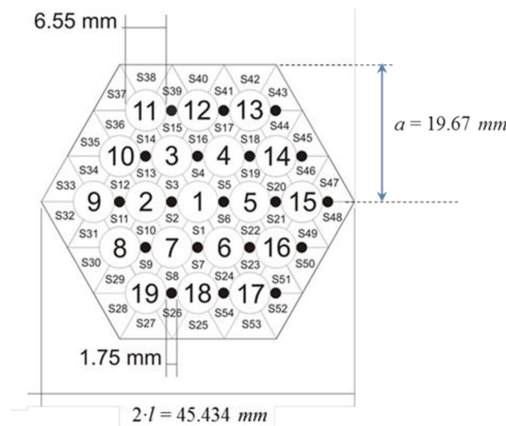

Figure 2. Cross-section of the electrical wire-spaced fuel pin bundle simulator of NACIE-UP.

The total length, which includes the non-active length and the electrical connectors, is 2000 mm while the active part is 600 mm long.

SYSTEM CODES USED BY THE PARTICIPANTS

ENEA model using CATHARE

The "best-estimate" CATHARE code is a T/H system code employed for safety analysis of water reactor and management of accidental scenarios but also for the definition of operational procedures and for nuclear power plant (NPP) licensing support. The CATHARE code treats the thermal-hydraulics of fluids mainly in one-dimensional motion flow with a two-phase model (liquid and gas). The CATHARE code has already been modified in the recent past to treat several other fluids [2]. Within a Specific Topic of Cooperation between ENEA and CEA, the lead and lead-bismuth eutectic (LBE) thermodynamic properties [3] have been implemented [4] and made available to the CATHARE users. The CATHARE code version used for the present blind simulations is the CATHARE V2.5_3 Mod 2.1.

The model nodalization of NACIE-UP facility for CATHARE system code is illustrated in Figure 3.

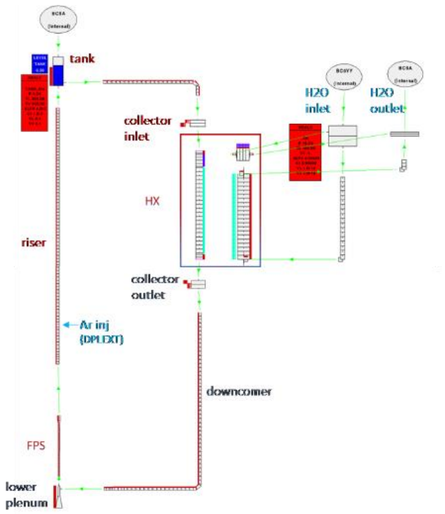

Figure 3. NACIE-UP nodalization for CATHARE code.

The complete natural circulation flow path of the primary circuit cooled by LBE is modelled mainly with one-dimensional elements (AXIAL module), except the lower plenum, the expansion tank, and the heat exchanger inlet and outlet collectors. Both the primary and secondary sides are modelled with zero-dimensional elements (VOLUME module). The secondary side, cooled by water, is limited to the heat exchanger driven by boundary conditions. Due to CATHAREv2 limits in treating non-condensable gas dispersed in HLM, the pressure head contribution due to the argon injection is simulated with an externally imposed differential pressure, DPLEXT, calibrated with the help of the preliminary tests. The thermal structures of the primary side are completely simulated: pipes, tank, mineral-resin insulation and the FPS. The detailed thermal structures of the secondary side are limited to the heat exchanger: interfaces between the primary and secondary sides, collector's flanges, tube grids, shell wall and mineral-resin insulation. The other secondary side parts are considered as adiabatic.

GRS model using ATHLET

The thermal-hydraulic system code ATHLET [5] (Analysis of THermal-hydraulics of LEaks and Transients is being developed by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, for the analysis of the whole spectrum of leaks and transients in light water reactors (PWR,BWR, VVER, RBMK) without core damage, small modular reactors (SMR) as well as in GEN-IV reactors with helium or liquid metal coolants (Pb, LBE, Na). The main code features are the advanced thermal-hydraulics, the modular code architecture, the separation between physical models and numerical methods, the pre- and post-processing tools, and the portability to the prevalent computer platforms. Interactive code control and visualization of simulation results is enabled by the GRS analysis simulator ATLAS. ATHLET has a 3D module and is coupled to the CFD programs ANSYS CFX and OpenFOAM.

The numerical model of the NACIE-UP facility is shown in Figure 4. The primary side of the loop consists of the thermo-fluid object (TFO) HEATER which is coupled with the heat conduction objects (HECU) PIN1 representing the 19 fuel rods. Above the TFO HEATER the RISER is implemented with the argon injection from the side by the object FILL. After the RISER the LBE flows in the TFO VESSEL and in the vessel downwards (TFO DC_BOT) and then sideward into the horizontal pipe LINK2. Additionally, there is a time dependent volume above the VESSEL as boundary condition for the system, e.g. the gas flow.

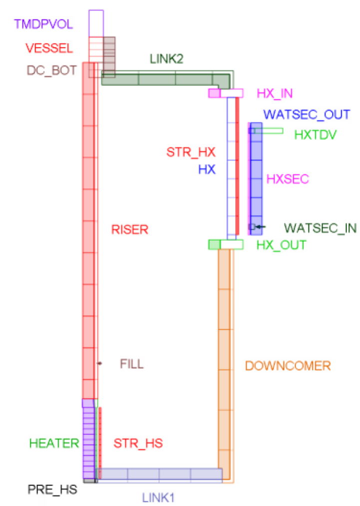

Figure 4. NACIE-UP nodalization with ATHLET code.

