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Pool temperature stratification analysis in CIRCE-ICE facility with RELAP5-3D© model and comparison with experimental tests

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Abstract. In the frame of heavy liquid metal (HLM) technology development, CIRCE pool facility at ENEA/Brasimone Research Center was updated by installing ICE (Integral Circulation Experiments) test section which simulates the thermal behavior of a primary system in a HLM cooled pool reactor. The experimental campaign led to the characterization of mixed convection and thermal stratification in a HLM pool in safety relevant conditions and to the distribution of experimental data for the validation of CFD and system codes. For this purpose, several thermocouples were installed into the pool using 4 vertical supports in different circumferential position for a total of 119 thermocouples [1][2].The aim of this work is to investigate the capability of the system code RELAP5-3D© to simulate mixed convection and thermal stratification phenomena in a HLM pool in steady state conditions by comparing code results with experimental data. The pool has been simulated by a 3D component divided into 1728 volumes, 119 of which are centered in the exact position of the thermocouples. Three dimensional model of the pool is completed with a mono-dimensional nodalization of the primary main flow path. The results obtained by code simulations are compared with a steady state condition carried out in the experimental campaign. Results of axial, radial and azimuthal temperature profile into the pool are in agreement with the available experimental data Furthermore the code is able to well simulate operating conditions into the main flow path of the test section.

1. Introduction

The Fukushima Daiichi nuclear power plant (NPP) accident, happened on March 11, 2011, highlighted the need of NPP capability to assure residual heat removal for long periods and to limit significant off-site releases after the occurrence of a severe accident.

The lesson was acknowledged by Generation IV International Forum (GIF) and it established the requirement of highest level of safety for innovative nuclear systems [3].

Lead-cooled fast reactor (LFR) belongs to the six concepts selected by GIF as Generation IV systems and includes lead and lead-bismuth eutectic alloy (LBE) technologies; both coolants are chemically inert and they offer other attractive characteristics in terms of interaction with structural materials and thermodynamic features. LFR systems also well respond to lesson of Fukushima accident allowing natural circulation both in nominal and accident conditions. This feature offers considerable grace time in order to cope with unprotected loss of flow transient and it permits to introduce fully passive decay heat removal system (DHR), assuring very high safety features over long periods without need for operator actions, combined with active systems [3].

Considerable research and development (R&D) activities were carried out in Europe. In this frame, the CIRCE pool facility (CIRColazione Eutettico), at ENEA Brasimone research center, was refurbished in order to host the test section ICE (Integral Circulation Experiment) which aims to simulate the thermal-hydraulic behavior of the primary system in a HLM cooled pool reactor. The test section is equipped with a fuel pin simulator (FPS), which electrically simulates the core of the facility, the heat exchanger (HX) and the DHR system, immersed in the upper part of the pool. The LBE circulation into the main flow path is enhanced by the injection of argon at the inlet section of the riser [5].

The experimental campaign performed on CIRCE-ICE facility aims to investigate mixing and thermal stratification phenomena in a pool type reactor, which should induce thermo-mechanical stress on the structures [2]. Moreover, the validation of TH (Thermal Hydraulic) codes against experimental data is a fundamental step in order to justify their use in the design phase for improving safety aspects.

In this work the experimental campaign was reproduced using the system code RELAP5-3D© in order to investigate the capability to simulate thermal phenomena which occur into the pool of innovative HLM reactor. The RELAP5-3D© model has been set up by coupling mono-dimensional model of the main flow path, HX and DHR secondary side included, with the 3D model of the pool.

2. Experimental campaign

2.1. CIRCE-ICE test facility

CIRCE is a multipurpose pool facility designed to host different test sections welded to and hung from bolted vessel heads for the investigation of thermal-hydraulic aspects related to the HLM pool system.

The facility consists of a main vessel, earmarked for containing test section and filled with about 70 tons of molten LBE, two auxiliary tanks, dedicated to store LBE during maintenance phases and to transfer liquid metal during loading and drainage phases, and data acquisition system [6].

