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Numerical analysis of temperature stratification in the CIRCE pool facility

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Abstract. In the framework of Heavy Liquid Metal (HLM) GEN IV Nuclear reactor development, the focus is in the combination of security and performance. Numerical simulations with Computational Fluid Dynamics (CFD) or system codes are useful tools to predict the main steady-state phenomena and how transitional accidents could unfold in GEN IV reactors. In this paper, to support the validation of CFD as a valid tool for the design, the capability of ANSYS CFX 15 to simulate and reproduce mixed natural convection and thermal stratification phenomena inside a pool is investigated. The 3D numerical model is based on the CIRCE facility, located in CR ENEA Brasimone. It is a pool facility, structured with all the components necessary to simulate the behavior of an HLM reactor, where LBE flows into the primary circuit. For the analysis, the LBE physical properties are implemented in CFX by using recent NEA equations [2]. Previously published RELAP5-3D© results [1] are employed to derive accurate boundary conditions for the simulation of the steady-state conditions in the pool and for CFX validation. The analysis focuses on the pool natural circulation with the presence of thermal structures in contact with LBE, considered as constant temperature sources. The development of thermal stratification in the pool is observed and evaluated with a mesh sensitivity analysis.

1. Introduction

In the Heavy Liquid Metal (HLM) - GEN IV Nuclear reactor development one of the main task deals with the thermal-hydraulics analysis of HLM-cooled fast reactor.

The attention is mainly focused on Lead and Lead-Bismuth Eutectic alloy (LBE) cooled reactors, due to their high capability to meet the safety requirements. Lead-cooled Fast Reactor (LFR) is one of the six concepts selected by Generation IV International Forum (GIF) and includes lead and LBE as primary coolant; both are chemically inert, and they offer other attractive characteristics in terms of interaction with structural materials and thermodynamic features.

Main interest for safety is the establishment of the natural circulation, an essential condition for a GEN IV reactor: these coolants guarantee the natural circulation cooling during the normal and transient operation. Key feature is the transient operation; this because, in case of an accident, the reactor is able to guarantee a long-term refrigeration of the core, thus preventing its meltdown. This aspect offers a considerable grace time in order to face an unprotected loss of flow accident and it permits to introduce



a combined mix of active and passive systems. Passive systems, as Decay Heat Removal system (DHR), assure optimal safety features over long time periods without needing human actions [3], as studied for ALFRED reactor [10], [11].

Nowadays, numerical simulations play an increasingly key role in the design of components and systems and new models and new software tools are developed to investigate thermal-hydraulics issues related to HLM technology. All these incoming tools must be validated in order to be used for safety analyses.

The activity aims to define, implement and carry out experimental results on the CIRCE (CIRColazione Eutettico) pool facility with the ICE (Integral Circulation Experiment) test section at ENEA Brasimone research center, in order to support the qualification of CFD as a valid tool for the design, control and analysis of complex three dimensional convection patterns in a large pool configuration, simulating the pool stratification phenomena in LBE and Lead cooled reactors and to investigate HLM mixing, which should induce thermo-mechanical stress on the structures. Another important scope is the validation of the models for the design of new HERO test section experimental campaign [9].

2. The CIRCE – ICE facility

The CIRCE – ICE facility, which aims to simulate the thermal-hydraulic behavior of the primary system in an HLM cooled pool reactor and the convection currents within the pool, is equipped with a Fuel Pin Simulator (FPS), which electrically simulates the core of the facility, the Heat Exchanger (HX) that simulates the steam generator and the DHR system, which simulates the security system for the transient operation.

CIRCE is a multipurpose pool facility designed to host different test sections, like ICE, 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 a data acquisition system [4].

The ICE test section is placed inside the main vessel, allowing to simulate the heat exchanger for primary cooling system of HLM pool-type reactor coupled with the secondary cooling system for the steam production. 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 and connects the lower plenum and the FPS. A Venturi-nozzle flow meter is installed into the feeding conduit in order to measure the primary flow rate through the FPS bundle, which consists of an electrical pin bundle with a nominal thermal power of 800 kW and an active length of 1000 mm. Molten LBE flows upward and increases his temperature passing through this part. The FPS is assembled with 37 electrical pins arranged in a wrapped hexagonal lattice and characterized by a pitch to diameter ratio equal to 1.8. Each pin has an outer diameter of 8.2 mm, a maximum thermal power of 25 kW and a heat flux at the pin wall of 1 MW/m². The hot fluid is introduced into the fitting volume and then flow upward into the riser which is a double wall pipe that connects the fitting volume with the separator. At the inlet section of the riser, a nozzle is installed allowing the injection of Argon that ensure the LBE assisted circulation into the primary circuit through the riser. The mixture flows upward and collects in the separator, where the gas is outstripped from the liquid metal: the former flows upward to the gas plenum, whereas the LBE is directed to the HX. The HX is made of 91 bayonet tubes with an active length of 3462 mm. 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, LBE flows downward decreasing the temperature. The volume between middle and outer tube is filled by pressurized helium to detect any leakage. The LBE, released by the HX, enters the pool, flowing downward, and reaching the lower plenum [4].

