NENE 2024 September 9 - 12 PORTOROŽ SLOVENIA
33rd International Conference Nuclear Energy for New Europe

Non-condensable Gas-Liquid Interface in LFR: analysis of STH code response for the manometer test case

B. Calgaro, D. Pellini
newcleo SpA
via Giuseppe Galliano 27,
10129 Torino, Italy
donella.pellini@newcleo.com, barbara.calgaro@newcleo.com

C. Robazza, N. Forgione
University of Pisa, Dipartimento di Ingegneria Civile ed Industriale (DICI)
Largo Lucio Lazzarino 2, 56122 Pisa, Italy
c.robazza@studenti.unipi.it, nicola.forgione@unipi.it

ABSTRACT

In recent years, interest in Liquid Metal-cooled Fast Reactors (LMFRs) has grown due to increased energy demand and the need for sustainable energy production. The Lead-Cooled Fast Reactor (LFR) is a promising solution, with compatibility for fast neutron spectra and safety-oriented characteristics. However, limited operational experience and scarce experimental facilities necessitate reliance on simulations for design and safety analysis.

System codes (STH), commonly used for simulating nuclear power plant behaviour, can be extended to liquid metal-cooled reactors. One critical issue is simulating the liquid-gas interface, especially its impact on reactor operational transient simulations.

This paper analyses the behaviour of the liquid-gas interface in a U-shaped tube partially filled with lead-liquid and argon as cover gas. Various system codes (STH), including RELAP5/Mod3.3, ASYST-LM and ATHLET, are used for assessment. The study highlights different codes' capabilities and identifies parameters for optimisation when safety analyses must be carried out for LFR.

1. INTRODUCTION

The increasing energy demand worldwide and the need for sustainable energy production have recently focused interest on fast reactors. Their features allow the use of uranium resources to the greatest extent possible and reduce nuclear waste [1][2] through the possible closure of the nuclear fuel cycle. Furthermore, the new concept of nuclear plants should meet the needs of better affordability, shorter construction time, wider range of users, site flexibility, reduction of greenhouse gas and pollution and integration with renewables [3][4]. The Lead-cooled fast reactor technology can cope with those requirements.

The lead's high boiling temperature eliminates pressurization and reduces boiling concerns, thus enhancing the inherent safety of the reactor core. However, different core layouts and fuel compositions are still under investigation. Other characteristics to be mentioned are the expected low reactivity associated with hypothetical voiding of coolant, the potential high actinide solubility in the coolant that minimises the potential for the core melts re-criticality, and the absence of chemical reactivity with air and water. These behaviours allow us to rely further on passive safety, even in support of any other active safety system, and enable compact and small reactor design [5].

The LFR operational experience was gained with the lead-bismuth submarines [6] built in the USSR in the ‘60s and further studied in Russia. One of the most important lead drawbacks that emerged was the corrosion of steel. However, the recent findings concerning suitable structure materials for such reactors [7][8] have shown a possible solution to this issue, thus renewing the interest in LFR reactors.

Given the limited experience, the role of numerical simulations in supporting the design of LFR is crucial. System codes (STH) like RELAP5 [9], RSSIM [10], and more recently ASYST-LM [11], and ATHLET [12] are used for the simulation of the nuclear system behaviour and applied to a wide range of safety scenarios, including Design Basis Accidents (DBA) and Design Extension Conditions (DEC), especially for Light Water Reactors [13]. Their development started in the ’70 and required extensive validation activity, which brought them to a high maturity level [14].

This level of maturity is not reached in their application to liquid metals. Experiments are needed for validating the codes and solving open issues. One of these is the correct evaluation of the liquid metal-non-condensable gas interface. This may affect the establishment of natural circulation, which represents one of the most important safety features in lead-cooled reactors.

2. U-TUBE TEST CASE: ANALYTICAL MODEL

The U-tube manometer problem is among the reference cases proposed for testing the robustness of the numerical scheme adopted in thermal hydraulic codes. It has been used as a reference test for benchmarking the dispersive and dissipative characteristics of a numerical prediction [15][16] but also for evaluating the role of numerical damping in a system where damping exists inherently. This is of particular interest in LFRs thermal-hydraulic simulations, in which the problem involving liquid lead and non-condensable gas interface affects the correctness of the free-level evaluation. This plays a crucial role in the characterization of the natural circulation established in a pump coast-down scenario, which is one of the relevant hypothetical accidents in this kind of reactor.