The ICE test section, placed inside the main vessel, aims to simulate the primary system of HLM pool-type reactor. Main components and their positioning are showed in Figure 1 while the main flow path is highlighted in Figure 2. The feeding conduit is the inlet pipe of the test section which allows connection between the lower plenum and the fuel pin simulator. A Venturi-nozzle flow meter is installed into the feeding conduit in order to measure the primary flow rate through the "fuel" bundle. Molten LBE flows upward and it increases temperature passing through the FPS, which consists of an electrical pin bundle with a nominal thermal power of 800 kW and an active length of 1000 mm. It is composed of 37 electrically heated pins arranged in a wrapped hexagonal lattice and characterized by a pitch to diameter ratio equal to 1.8 (Figure 3). Each pin has an outer diameter of 8.2 mm, a thermal power of 25 kW and a heat flux at the pin wall of 1 MW/m^2. The hot fluid, exiting the heat source (HS), is introduced into the fitting volume and then it flows upward into the riser which is a double wall pipe connecting the fitting volume with the separator. At the inlet section of the riser, a nozzle is installed allowing the injection of argon. The mixture flows upward and it collects in the separator where the separation of LBE and Ar occurs (LBE enters the HX while Ar flows upward into the gas plenum through the free surface). The heat exchanger is made of 91 bayonet tubes with an active length of 3462 mm; Figure 4 shows a sketch of the bayonet element which consists of three concentric tubes. The feed-water flows downward into the inner tube and then upward into the annular region between inner and middle tube, where the change of phase take place; outside the tubes, the LBE flows downward decreasing the temperature. The volume between middle and outer tube is filled by pressurized helium to detect any leakage. Exiting the HX, primary coolant flows through the downcomer reaching the lower plenum [6].

The positioning of the DHR system is shown in Figure 1. It consists of only one bayonet tube and the decay power is removed by forced circulation of air. The bayonet is inside a double wall shell with a thin air insulation gap to thermally decouple the DHR from the external LBE pool. Hot LBE enters the DHR by the upper inlet section, it flows downward decreasing the temperature and it exits the component in the downcomer [1].

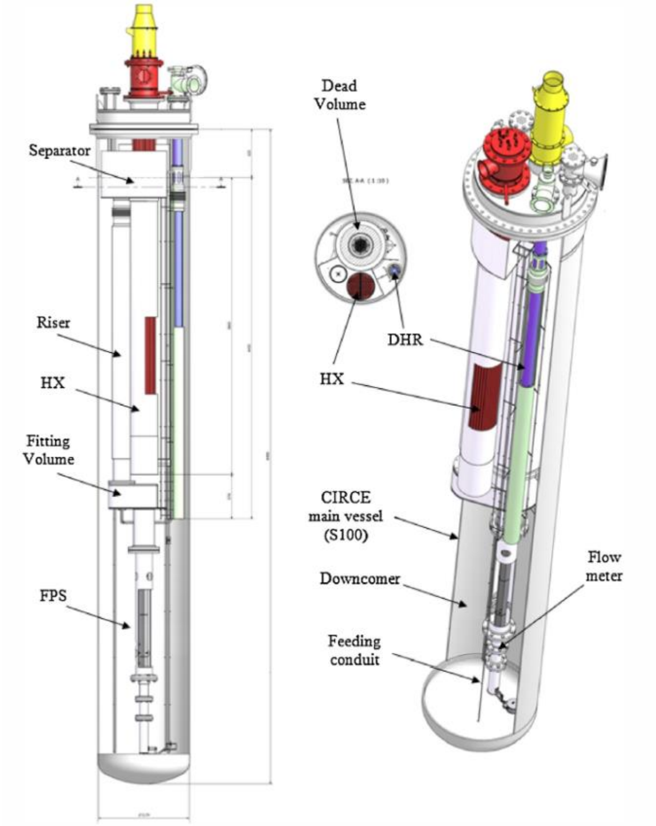

Figure 1. ICE test section[1]