The heat exchanger section is flanged at the end of the bend of LINK2. First, there is the branch HX_IN that is the inlet for the 7 pipes (TFO HX) of the heat exchanger and the outlet is again modelled with the branch HX_OUT. The secondary side of the heat exchanger is modelled by the TFOs WATSEC_IN for the inlet, HXSEC that is coupled via the HECU STR_HX, and WATSEC_OUT for the outlet, which is finally coupled with the time depending volume HXTDV. All structures are insulated (shattered objects) using the given material properties of the insulation. The outer side of the insulation is coupled via a normally used heat transfer coefficient (HTC) to the environment with a fixed temperature of 25°C. Gas injection is basically modelled as an argon mass source (without momentum) at the elevation of the injection line.

University of Rome model using RELAP5-3D

The University of Rome "Sapienza" (URom) activity in the NACIE-UP Benchmark was carried out using RELAP5-3D© [6] system thermal-hydraulic code (Version 4.3.4). Its validation was accomplished through a series of experimental tests for the evaluation of the code capability to simulate a two-phase system with liquid lead-bismuth eutectic and gas, both for steady state conditions and during transients from natural circulation to gas-enhanced circulation and vice-versa. The scheme of the nodalization (Figure 5) consists in a one-dimensional model of several pipes and junctions connected to each other in such a way to build a truthful simulation of the different parts of the loop.

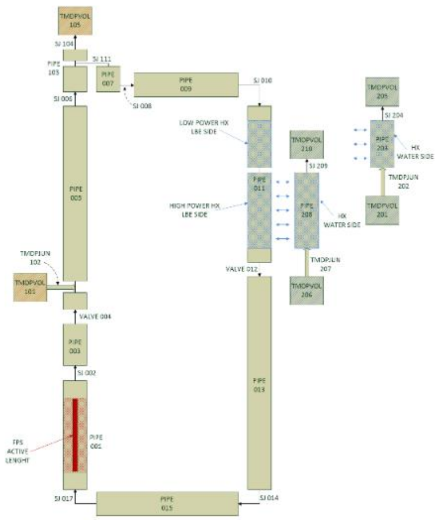

Figure 5. NACIE-UP nodalization with RELAP5-3D.

The NACIE-UP model is composed by the following parts: the FPS (PIPE 001), its outlet pipe (PIPE 003), the riser (PIPE 005), the expansion tank (PIPE 103 and PIPE 007), the HX primary side (PIPE 011), the HX low and high power secondary side (PIPE 203 and PIPE 208), the downcomer (PIPE 013) and the two horizontal legs (PIPE 009 and PIPE 015). The TMDPVOL 101 and TMDPJUN 102 assure the argon injection in the middle of the riser, while the TMDPVOL 105 on the top of the expansion tank represents the outlet of the gas. The division in volumes of the loop has been carried out to consider the correct position of the bubble tubes and the thermocouples located along the loop. The thermal coupling has been simulated through the heat structures:

- Between the active length of the FPS and the LBE in the primary side;
- Between the LBE of the primary side and the water in the secondary system;
- Between the primary system and the external environment;
- The 19 pins of the FPS and the 7 pipes of the HX have been simulated, respectively, with a single equivalent heat structure;
- The power supplied by the thermal flow meter FM-101 has been simulated with an additional heat structure coupled with few volumes of PIPE 015.

University of Pisa model using RELAP5/Mod3.3

The STH code used at the University of Pisa (UniPi) was a modified version of RELAP5/Mod.3.3 code [7]. The modified version was implemented by UniPi to include liquid metals (Na, Pb and LBE) among the code working fluids [8] and to choose specific convective heat transfer correlations for LMs (e.g. *Seban and Shimazaki* [9] or *Ushakov* [10] for bare fuel bundle with triangular lattice). The thermodynamic properties of lead, LBE and sodium, for both saturation and single-phase conditions were implemented from Sobolev's work [11], together with their transport properties (i.e., thermal conductivity, dynamic viscosity and surface tension). These latter were included directly inside the FORTRAN source file of the code. The modified version of RELAP5/Mod.3.3 was qualified in previous works at UniPi, which focused, in particular, on the development of STH-CFD coupling tools [12, 13]. The RELAP5 model for NACIE-UP, depicted in Figure 6, is mainly composed by several pipes, branches and junctions reproducing the facility primary and secondary sides. Time-dependent volumes and time-dependent junctions were employed where necessary to set the boundary conditions.

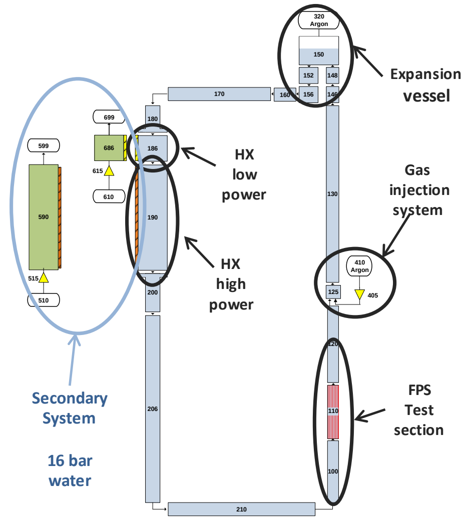

Figure 6. UniPi nodalization with RELAP5/Mod3.3.