The DHR system consists of only one bayonet tube that has to remove the decay power by forced circulation of air; its height is 5012 mm, with an active length of 3205 mm. The bayonet is inside a

double wall shell with a thin air insulation gap to thermally decouple the DHR from the external LBE pool. During the transient operation, the hot LBE enters the DHR by the upper inlet section, it flows downward decreasing its temperature and exiting the component in the bottom half of the pool.

The ICE test section is installed in the pool; it has a radius of 585 mm and it is high 8490 mm, height where there is the closure of the vessel.

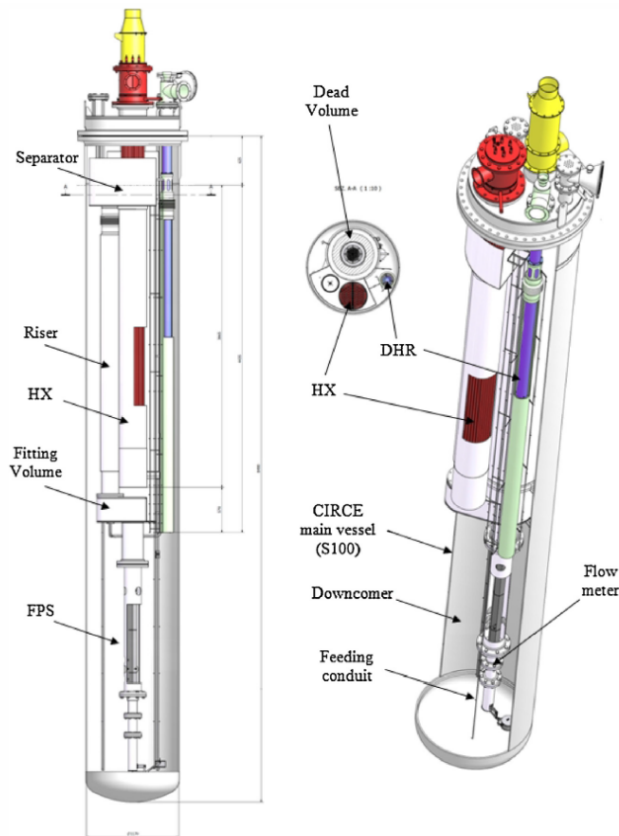


Figure 1. ICE test section [1]

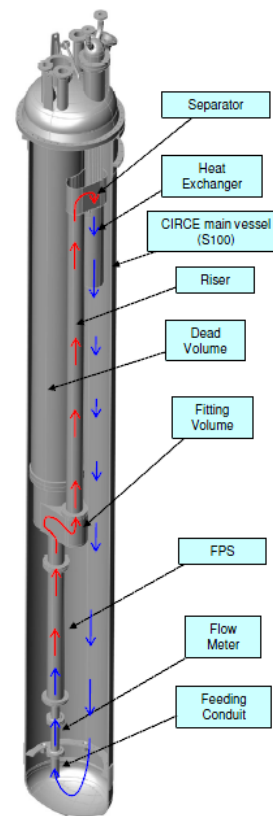


Figure 2. ICE test section: primary system main flow path

3. Problem formulation

This work is based on Ref. [5] to reproduce the geometry of CIRCE-ICE test facility and on Ref. [1] to initialize the simulation and to compare the obtained results.

The aim is to investigate the thermal stratification and convective phenomena of LBE. The primary cooling circuit of LBE is not investigated but it is assumed as data boundary condition for the model. To perform this analysis the CFD code ANSYS – CFX v15.0 is used.

3.1. ANSYS – CFX Geometry

A three-dimensional finite volume model, shown in the figures below (Figure 3, Figure 4 and Figure 5), has been built first by reproducing the structural components, and then subtracting them to the volume enclosed by the containment vessel.

Fluid domain has been sliced by fixed height multiple plane, creating 38 fluid volumes with heights equal to those volumes used in the RELAP5-3D® calculations presented by Narcisi et al. [1] to allow the use of these results as boundary conditions for the present simulation.

The geometry of CIRCE-ICE facility is not reproduced in its completeness, but only up to the entrance of the separator. Mesh generation is a key part of the analysis and will be discussed further.