The model considered in this work refers to the U-tube scheme shown in Figure 1. It is a U-tube manometer with constant cross-sectional area *A*, filled with liquid lead. The elevation of the free liquid level is different in the two legs, and the upper part of the U-tube is filled with argon which is maintained at constant pressure.

At time t=0, the incompressible fluid is supposed to be at rest in a condition where the two free levels are at different elevations. Subsequently, the liquid starts to oscillate, until it reaches an equilibrium condition. The current analytical model aims to describe this oscillatory behaviour of the liquid levels inside the U-tube.

The transient, during which the fluid level is oscillating, is governed by the continuity and momentum equations:

$$\frac{\partial \rho}{\partial t}+\frac{\partial G}{\partial s}=0 \qquad (1)$$

$$\frac{\partial G}{\partial t}+\frac{\partial}{\partial s}\left(\frac{G^2}{\rho}\right)=-\frac{\partial p}{\partial s}-\frac{f\,G\,|G|}{2\,D\,\rho}-\rho\,g\cos\theta \qquad (2)$$

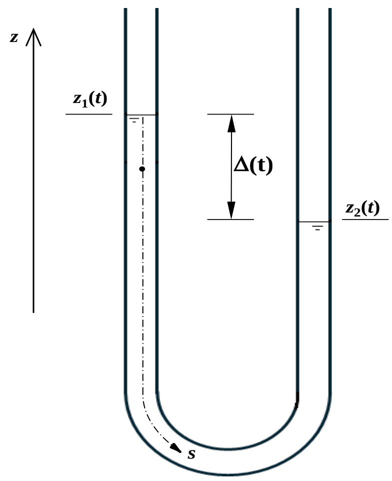


Figure 1: Scheme of a U-tube manometer

where G is the mass flux of the fluid in the cross-section, s is the coordinate in the flow direction along the channel length and θ is the angle between the s-coordinate direction and the positive vertical.

Since the cross-sectional area remains constant along the s-coordinate and the density can be considered constant (incompressible liquid), according to the continuity equation the speed averaged on the cross-sectional area, w, will not depend on s, but it only depends on time.

The quantities $z_1(t)$ and $z_2(t)$ represent the elevation of the free level in the two vertical legs of the U-tube at the generic instant t and Δ_0 indicate the initial difference between the free levels. Additionally, the quantity Δ representing the difference between the two free levels at the given instant t, can be defined as follows

$$\Delta \equiv z_1 - z_2 \tag{3}$$

Considering that is:

$$G = -\rho \frac{dz_1}{dt} \quad \text{and} \quad G = \rho \frac{dz_2}{dt} \tag{4}$$

a relationship can be established between the mass flux G and the quantity Δ:

$$G = -\frac{1}{2} \rho \frac{d\Delta}{dt} \tag{5}$$

This last expression can be substituted inside the momentum equation, which will be integrated along the entire length of the tube filled with the liquid (i.e. from s=0 to s=L). In this way, the differential equation of motion of the incompressible liquid is obtained in terms of Δ:

$$\frac{d^2\Delta}{dt^2} + \frac{f}{4D}\left|\frac{d\Delta}{dt}\right|\frac{d\Delta}{dt} + \frac{2g}{L}\Delta = 0 \tag{6}$$

The above differential equation allows for the analysis of the oscillatory motion of the liquid inside the U-tube legs over time.

The friction factor f was obtained using the same correlations employed in the RELAP5 code. In particular, in laminar flow conditions (Re $\leq$ 2200):

$$f_{lam} = \frac{64}{\text{Re}} = \frac{64\nu}{|w|D} \tag{7}$$

If Re has values in the range from 2200 to 3000, the following expression for f is used:

$$f_{int} = f_{lam}(2200) + \left(3.75 - \frac{8250}{\text{Re}}\right)\left[f_{turb}(3000) - f_{lam}(2200)\right] \tag{8}$$

If the flow is turbulent (Re $\geq$ 3000), the Zigrang-Sylvester correlation is used.

$$f_{turb} = -2\log_{10}\left[\frac{\varepsilon / D}{3.7} + \frac{2.51}{\text{Re}}\left(1.14 - 2\log_{10}\left(\varepsilon / D + \frac{21.25}{\text{Re}^{0.9}}\right)\right)\right]^{-2} \tag{9}$$