The gas injection system is modelled through time-dependent volume 410 and time-dependent junction 405 that injects argon in branch 125, simulating the experimental injection elevation. The injected gas flows in the riser (pipe 130) up to the expansion vessel (components 146, 148, 150, 152 and 156) and separates from the LBE in branch 150. Time-dependent volume 320 allows to set the cover gas pressure boundary condition. The 7-tubes heat exchanger is modelled with two pipes (186 and 190), for the low power and high-power sections respectively. The secondary side of the heat exchanger is modelled with pipes 686 and 590, time-dependent junctions (515 and 615) and volumes (610, 699, 510 and 599). A heat structure component was linked to HX sections to model the heat transfer surfaces and thermal resistances. Other heat structures are the active region of the fuel bundle (associated to the pipe 110) and the power source of the thermal mass flow meter (associated to two volumes of pipe 210). Heat structures were also used to model the thickness of the pipe, flange and the thermal insulator walls, to consider the heat losses toward the environment.

THE NACIE-UP STH CODE BENCHMARK

Overview

The stand-alone code benchmark consists in blind simulations of a set of experiments performed on the NACIE-UP facility reproducing three transients (operative and accidental) relevant for HLM nuclear systems; the three tests are:

1. Gas flow transition (**Test-1**). It consists in a reduction of the injected argon flow from 20 to 10 Nl/min, maintaining the FPS power to a constant level of 50 kW.
2. Power transition (**Test-2**). It consists in a FPS power reduction from 100 to 50 kW (decreasing rate 1 kW/s) maintaining the injected argon flow to 18 Nl/min.
3. Protected Loss of Flow Accident, PLOFA (**Test-3**). It consists in a decrease of the FPS power from 100 to 10 kW (decreasing rate of 10 kW/s) and the complete deactivation of the injected argon flow from 20 to 0 Nl/min. This kind of transition reproduces a protected loss of flow caused by the removal of the gas lift enhancing the loop circulation and the establishment of natural circulation. In this case, the transition to a low FPS power requires the reduction of the secondary water flow from 10 to 6.6 m^3/h.

The three tests boundary conditions are shown in Figure 7.

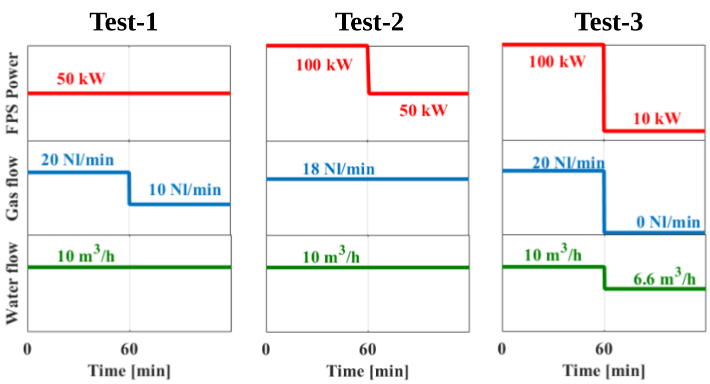

Figure 7. Boundary conditions of the benchmark tests.

Each test is characterized by two steady-state conditions: prior (S.St-1) and subsequent (S.St-2) the transition event. The transition event in the simulations set after 60 minutes from the beginning of the simulation (in S.St-1 conditions).

The primary side is filled up to the high-level sensor of the expansion tank with a cover gas (argon) pressurized at 1.4 bar. The secondary side, filled with water at 16 bar, is operated with an inlet temperature of 170°C and a total volumetric water flow rate of 6.6 or 10 m^3/h depending on the power level. Only the high-power section of the HX is operated during the tests.

A set of integral physical parameters has been selected based on their relevance for the facility thermal-hydraulic characterization. These parameters have been acquired during the experimental campaign and used in the post-test analysis. The whole set of parameters and their location in the NACIE-UP circuit are illustrated in Figure 8, while

Table 1 summarizes only the parameters of interest for the actual discussion.

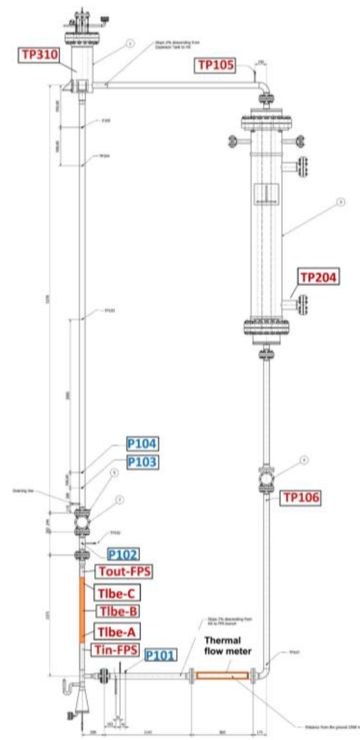

Figure 8. Instrumentation position in NACIE-UP.

Table 1: Parameters for the STH codes benchmark.