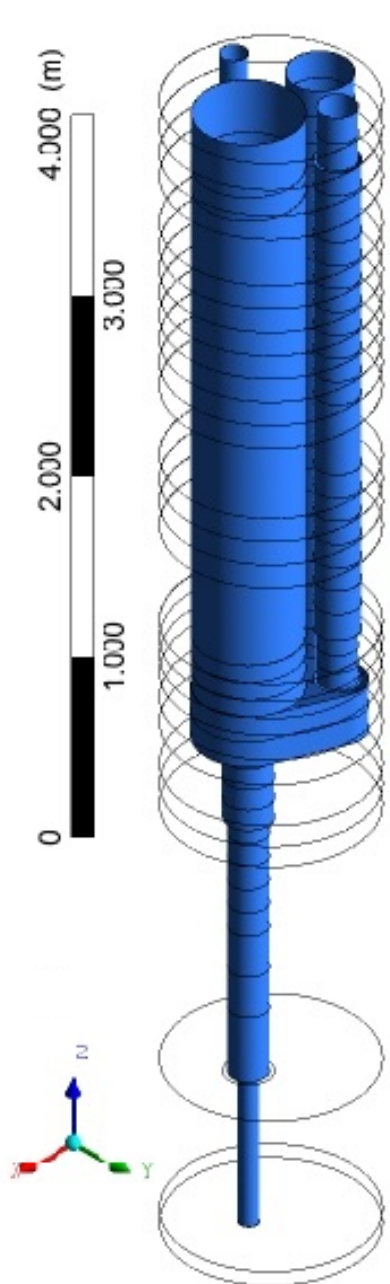


Figure 4. Numerical model CIRCE-ICE isometric view

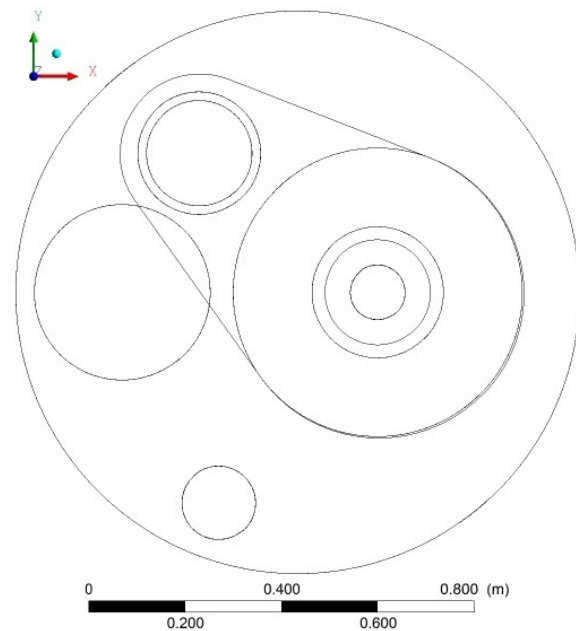


Figure 3. Numerical model CIRCE-ICE Z vertical view

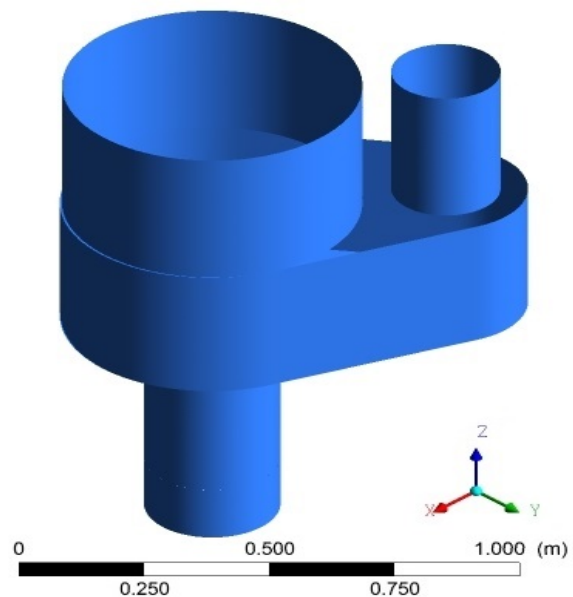


Figure 5. CIRCE-ICE fitting volume numerical model

3.2. Governing Equations

The simulation is a Reynolds Averaged Navier-Stokes (RANS) calculation, single-phase, using the $k-\omega$ Shear Stress Transport (SST) turbulence model, in order to account for the turbulence generated in the LBE domains, because the LBE is expected to pass from points where velocity is around 0.5 m/s to other points where the velocities decrease in order of magnitude of $10^{-2} \div 10^{-3}$.

The LBE was modelled with temperature-dependent thermophysical properties in order to obtain more accurate results; the equations are summarized in Table 1.