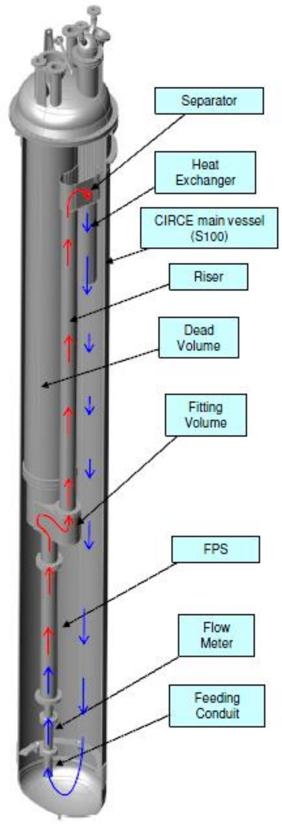

Figure 2. ICE test section: primary system main flow path

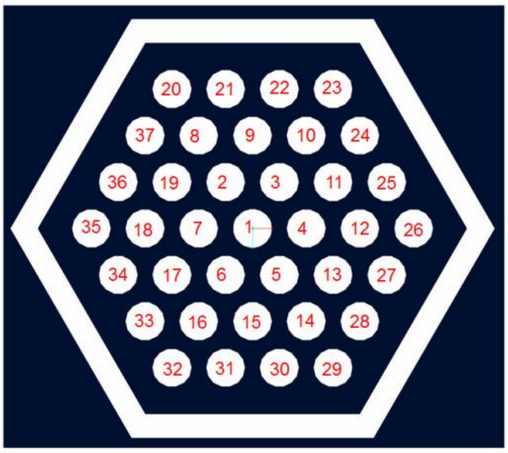

Figure 3. FPS cross section

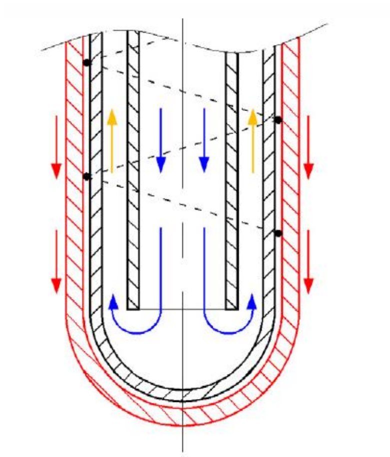

Figure 4. HX bayonet tube[6]

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2.2. *Test matrix*

In this work, the steady state condition reached during the full power operation is analysed. The FPS supplies a power of about 720 kW and 0.65 kg/s of feed-water flows into the main HX; during the test, the DHR system is not activated.

The test considered is TEST I [1]; the main parameters are showed in Table 1.

Table 1. Initial and boundary conditions of the test

	Duration (h)	Electrical power supplied(kW)	Initial LBE temperature (K)	LBE mass flow rate (kg/s)	Feed-water mass flow rate (kg/s)
TEST I	7	720	600	55	0.65

3. RELAP5-3D© modelling

Post-test simulations are carried out using RELAP5-3D© v. 4.3.4 (R5-3D). RELAP5 code was developed to allow transient simulation of light water reactor during postulated accidents. R5-3D is the last version of the series of RELAP5 code and it contains several improvement; the two most enhancements from the previous versions are the multi-dimensional thermal-hydraulic capability and the addition of new working fluids, including heavy liquid metals [7].

The nodalization scheme of the CIRCE-ICE facility is divided into two macro-regions. The first one is depicted in Figure 5 and represents the mono-dimensional model of the ICE test section.