Parameter	Loop position	Variable
LBE mass flow rate	Entire Loop	LBE-MFR
LBE Temperatures	FPS inlet FPS outlet HX inlet HX outlet	Tin-FPS Tout-FPS TP105 TP106
Water Temperature	HX secondary side outlet	TP204
Loop Pressure	Downstream the FPS	P102

A basic STH code assessment with the experimental data is represented by the preliminary tests, the outcomes of which were given to the participants to calibrate the respective models in terms of thermal losses towards the environment (Pre-Test1) and in terms of primary side pressure losses in assisted circulation (Pre-Test-2). This latter provided the LBE mass flow rate obtained for a stepwise ramping of injected argon, in isothermal conditions. To assess the capability of the models/codes to correctly reproduce the gas-enhanced circulation (whenever possible) both the numerical and experimental results from Pre-Test-2, are shown in Figure 9, which plots the steady state LBE mass flow rate versus the argon flow rate. The experimental results are reported within a 95% confidence band.

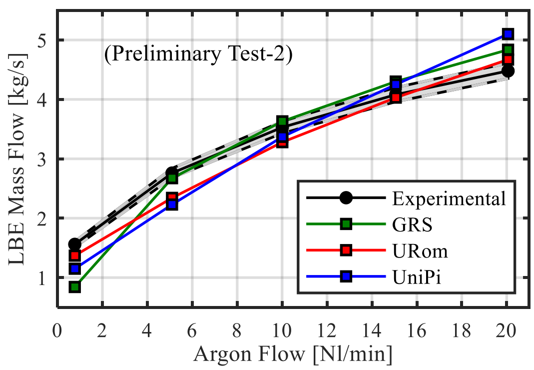

Figure 9. LBE mass flow rate vs argon flow.

The ENEA results are not reported as the CATHARE code does not reproduce the gas injection and therefore uses different modelling approach. It is clear that the experimental trend is not adequately reproduced for the whole range of gas flow (0.7-20 Nl/min). In particular, at the minimum gas flow rate of 0.7 Nl/min, all the codes underestimate the resulting LBE circulation, while for 20 Nl/min the resulting LBE circulation is overestimated. For intermediate values, a better agreement with the experimental behaviour is found (10-15 Nl/min). From these observations, it seems that difficulties arise when reproducing the enhanced circulation phenomenon for a wide range of gas flow injections. For the purpose of the present discussion, the range of interests goes from 10 to 20 Nl/min.

Test-1: Gas flow transition

The LBE mass flow rate in the circuit is reported in Figure 10. Before the argon flow reduction, the LBE mass flow rates range between 4.9 kg/s (GRS and URom) and 4.7 kg/s (ENEA and UniPi). The gas lift reduction from 20 to 10 Nl/min brings the system to a new steady state (S.St.-2) characterized with LBE flow rates of 4 kg/s for URom, 3.9 kg/s for ENEA and GRS, and 3.6 kg/s for UniPi. In the transition phase, of about 10 minutes, a comparable trend is observed for all the participants. More specifically, immediately after the gas flow transition, a sudden LBE flow reduction to a minimum value occurs, followed by an oscillating trend that gradually dumps to the new equilibrium value. This behaviour can be physically interpreted assuming the gas reduction as a prompt break for the LBE circulation, followed by the rebalance of the buoyancy effects leading to a typical dumped oscillating system behaviour.

The LBE inlet and outlet temperatures in the FPS and HX are reported in Figure 11 and Figure 12 respectively, showing a similar trend for all the participants. At the transition (at t ≈ 60 min), the FPS outlet temperature (Figure 11.b) exhibits a sudden increase which propagates with a certain delay, a smother shape and a reduced value (due to the thermal losses), to the HX inlet (Figure 12.a). Here, the outlet temperature shows a decreasing trend from the previous steady state before reaching the new steady state (transient time ~ 15 min). The same trend is observed at the FPS inlet (Figure 11.a) except for a small peak attributed to the effect of the thermal flow meter (TFM) after the flow reduction.

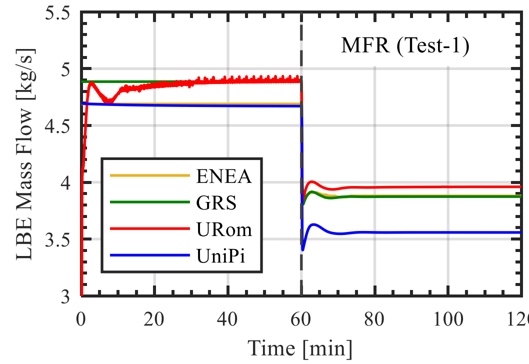

Figure 10. MFR (Test-1).

In steady state conditions, the LBE temperature differences, ΔT, through the FPS and the HX, are determined by the mass flow rate and the FPS power, while the average temperature (T_{avg}), is related to the secondary inlet water parameters (mass flow and temperature fixed to 170°C) and to the HX overall heat transfer coefficient. This latter (given the HX geometry) depends on the thermal parameters (HTC, k_{ss}, k_{powder}) adopted by each participant to model the HX component, and leads to the discrepancies on the loop average temperature. In particular, ENEA simulations exhibit the highest T_{avg}. The mass flow reduction induces a rapid increase of both the FPS T^{out} (prompt) and the HX T^{in} (delayed), while a smoother temperature decrease is observed for both FPS T^{in} and HX T^{out}. The temperatures transient reproduced by each participant follows the same mass flow rate oscillating trend before achieving the new steady state.