Table 1 Thermophysical properties of LBE [2] (Temperature in K)

Variable	Unit	Expression
Density	[kg m ⁻³]	$\rho = 11065 - 1.293 \cdot T$
Heat Capacity	[J kg ⁻¹ K ⁻¹]	$c_p = 164.8 - 3.94 \times 10^{-2} \cdot T + 1.25 \times 10^{-5} \cdot T^2 - 4.56 \times 10^5 \cdot T^{-2}$
Viscosity	[Pa s]	$\mu = 4.94 \times 10^{-4} \cdot e^{\left(\frac{754.1}{T}\right)}$
Thermal Conductivity	[W m ⁻¹ K ⁻¹]	$\kappa = 3.284 + 1.617 \times 10^{-2} \cdot T - 2.305 \times 10^{-6} \cdot T^2$
Thermal Expansion	[K ⁻¹]	$\beta = \frac{1}{8558 - T}$

Since the density is represented as function of the temperature, the full Buoyancy model [12] is employed to calculate the buoyancy forces arising in the pool to provide better accuracy in the evaluation of the heat transfer and liquid metal velocity field. A turbulent-Prandtl number of 2 has been employed, as suggested in [6] [7], to hence the conduction heat transfer prevails on the convection (i.e. turbulence-driven) heat transfer.

3.3. Boundary Conditions

The inlet is set at the exit of the HX and outlet at the LBE ingress in the feeding conduit: both BCs are characterized by a fixed mass flow rate to and from the, not-modelled, test section internal hydraulic circuit. An “opening”, to simulate the behavior of the argon gas plenum, is set as boundary condition at the top surface condition that is necessary to obtain the correct pressure profile along the height of the pool without the need to simulate a more complex multiphase flow involving the Ar-LBE mixture (BCs Table 2).

From the results obtained by the RELAP5-3D[®] analysis, [1], it is possible to set as boundary conditions the temperatures or the heat fluxes on the surfaces of structures in contact with LBE. Due to instabilities that the imposed heat flux may create, it was considered as appropriate choice to set the wall temperatures as a boundary condition. The thermal boundary conditions are reported in Table 3.

Table 2 CFX model momentum and mass boundary conditions

BC Name	BC Detail	Value
Inlet	Mass flow rate [kg s ⁻¹]	57.737
	Temperature [K]	555
Outlet	Mass flow rate [kg s ⁻¹]	57.737
Opening	Pressure [kPa]	107.5
	Temperature [K]	613

Table 3 CFX model heat transfer wall temperature boundary conditions among the CIRCE height

BC	H	FPS	Release Pipe	Fitting Vol	Dead Vol	Riser	HX	Pool	DHR
[#]	[mm]	[K]	[K]	[K]	[K]	[K]	[K]	[K]	[K]
1	170					638.6	620.1	613.8	
2	170					638.6	616.1	610.3	
3	150					616.0	610.1	603.7	
4	300					606.0	604.3	598.0	
5	150					604.4	600.7	596.2	
6	150					601.5	597.0	592.9	
7	150					599.9	593.6	591.2	
8	150					597.8	590.2	588.8	
9	150					596.2	586.9	587.0	
10	150					594.6	583.7	585.0	
11	150					593.0	580.5	583.1	
12	450					589.2	574.5	579.0	
13	150					582.7	568.7	574.1	
14	150					579.3	566.1	572.5	
15	150					576.5	563.7	571.8	
16	150					576.5	561.4	571.5	
17	150					576.1	559.2	571.6	
18	150					575.5	557.1	571.6	
19	170					575.5	557.9	571.6	
20	110				626.1	598.4	557.7	571.6	
21	110				628.0	634.6	557.6	570.8	
22	110				629.8	634.7		569.3	
23	160			619.6				563.6	
24	160			619.3				560.0	
25	132.5		622.5	610.6				557.5	
26	132.5		615.8					557.5	
27	132.5		617.1					556.5	
28	132.5		619.0					556.5	
29	100	620.6						556.5	
30	150	619.5						556.5	
31	150	618.1						556.5	
32	150	612.5						556.5	
33	150	603.8						556.5	
34	262.5	589.7						556.5	
35	262.5	576.6						556.5	
36	415	560.1						556.5	
37	970							556.5	
38	440							556.5	

3.4. Domain Discretization

To further evaluate the accuracy of the results, three different meshes have been generated. Each of them has an increased number of nodes and elements to perform a mesh sensitivity analysis. The resolution between the meshes is given by an increase of thinning in the axial divisions of the model. Meshes are characterized by hexahedral and tetrahedral elements and a near wall inflation layer with $y_1 = 20$: this is a good compromise between the accuracy and the computational cost, as solving the viscous sublayer is not an objective of the present analysis; statistics information about the three meshes are summarized in Table 4. All the boundary conditions are the same for each simulation as shown in Table 2 and Table 3.