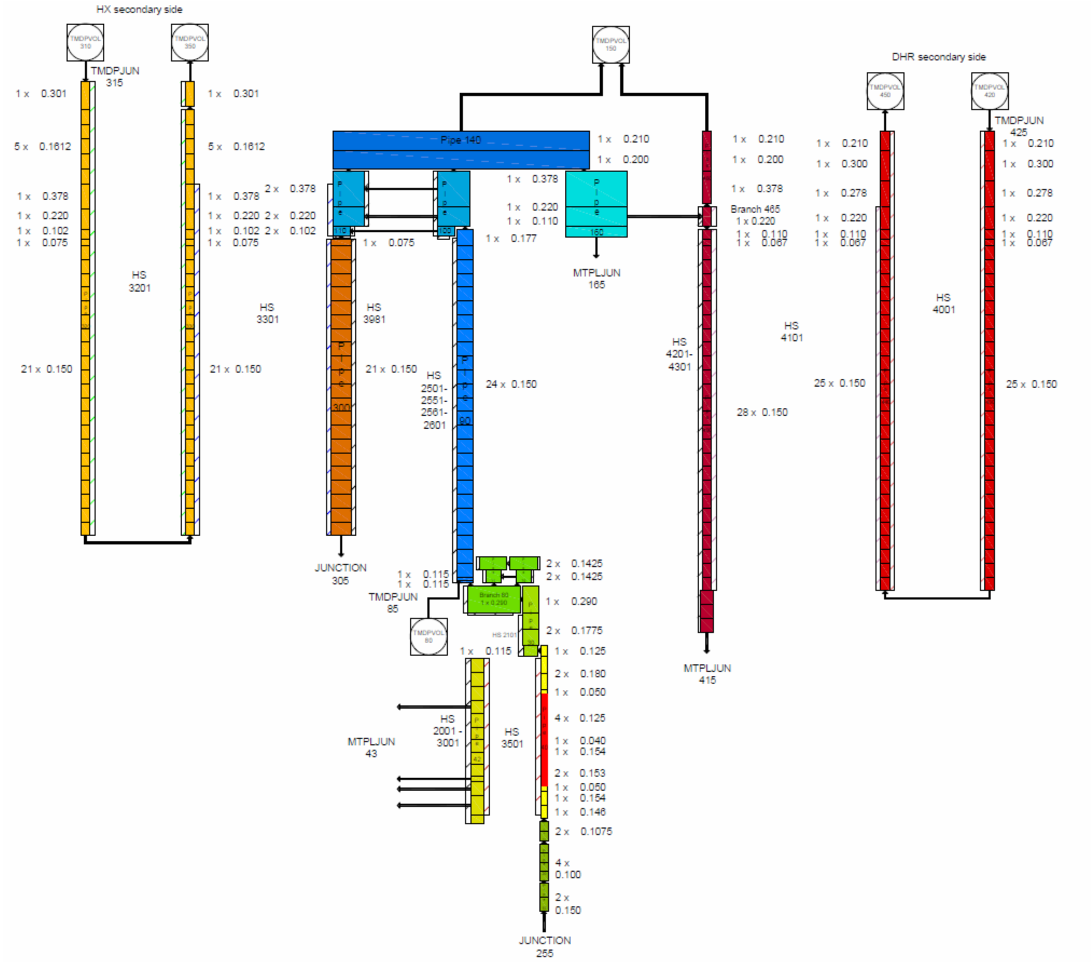


Figure 5. Region #1: mono-dimensional scheme of the ICE test section, DHR and HX

The 1-D scheme reproduces all components described in previous section. The HS is simulated by a single equivalent pipe and one heat structure, which reproduces the 37 electrical pins. In R5-3D, for the evaluation of the heat transfer coefficient (HTC) on heavy liquid metals, Todreas & Kazimi correlation [8] is implemented. Previous simulations of HLM system showed that this correlation underestimates the Nusselt number for pitch-to-diameter ratio greater than 1.3 [9]. Additionally, R5-3D does not permit a pitch-to-diameter ratio of 1.8 and the *p/d* of the pin bundle is set to the maximum allowed value of 1.6. In order to improve the HTC according to Ushakov correlation [10] (more accurate in this case) and to correct the heat exchange to experimental *p/d* value, an artificial fouling factor of 0.86 is applied to the heat transfer coefficient.

Upstream the FPS, the pressure drop of the Venturi nozzle is simulated by a concentrated pressure loss coefficient *K*, dependent on the flow conditions [11], according to equation (0.1).

$$K_{Venturi} = 10.5\,\mathrm{Re}^{-0.014} \tag{0.1}$$

The argon injection at the inlet section of the riser is simulated by boundary conditions: the time dependent volume sets gas inlet conditions and the time dependent junction adjusts the mass flow rate injection. An additional time dependent volume sets the pressure of the gas plenum of the facility.

The HX primary side is simulated by a single equivalent pipe and one heat structure, which thermally couples LBE and water side. A calibrated fouling factor of 1.02 is applied on the LBE side to increase the HTC, according to Ushakov correlation. The bayonet tubes are modelled by only two pipes, in order to simulate the descending and ascending side of water/steam tubes, and one heat structure, to model heat dispersion between the two pipes.

The pressure losses due to grids installed into FPS and heat exchanger are calculated by the Rheme correlation [12]:

$$\Delta p_{grid} = C_v \cdot \varepsilon^2 \cdot 0.5 \cdot \rho \cdot v^2 \tag{0.2}$$

where ρ and v are respectively the density and the velocity of the fluid while ε represents the blockage factor of the grids, calculated as:

$$\varepsilon = \frac{A_{grid}}{A_{flow}} \tag{0.3}$$

The C_v parameter is a modified drag coefficient and it is calculated as [12]:

$$C_v = MIN\left[3.5 + \frac{73.14}{\mathrm{Re}^{0.264}} + \frac{2.79 \cdot 10^{10}}{\mathrm{Re}^{2.79}}, \frac{2.6}{\varepsilon^2}\right] \tag{0.4}$$

The bayonet tube of the DHR system is also simulated and it is composed of one pipe for the LBE channel and two pipes to model the descending and ascending air side.