The inlet temperature of the FPS, T^{in}, is generally higher than the outlet temperature of the HX, T^{out}, due to the effect (when simulated) of the thermal flow meter, TFM, positioned between the two components in the lower horizontal section. In fact, the TFM operation foresees the heating of the LBE flow passing through it, providing to the flowing LBE an additional external power (1-2 kW). On the contrary, the thermal losses associated to the riser and to the upper horizontal piping, cause the HX inlet temperature, T^{in}, to be a few degrees lower than the FPS outlet temperature, T^{out}. Figure 13.a reports the secondary water outlet temperature in the HX, showing essentially a good agreement among the participant results. The slight discrepancies may be related to the HX removed power and the assumption on the water density.

For what concerns the pressure inside the loop, Figure 13.b reports the values for P102 (downstream the FPS). The pressure values obtained by the participants are quite different from each other. The discrepancies can be ascribed to various factors as: the differences in the choice of the vertical nodalization, the level inside the expansion tank and the loop temperatures. Despite these discrepancies, the pressure response is quite similar among the numerical models, exhibiting a sudden jump after the gas transition that can be attributed to the LBE density increase in the riser immediately after the reduction of the gas injection.

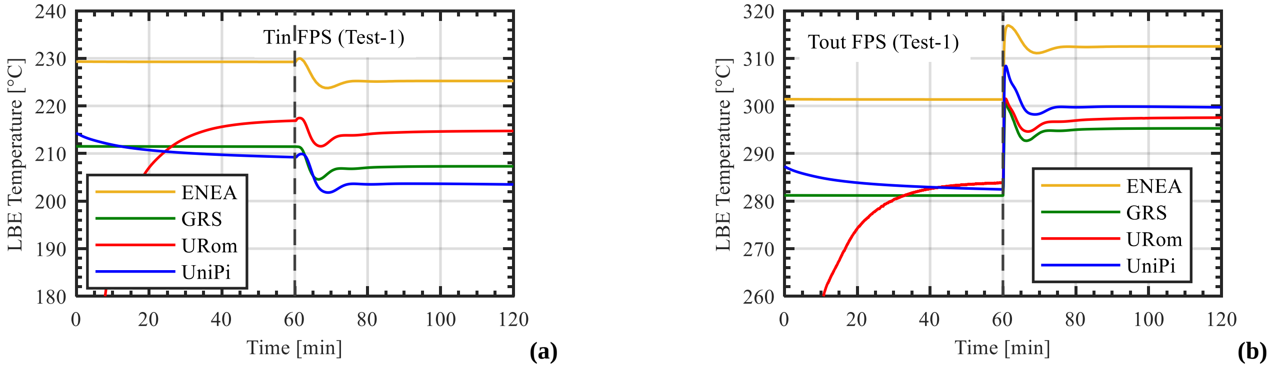

Figure 11. LBE temperature at the FPS Inlet (a) and outlet (b); (Test-1).

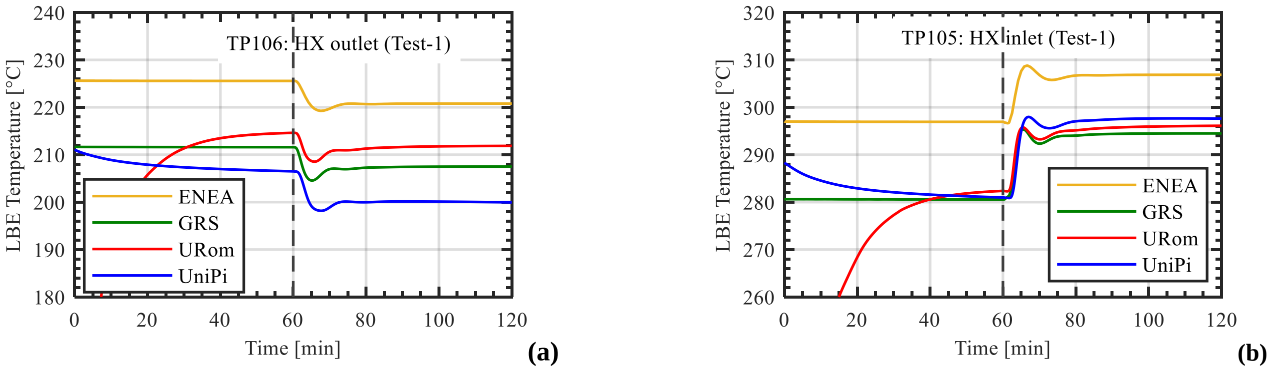

Figure 12. LBE temperature at the HX outlet (a) and inlet (b); (Test-1).