Table 4 Mesh statistics

Mesh	Nodes	Elements	Ave. Orth. Quality	Ave. Skewness
#1	1965090	2044636	0.96856	0.10708
#2	3485837	3495472	0.97682	0.09512
#3	8961424	8637335	0.98981	0.07959

4. Result and discussion

The steady state CFD analyses have been carried out to evaluate the thermal stratification inside the CIRCE pool, comparing the calculated axial temperature profile with the experimental data; the convective phenomena, recirculation and stagnation zones within the pool which can cause hotspots that can produce strong thermal stress, have been also investigated

The value of mass flow rate at the entrance of the feeding conduit to be compared with the results from [1] and experimental data [8]: as expected, the result is the same of the RELAP5-3D[®] simulation due to the fixed boundary condition, returning a mass flow rate of 57.74 [kg s⁻¹]

The evaluated mass flow rate at the opening is close to 0 [kg s⁻¹], as expected, for all the meshes. Refining the mesh, the mass flow through the area increases, passing from a magnitude of 10⁻⁷ (mesh #1) to 10⁻⁵ (mesh #2) and 10⁻⁴ (mesh #3). Therefore, no relevant LBE flow from and to the pool is present at the top surface and no significant error is introduced by not modelling the Argon in the gas plenum.

The axial pressure profile along the height of the pool is shown in Figure 6. Pressure grows linearly along the height, resulting at the opening 107.5 [kPa] and at the entrance of feeding conduit: 829.06 [kPa] (mesh #1), 828.80 [kPa] (mesh #2) and 829.27 [kPa] (mesh #3).

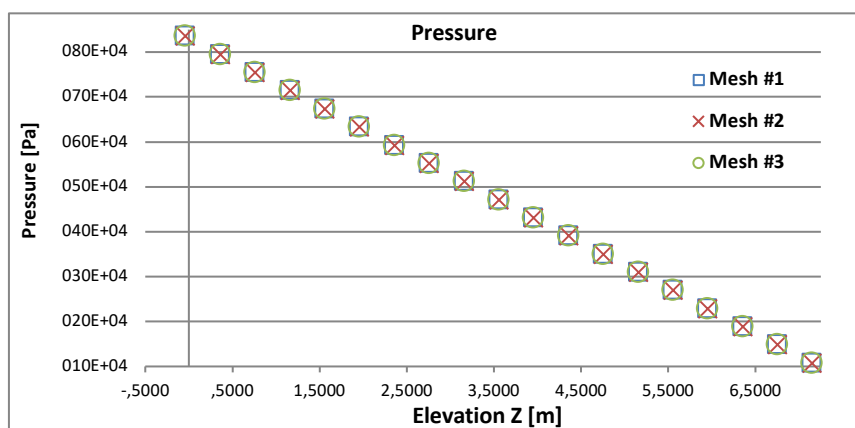


Figure 6 Axial pressure profile among the height

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 7 [8]. The 3D model used in CFX allows to compare the LBE temperature in the actual position of the TCs.