The second region, depicted in Figure 6, represents the 3D model of the main vessel, composed of 51 axial levels, 4 radial meshes and 8 azimuthal intervals. The internals depicted in Figure 6 are only representative of the positioning into the multi-dimensional component.

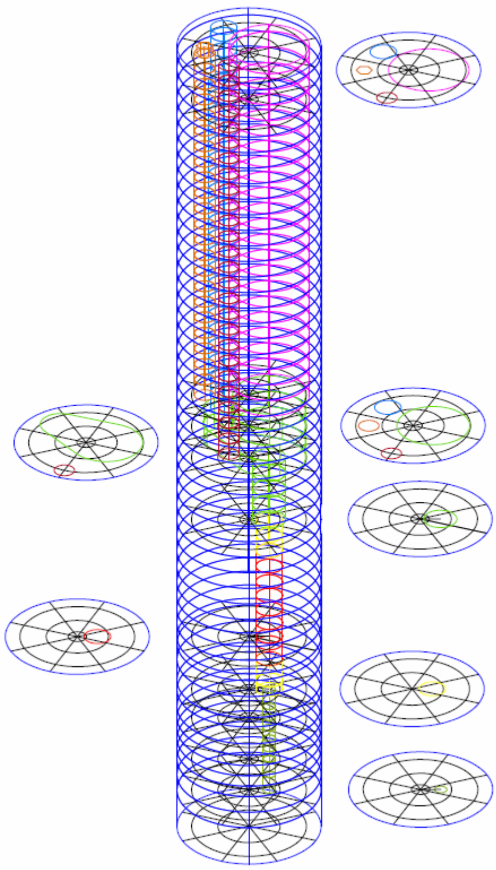


Figure 6. Region #2: multi-dimensional scheme of the CIRCE pool

Mono-dimensional and multi-dimensional components are coupled by junctions, showed in Figure 5. Several heat structures model the heat losses between the LBE cold pool and the hot internal components, which influence the LBE temperature at the inlet section of HX. Additionally, main vessel heat losses are simulated by calibrated heat transfer coefficients.

CIRCE-ICE model is completely composed of 1929 control volumes, 4856 junctions and 15353 heat transfer nodes.

4. Results analysis

The simulation analysis are conducted using default thermophysical properties correlations of R5-3D and repeated using the most recent correlations for LBE [13], implemented in R5-3D as described in [14].

Table 1 summarize the boundary conditions of the experimental tests. TEST I simulations are carried out reducing by 5% the electrical power supplied to the FPS, to take into account the power dissipated by joule effect in the cables and connectors, which does not contribute to the thermal power supplied to the LBE by the HS.

The LBE mass flow rate, measured by the Venturi-nozzle, is represented in Figure 7. The strong oscillations, during first phase of the experimental test, are due to the volumetric blowers used to inject argon into the riser and, after 13000 seconds, they are dumped by installing a check valve into the gas injection system [1]. The experimental data are compared to the simulated values, calculated with default correlations of R5-3D and Nuclear Energy Agency (NEA) recommended correlations. Unless the fluctuations, Figure 7 highlights that both calculated values well reproduce the experimental data, reaching a value of about 55 kg/s. According to [14], the simulation with default correlations underestimates the LBE mass flow of about 1%, because the smaller value of the natural driving force, depending on temperature drop across the core and the heat exchanger. The experimental trend of LBE temperature at the inlet and outlet sections of the HS, both represented by the average value of three thermocouples, is compared in Figure 9 with the calculated values. Obtained numerical results well reproduce the experimental trend. In particular the simulation with NEA correlations highlights a higher temperature drop of about 3% (mainly due to the different specific heat capacity) and, as a consequence, a slight overestimation of the experimental data.

Figure 10 depicts the comparison of the LBE temperature at the heat exchanger inlet and outlet sections, obtained averaging respectively the values of three and six thermocouples. The temperature at inlet section is lower than the value at the outlet of the FPS, due to the heat losses through the hot leg (towards the pool), which are well predicted by the simulations. The difference between the experimental and calculated temperature at the outlet of the HX depends on the relative positioning between the thermocouples and the volume control, arranged 45 mm upstream. The use of the NEA correlations results an increment of about 4% in the temperature drop, and a better agreement with the experimental data.

Figure 8 shows the comparison of the thermal power removed by the he13at exchanger. The calculated values are essentially the same and they both slightly overestimate the experimental data, probably due to the fouling which is not considered during the simulations.