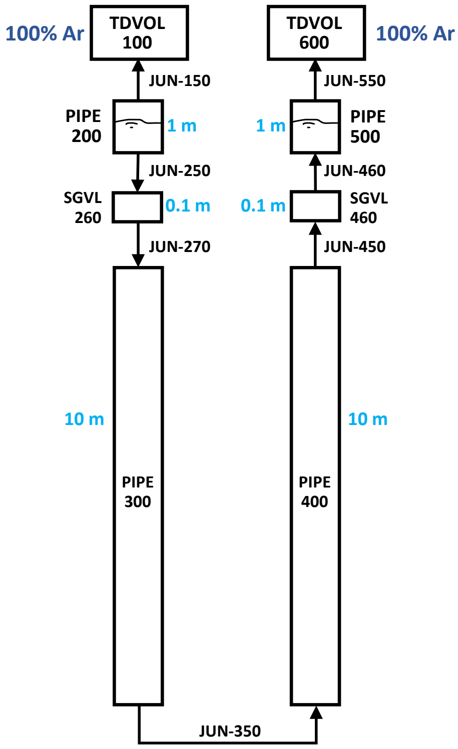
The Eq.(6) has been solved using MATLAB [17] in order to have a reference solution of the analytical model, whose results have been compared with those obtained by the STH codes. A very important characteristic of the analytical model is that the expected results must be independent from the cross-flow area A.

3. RELAP5/MOD3.3 AND ASYST-LM CODE SIMULATIONS

The STH code simulations have been performed by using the RELAP5/Mod 3.3, modified at the University of Pisa to be able to account for liquid metals as working fluids [18], ASYST-LM [11] and ATHLET [12].

In particular, the validation of RELAP5 for liquid metals has been carried out by using it for the simulation of several experimental tests, such as those performed at ENEA R.C. with the facilities NACIE [19], CIRCE[20], THALLIUM [21] and LIFUS V[22].

The U-tube domain has been reproduced in RELAP5 and ASYST-LM using the geometrical nodalization shown on the left side of Figure 2, while the main characteristics of each component are reported on the right side.



Component	Main Characteristic
TDVOL 100 (filled by Argon)	A=1.0 m^2; L=1.0m; Dh=1.0m; P=1.0e^5 Pa; T=700K Inc_angle=90°
PIPE 200 (10 Subvolumes)	A=7.854e^5 m^2; L=1.0m; D_h=0.01m; Inc_angle=90° First 2 sub-volumes filled by Argon
SGVOL260	A=7.854e^5 m^2; L=0.1m; D_h=0.01m; Inc_angle=90°
Pipe 300 (50 Subvolumes)	A=7.854e^{5}m^2; L=10.0m; D_h=0.01m Incl_angle=90°
Pipe 400 (50 Subvolumes)	A=7.854e^{5}m^2; L=10.0m; D_h=0.01m Incl_angle=90°
SGVOL460	A=7.854e^5 m^2; L=0.1m; D_h=0.01m; Inc_angle=90°
PIPE 500 (10 Subvolumes)	A=7.854e^5 m^2; L=1.0m; D_h=0.01m; Inc_angle=90° First 2 sub-volumes filled by Argon
TDVOL 600 (filled by Argon)	A=1.0 m^2; L=1.0m; Dh=1.0m; P=1.0e^5 Pa; T=700K Inc_angle=90°

Note:
- Roughness 1. e^{-5}m for all the pipes
- K_{fwd} and K_{rev} have been set up equal to 0 for all junctions

Figure 2: Domain's nodalization for RELAP5 and ASYST-LM (left) and its main characteristics (right)

The domain is made of two vertical legs that on the bottom side are reproduced by PIPE 300 and PIPE 400, connected by junction 350. Both are 10 m tall and 0.01m in diameter. Above these two pipes there are the single volumes 260 and 460. The liquid free level is inside the pipes 200 and 500. These two pipes are 1 m tall and are divided into 10 cells. As initial condition, pipe 200 has been filled at 80% with lead, while pipe 500 has been filled with lead only for 20% of the volume. Two separate time-dependent volumes (TDVOL 100 and 600) maintain the constant pressure of the cover gas. The nodalization used for the ASYST-LM is practically the same as that used for the RELAP5/Mod3.3 code. The temperature of both liquid-led and argon has been initialized at 700 K.

In the initial phase of the work, sensitivity studies have been carried out using RELAP5 and ASYST-LM, while in the final part of the work the ATHLET code is also used.

In the following, the most representative results of the sensitivity study are presented. For reasons of brevity, not all the results obtained using the ASYST-LM code have been reported, also because they were almost coincident with those of the RELAP5 code.

3.1 Level tracking option

Level tracking in RELAP5 refers to the modelling and simulation of fluid levels within various components of a nuclear reactor system and it is critical for accurately predicting the performance and safety of these systems. The two options for level tracking (activated/deactivated) have been analysed for the two PIPES 200 and 500.