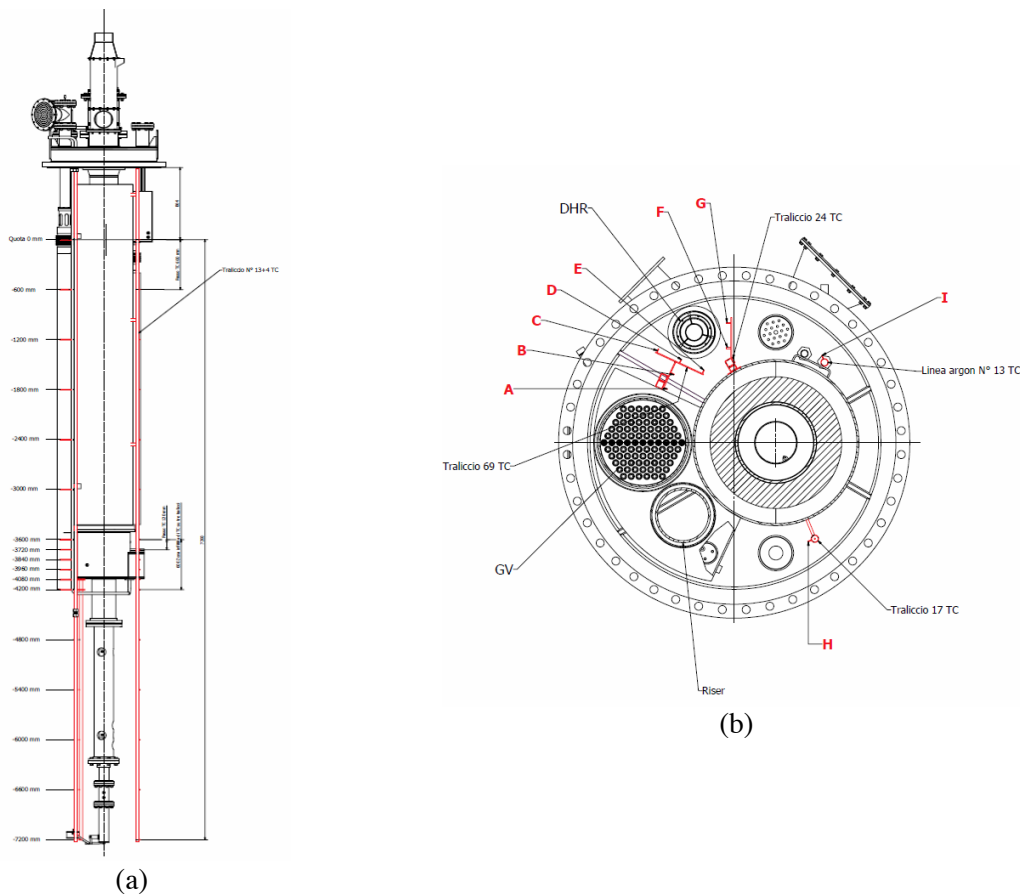
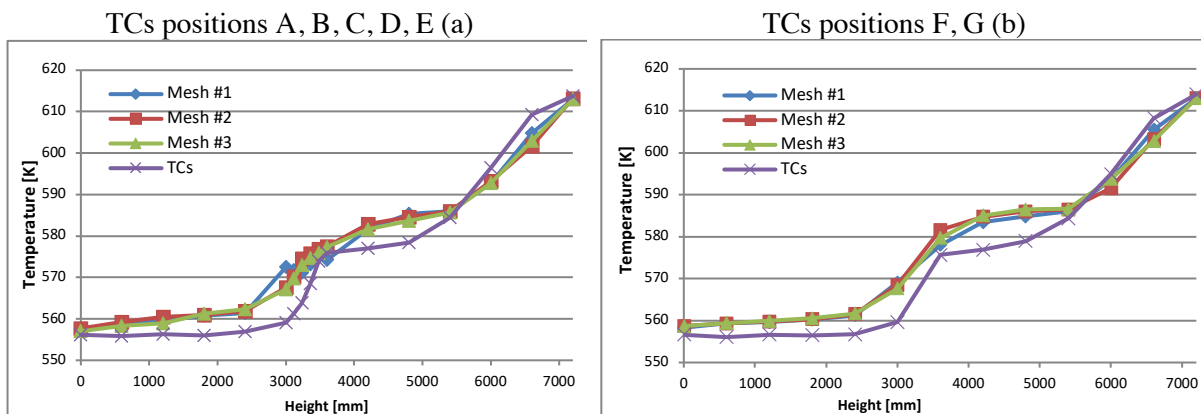


Figure 7 Thermocouples positions (a) (b)

The figure below shows a comparison between experimental and axial temperature profiles with the relative mesh in different circumferential positions. In Figure 8(a) and (b), the experimental values are obtained as the average temperature measured respectively by six and two TCs. Temperature profiles show a similar trend for each mesh in the different TCs positions. Some differences with the experimental data, as it is shown in 8(a) and 8(c) between 3000 mm and 4000 mm, have been obtained and there are some instabilities on the temperature trend for mesh#1 and mesh#2, therefore the experimental temperature plateau is not accurately reproduced in those calculations. Mesh #2 and #3 overestimates the temperature plateau in the same region but have a linear trend: these differences are probably due to the accuracy of the inflation layer that determines the y^+ and to the axial mesh discretization of the model.