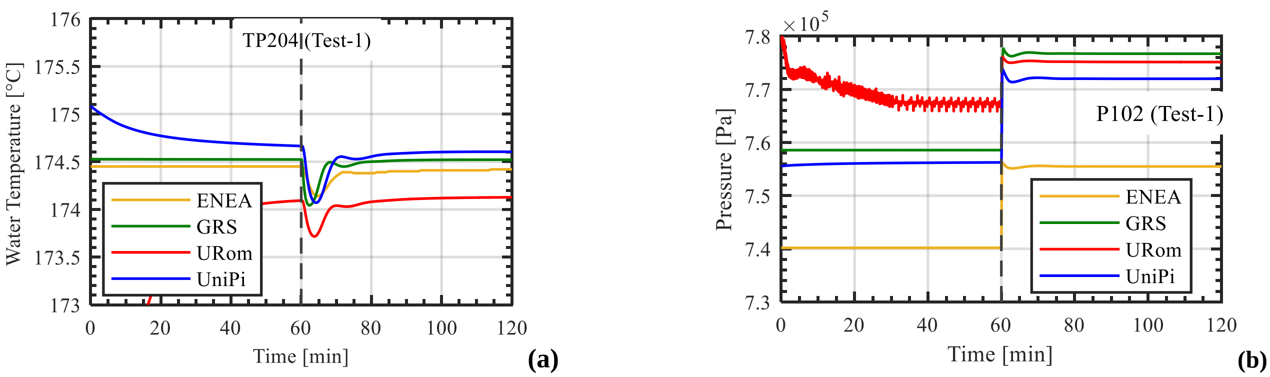

Figure 13. Water temperature at the HX outlet (a) and pressure downstream the FPS (b); (Test-1).

TEST-2: Power transition

In Test-2 the gas flow is kept unchanged and the mass flow rate reduction after the transition (see Figure 14) is exclusively consequence of the FPS power reduction. For each participant, the mass flow rate before the transition is found in the range of 4.7 and 5.3 kg/s; after the transition, the flow reduction varies from 0.2 and 0.8 kg. The mass transition trend appears almost similar for all participants. The LBE inlet and outlet temperatures in the FPS and HX are depicted respectively in Figure 15 and Figure 16, showing the same decreasing trend. In fact, the power transition from 100 to 50 kW causes the loop mean temperature to decrease.

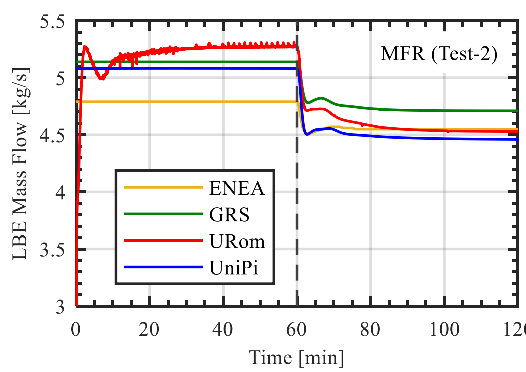

Figure 14. MFR (Test-2).

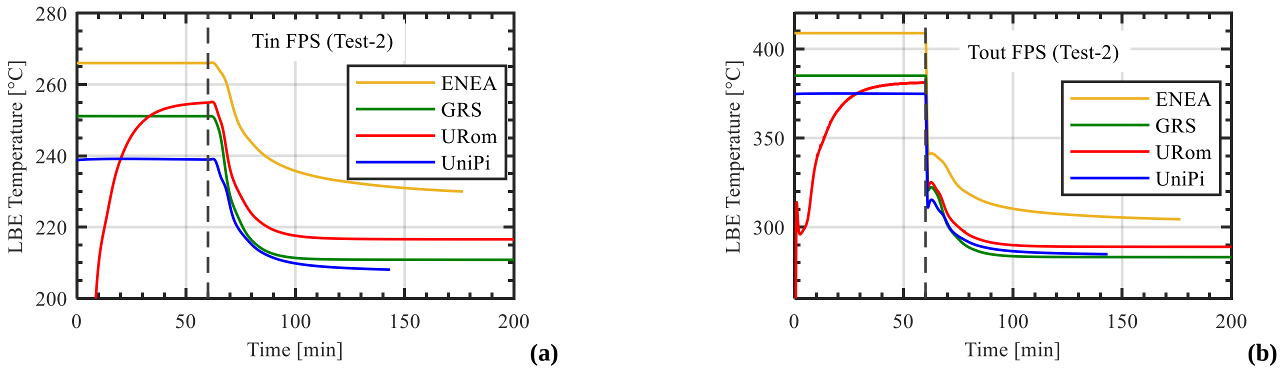

Figure 15. LBE temperature at the FPS Inlet (a) and outlet (b); (Test-2).

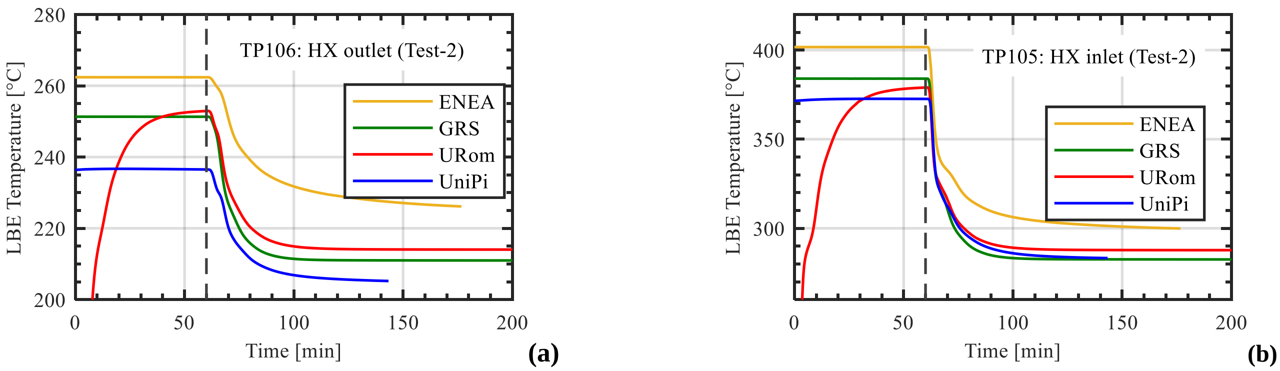

Figure 16. LBE temperature at the HX outlet (a) and inlet (b); (Test-2).