As can be seen in Figure 3, the level tracking activation plays a key role in the simulation's correctness. The prediction of the system oscillations differs in dependence on its activation. The oscillation dampens faster, and the values are slightly different in the case of deactivation, too. A full agreement of RELAP5 results with analytical data is obtained if the level tracking is activated, while different damping of the oscillations is obtained when the level tracking option is not activated.

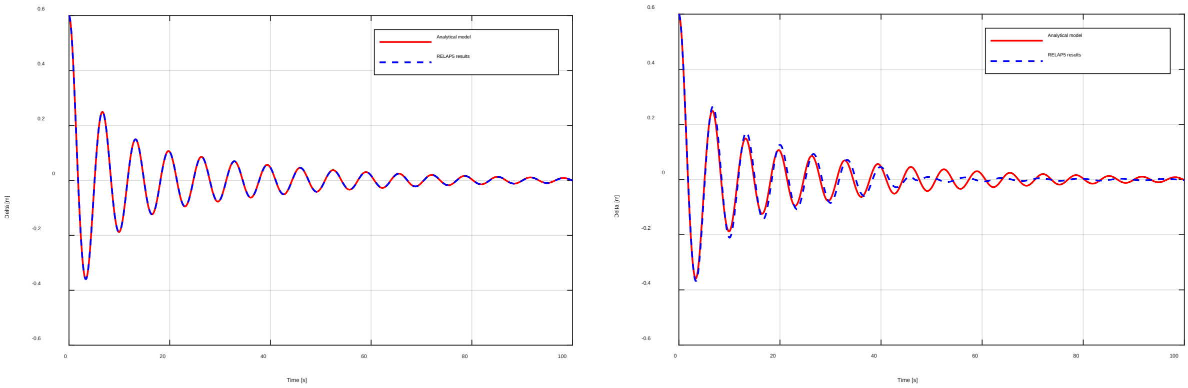


Figure 3: Obtained results for level tracking activated, *l*=1 (left), and not activated, *l*=0 (right)

3.2 Hydraulic diameter

Given the thermal-hydraulic importance of the hydraulic diameter, which helps to determine the flow regimes and the pressure drops, two different hydraulic diameters have been considered: 0.01 and 0.1 m. The obtained results concerning the two hydraulic diameters are shown in Figure 4.

The comparison of the results obtained from the two codes and the results from the analytical model has shown a full accord among them. As can be seen for both the considered cases, the results obtained by RELAP5 are in perfect agreement with the analytical model results.

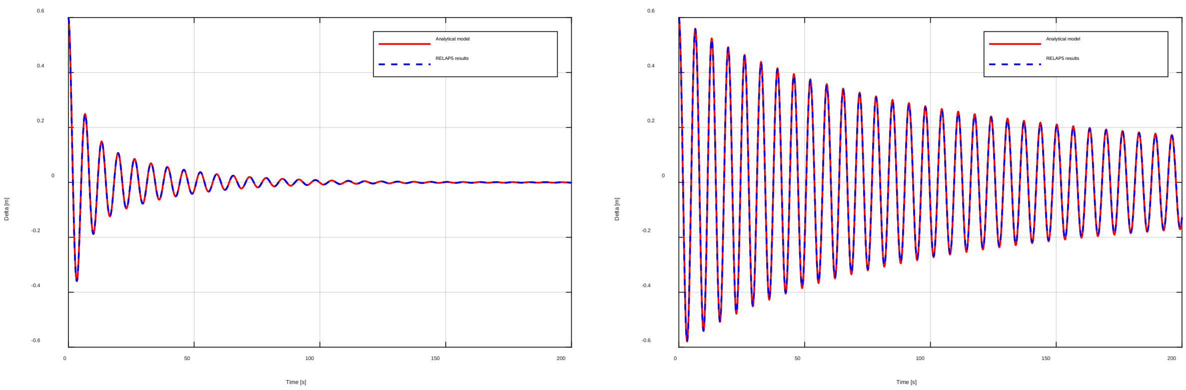


Figure 4: Obtained results for *D*=0.01 m (left) and *D*=0.1 m (right)

3.3 Cross-flow area

As already said in section 2, the analytical solution is independent from the crossflow area.

The two values for the cross-section area of 7.854e-5 and 7.854e-4 m2 have been considered to investigate any possible effect of the area variation in the simulation results.

As can be seen from Figure 5, the variation of the cross-sectional area does not produce any appreciable effect on the RELAP5 and ASYST-LM simulation results. In addition, comparing the two diagrams of Figure 5, it is possible to see that the RELAP5 and ASYST-LM codes give the same results.