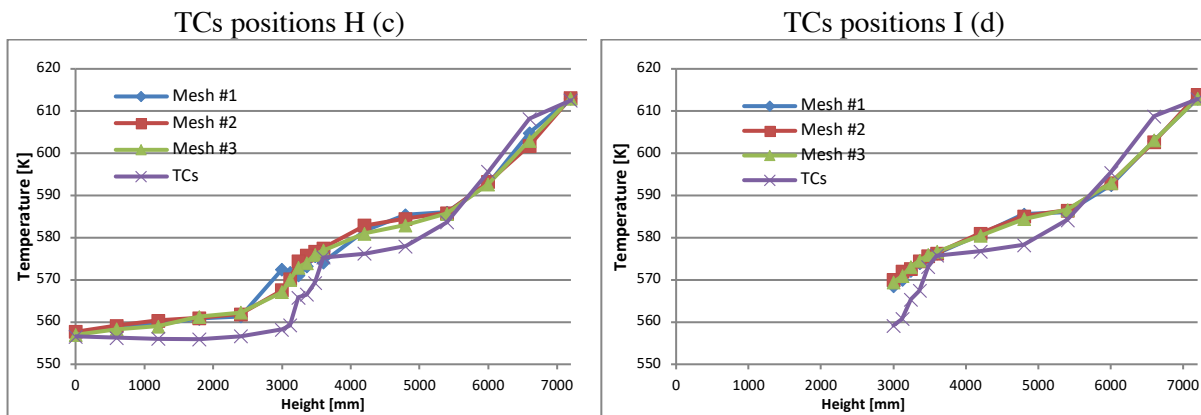


Figure 8 Thermal stratification along the axial profile

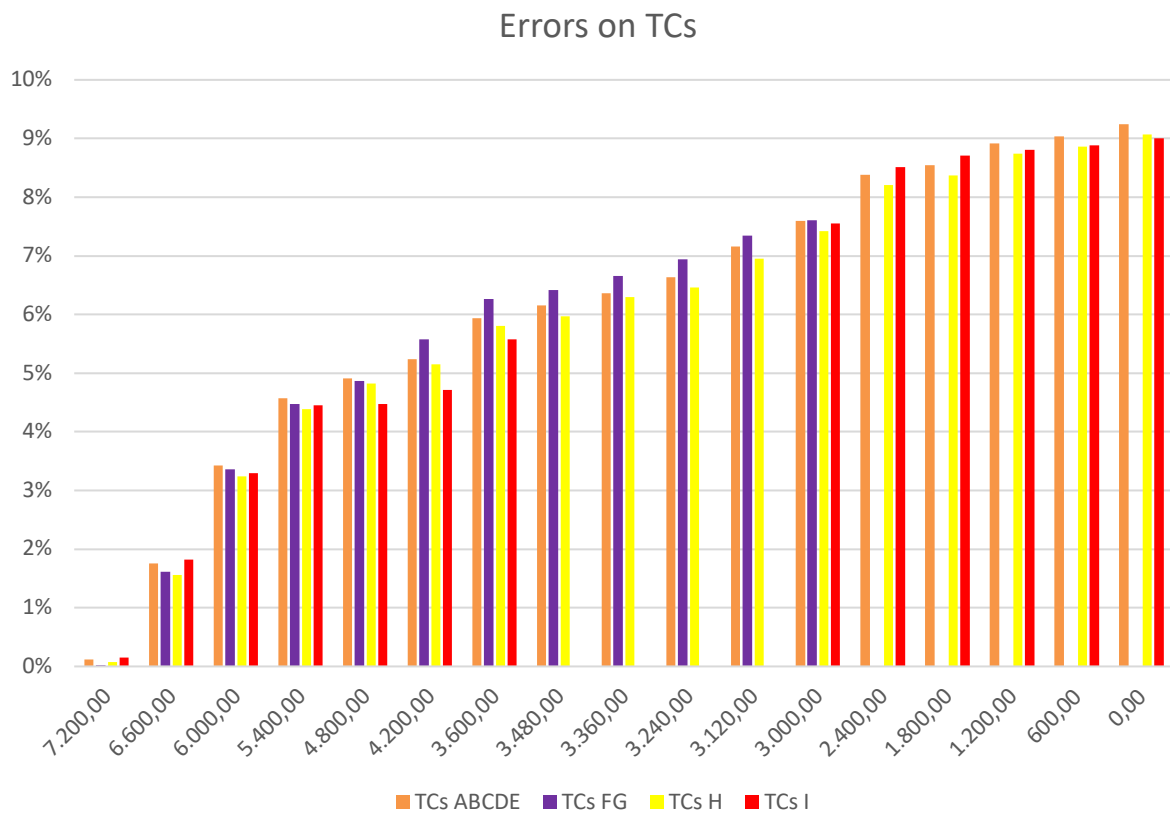
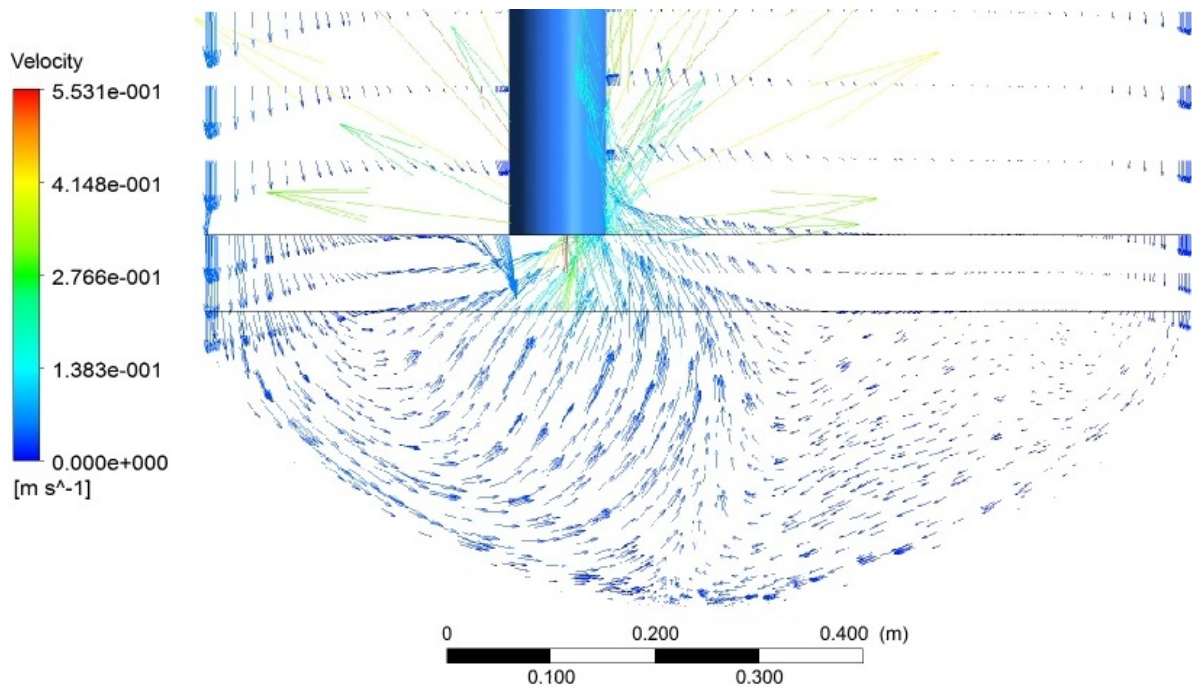