Although the mean temperatures T^{avg} are different among the participants (due to the HX modelling), the temperatures decreasing trends are similar and the transition time to reach new stationary temperatures varies slightly. The observation made for Test-1 are similar for Test-2. In particular, the FPS outlet temperature (Figure 15.b) exhibits a sudden decrease immediately after the power transient. The temperature decrease propagates, with a smoother trend and reduced value (due to thermal losses), along the circuit flow path towards the HX inlet (Figure 16.a).

Test-3: Protected Loss of Flow Accident, PLOFA

The LBE flow rate, depicted in Figure 17, goes from a gas lift circulation regime (range: 4.9-5.3 kg/s) to an exclusively natural circulation regime (range: 1.2-1.7 kg/s). The mass transient trends are almost similar for all the participants. Immediately after the gas circulation is deactivated, the LBE flow undergoes a sudden reduction, followed by an oscillatory trend, of about 15 min, just like for Test-1. The LBE inlet and outlet temperatures in the FPS and HX are reported respectively in Figure 18 and Figure 19. As for the previous tests, the temperature trends during the transition are similar among all participants. At the transition ($t \approx 60$ min), the FPS outlet temperature (Figure 18.b) exhibits a sudden decrease followed by a smooth increase and again a slow decrease (oscillating trend) to the stationary minimum value, that is reached in more than 180 min. In general, the loop temperatures transition slope varies accordingly to the thermal inertia assumed to model the system (LBE total mass, pipe thickness and heat losses).

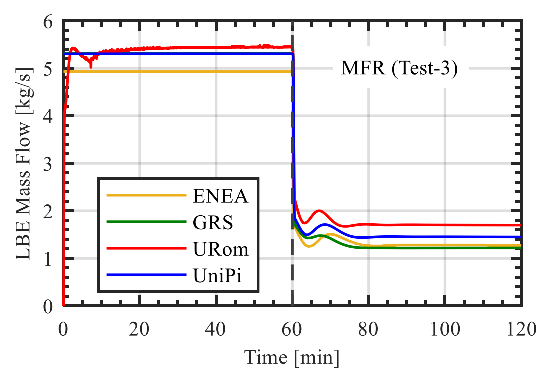

Figure 17. MFR (Test-3).

As for the previous tests, the FPS outlet temperature propagates trough the loop with a smoother shape and lower value (due to the thermal losses), as shown for the HX inlet temperatures (Figure 19.b). The HX outlet temperature, shown in Figure 19.a, propagates to the FPS inlet temperature (Figure 18.a) with a few degrees Celsius increase, caused by the thermal flow meter (when simulated). The small temperature peak observed immediately after the transition highlights the presence of the TFM.

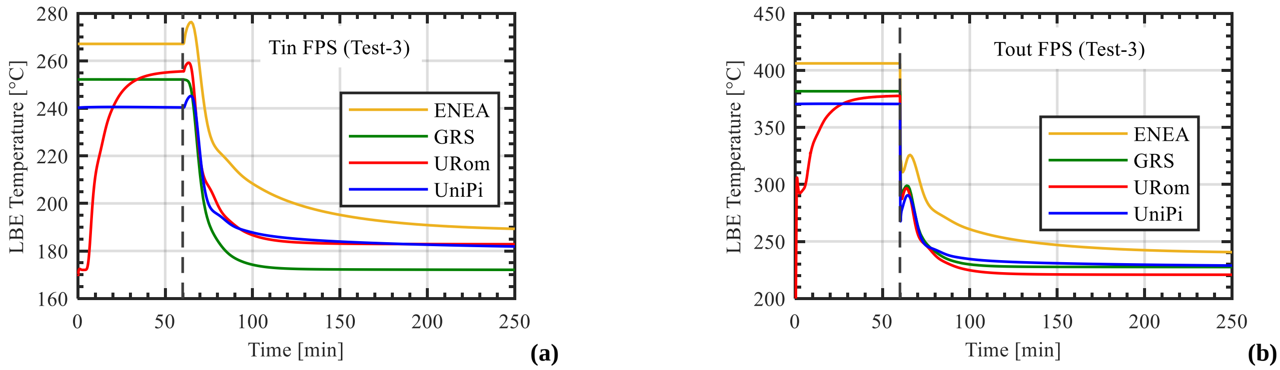

Figure 18. LBE temperature at the FPS Inlet (a) and outlet (b); (Test-3).