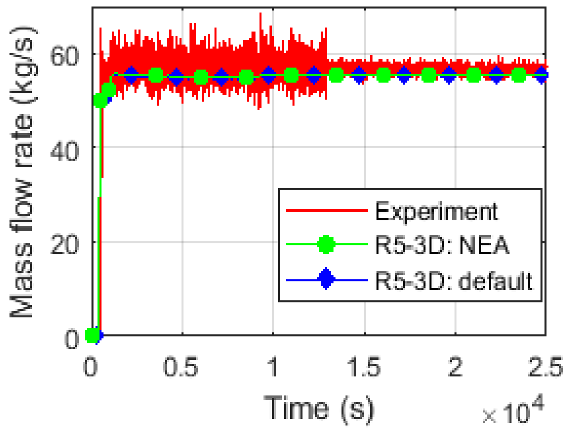


Figure 7. TEST I: LBE mass flow rate

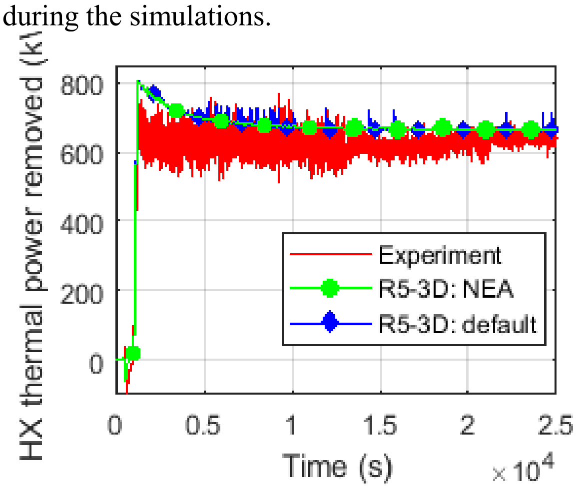


Figure 8. TEST I: HX removed power

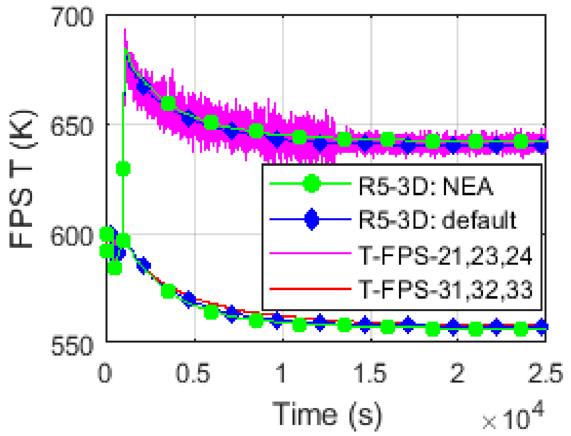


Figure 9. TEST I: temperature at FPS inlet/outlet

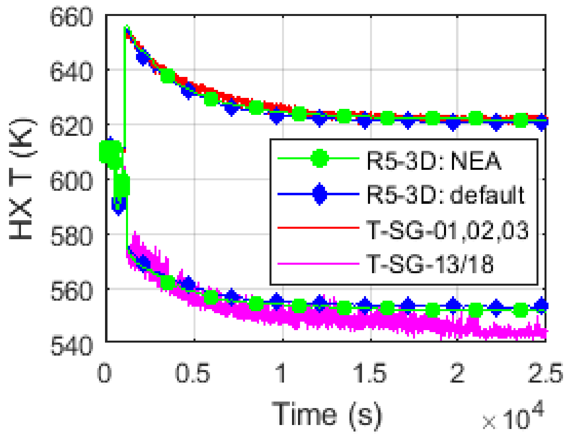
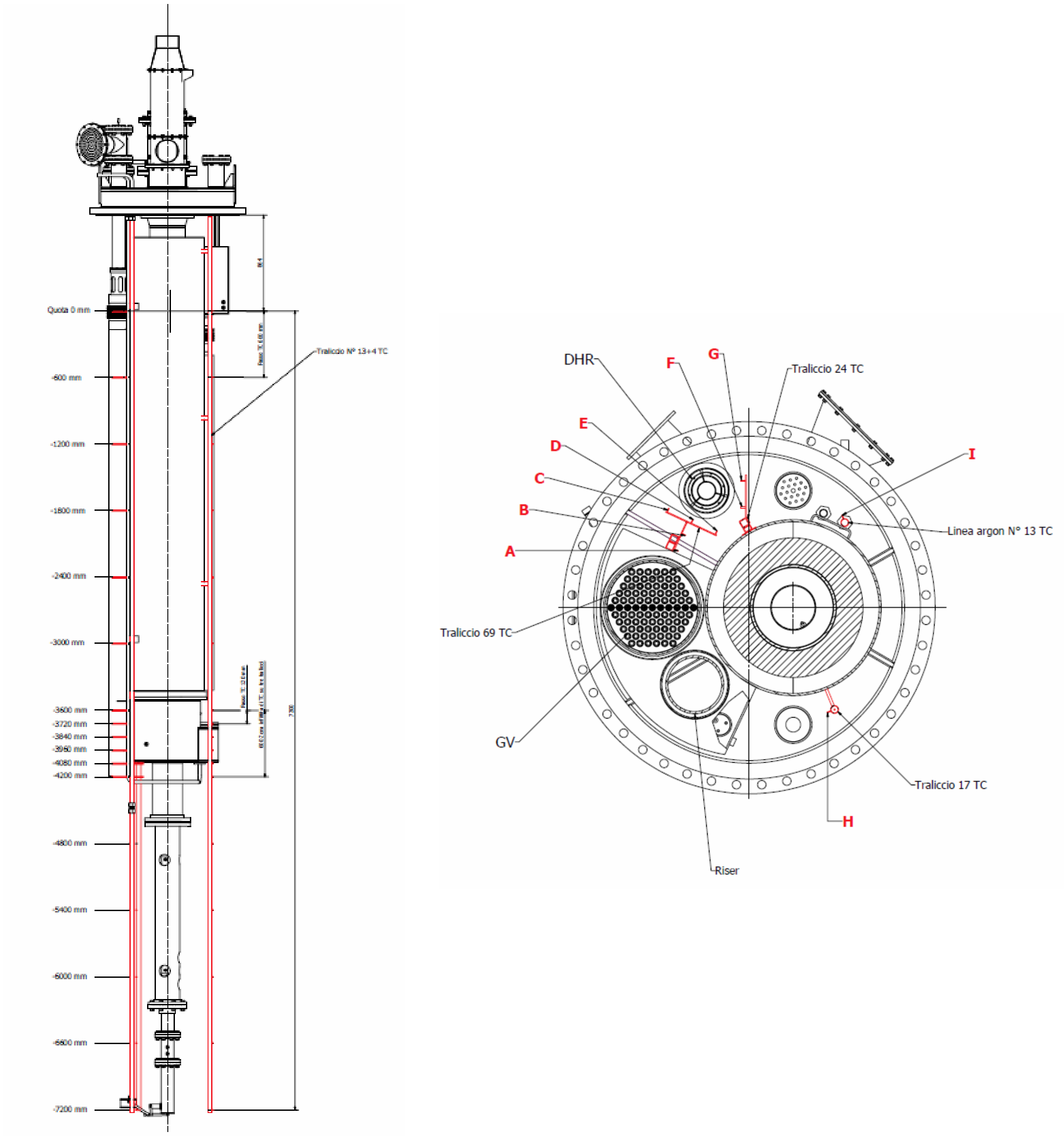


Figure 10. TEST I: temperature at HX inlet/outlet

In order to investigate thermal stratification and mixing convection phenomena into the pool, CIRCE is equipped with several thermocouples (TCs), arranged in different vertical and circumferential positions, as showed in Figure 11 [1]. The multidimensional component, on R5-3D model, is conceived to compare LBE temperature in the exact position of the TCs.



(a) (b)

Figure 11. Thermocouples positioning

Figure 12 shows a comparison between experimental and calculated axial temperature profile in different circumferential positions, at the end of the test. In Figure 12a and b, the experimental value is obtained as the average temperature measured respectively by six and two TCs. Temperature profiles show a similar (but not equal) trend in the different positions. Both simulations rather well reproduce the experimental data, except in the region between -1 and -4 m, where pool temperature is underestimated by R5-3D. The differences in the temperature profile are probably due to the the absence of the axial liquid conductivity correlation into the code.