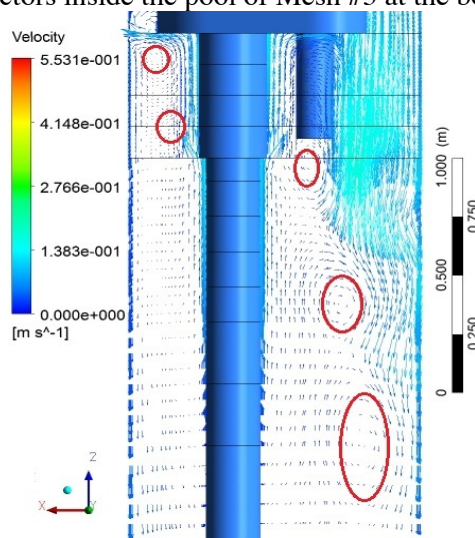
Figure 9: Errors bars regarding the TCs position of Mesh #3

The establishment of natural circulation is also confirmed in all simulations, thanks to the pressure drop and the temperature gradient inside the pool.

In Figure 10 (a) is represented the velocity field inside the pool of the mesh #3, the mixing phenomena is shown due to the vortex creation in the bottom part of the pool, the maximum velocity is reached at the entrance of the feeding conduit. The Figure 10 (b) shown the presence of vortex near the HX outlet and among the downward height, with recirculation points that also increase the mixing phenomena.



(a) Velocity vectors inside the pool of Mesh #3 at the bottom of the pool



(b) Recirculation point among the height in Mesh #3

Figure 10: Mixing phenomena in Mesh #3 (a) (b)

5. Conclusion

The experimental campaign conducted on the CIRCE-ICE facility at ENEA-Brasimone offers additional data for the validation of CFD thermal-hydraulics code in the frame of HLM pool-type reactors.

The main objective of this work was to investigate the thermal stratification and mixing convection phenomena into the pool. The developed 3D model consists of a pool with the structures of the primary system immersed in the LBE to reproduce only the volume of the pool. The boundary conditions are given from the RELAP5-3D[®] analysis carried out in [1].

The thermal-hydraulic behavior of the natural convection inside the pool is well reproduced by the CFX code. In particular, the activation of the buoyancy forces allows to identify a large number of recirculation point with the consequence of intense mixing convection phenomena.

The LBE temperature is well reproduced for all the meshes, except for the mesh #1, where the simulations return instabilities that differ from the experimental value.

An important parameter to correctly evaluate the thermal stratification is the heat losses distribution.

Further investigation for the thermal stratification profile in this zone is needed, with greater mesh nodes number to solve the viscous sublayer, and a thicker axial mesh. A fully coupled model with RELAP5-3D[®] can return also a better solution to reduce the instabilities.

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