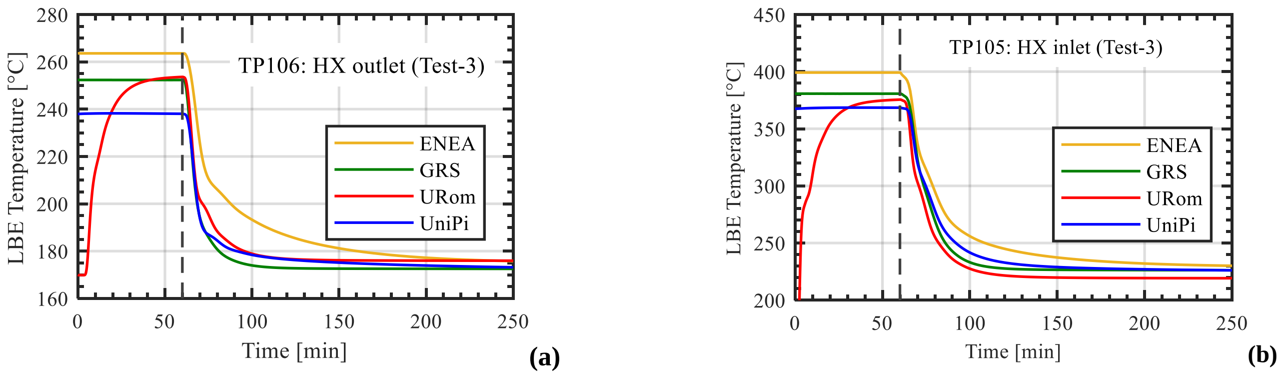

Figure 19. LBE temperature at the HX outlet (a) and inlet (b); (Test-3).

CONCLUSIONS

The SESAME benchmark on thermal-hydraulic STH codes was illustrated and the main outcomes were discussed. More specifically, the benchmark activity dealt with the comparative simulation of the NACIE-UP, LBE cooled, facility for three reference tests, specially designed for the achievement of this task. The reference tests were: a gas lift reduction (Test-1), a FPS power level reduction (Test-2) and a PLOFA-like event (Test-3). On the basis of the benchmark requirements, the participants involved in this analysis used four different system codes to model the experiments, namely: CHATARE for ENEA, ATHLET for GRS, RELAP5-3D for the University of Rome and RELAP5/Mod3.3 for the University of Pisa.

Two preliminary tests, Pre-Test-1 and Pre-Test-2, were conducted to provide experimental results to be used as references for the model calibration in terms of global heat losses and LBE enhanced circulation. This latter was experimentally carried out through a step-by-step increase/decrease of the injected gas flow (from 0.7 to 20 Nl/min), assessing the resulting LBE circulation that established in the circuit after a stable condition was reached. The simulation results highlighted that the modelling of the gas injection was not sufficiently accurate in reproducing the gas lift phenomenology for the entire range of injected flows. Nevertheless, in the range of interest for the tests, the obtained results (although different for each model) were acceptable for the purpose. Yet, specific efforts need to be made to improve the gas lift simulation methodology, in a wider range of parameters (flow, temperature, pressure, etc.).

Concerning the simulation of the fundamental tests, a sufficiently good agreement was found among the participants regarding the general behaviour of the loop in both steady states 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. The maximum discrepancies of the simulated mass flow rates were in the order of 10% for the enhanced circulation (Test-1 and Test-2) and 30% for natural circulation (Test-3). Accordingly, similar discrepancies were found for the FPS and HX temperature difference. The loop average temperature exhibited major discrepancies that were presumably related to the assumption made for the HX thermal model that mostly affected the heat transfer towards this component. Primarily the thermal conductivity of the stainless-steel powder filling the double tubes gap. In fact, lower values of the overall heat transfer coefficients led to higher values of the average temperature (ENEA exhibited the highest value). Differences were also observed in the loop pressure, presumably because of the different established loop temperatures (affecting the LBE density), the choice of the LBE level in the expansion vessel or the vertical elevation of the node where the pressure was measured. Minor differences were found in the water outlet temperature (HX secondary side) probably due to the choice of the water density value used to compute the water mass flow rate from the volumetric flow rate.

Although these differences, the transient behaviour was adequately reproduced for each of the simulated test. In particular, the mass flow prompt decrease and the following dumped oscillating trend were predicted by all the participants, as well as the transition temperatures, which showed similar trends in all the reference measurement positions (as the FPS outlet temperature prompt increase or decrease).

In conclusion, from the analysis of the numerical results, it emerged that the adopted STH codes represent a promising numerical tool for predicting a variety of conditions related to both operational and accidental transients in a facility like NACIE-UP. As future development of the activity, the participants will perform a further refinement of the numerical models after the release of the experimental data foreseen for the post-test simulation phase.

NOMENCLATURE

ATHLET	Analysis of THermal-hydraulics of LEaks and Transients
CATHARE	Code for Analysis of Thermalhydraulics during an Accident of Reactor and safety Evaluation
CEA	Commissariat à l'Énergie Atomique
CFD	Computational Fluid Dynamics
ENEA	Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile
FORTRAN	Formula Translation
FPS	Fuel Pin Simulator
GRS	Gesellschaft Fur Anlagen Und Reaktorsicherheit
HLM	Heavy Liquid Metal
HTC	Heat Transfer Coefficient
HX	Heat eXchanger
LBE	Lead-Bismuth Eutectic
LFR	Lead-cooled Reactor
LMFR	Liquid Metal Fast Reactor
LOCA	Loss of flow accident
LOFA	Loss Of Flow Accident
NACIE-UP	NAtural CIrculation Experiment- UPgraded
NPP	Nuclear Power Plant
PLOFA	Protected Loss Of Flow Accident
RBMK	Reactor Bolshoi Moschnosti Kanalynyi
RELAP	Reactor Loss Of Coolant Analysis Program
S.St.	Steady State
STH	System Thermal-Hydraulic
TDPJUN	Time dependent junction
TDPVOL	Time dependent volume
TFM	Thermal flow meter
TMDPJUN	Time dependent junction
TMDPVOL	Time dependent volume
UniPi	University of Pisa
URom	University of Roma "Sapienza"

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