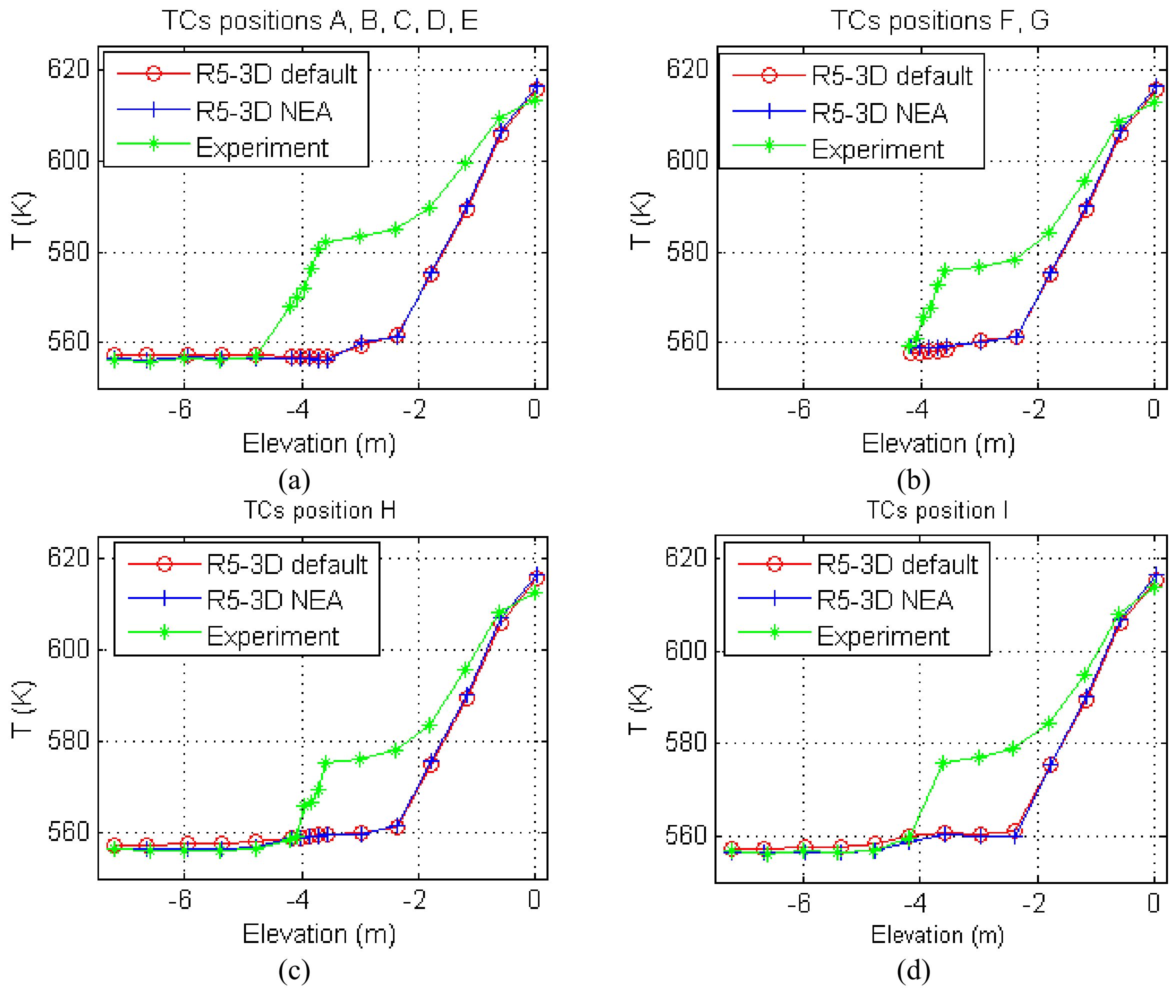


Figure 12. Axial temperature profile in the LBE pool at 25200 s

5. Conclusions

The experimental campaign conducted on CIRCE-ICE facility offers additional data for the validation of R5-3D code in the frame of HLM pool-type reactors.

The geometrical nodalization scheme consists of a mono-dimensional model, which reproduces the primary main flow path and the secondary side of the HX and DHR system, coupled with the three-dimensional model of the pool.

The thermal-hydraulic behavior of the primary flow path is well reproduced by the code. In particular the implementation of new thermophysical properties correlations, recommended by NEA, allows a better estimation of the Nusselt number and, consequently, a better reproduction of LBE temperature variation along the flow path and the heat losses through the internal structures.

The main objective of the 3D component, used in this work, was to investigate thermal stratification and mixing convection phenomena into the pool. The LBE temperature is well reproduced by the code, except between -1 and -4 m, where the simulations underestimate the experimental value. Further investigation for the thermal stratification profile in this zone is needed, with a heat losses detailed characterization which could be carried out with CIRCE-HERO experimental data contribution.

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