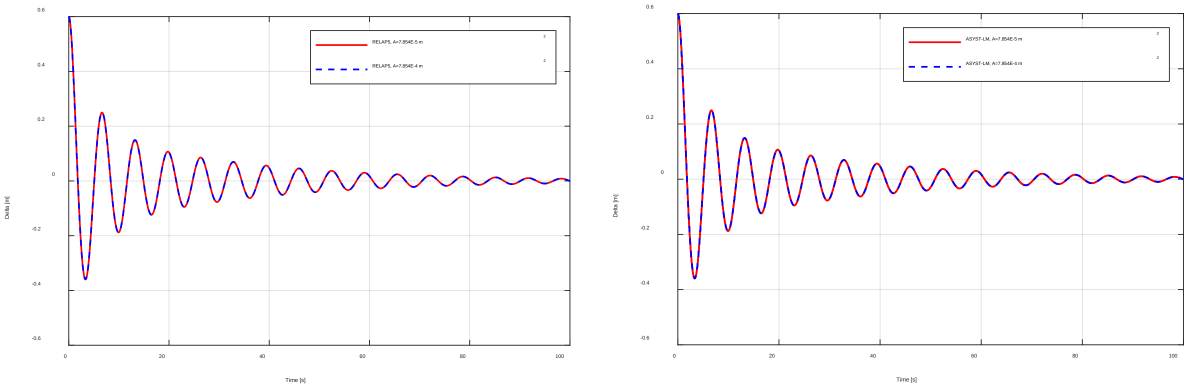
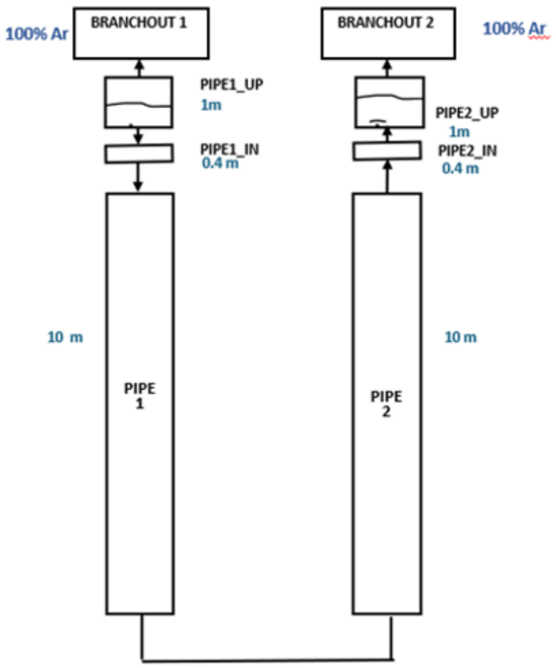


Figure 5: Obtained results for the two values of cross-flow area: RELAP5 (left), ASYST-LM (right)

4. ATHLET MODELING

The domain nodalization (see table in Figure 6) is made of two pipes (PIPE1 and PIPE2), which are 10 m tall, whose diameter is 0.01 m, and divided into 20 cells, whose length is 0.5 m each. They are filled with lead at a temperature of 700 K. Other two pipes (PIPE1_UP and PIPE2_UP) are placed above PIPE1 and PIPE2. They are 1 m tall divided into 10 cells, whose diameter is 0.01m and the length is 0.1 m each. They are filled at 50% with lead and 50% argon at 700 K and 3.5 MPa. Another pipe called PIPE1_IN is inserted between PIPE1 and the PIPE1_UP to trigger the pressure perturbation and start the oscillations.



Initial Conditions of non-condensable gas and lead	Temperature [K]	700
	Pressure [Pa]	$3.5 \cdot 10^5$
Boundary Conditions (Branchout)	Temperature [K]	700
	Pressure [Pa]	$3.5 \cdot 10^5$
Cross sectional area [m^2]	PIPE1	$7.854 \cdot 10^{-5}$
	PIPE2	
	PIPE1_UP	
	PIPE2_UP	
	PIPE1_IN	
Inlet Conditions PIPE1_IN	Fluid	Argon
	Temperature [K]	700
	Pressure [Pa]	$4.5 \cdot 10^5$

Figure 6: Domain's nodalization for ATHLET (left) and its main characteristics (right)

It is filled with Argon at 4.5 MPa and has a diameter of 0.01 m with a length of 0.4 m. The boundary conditions (see table in Figure 6 are represented by the elements BRANCHOUT1 and BRANCHOUT2. Both are filled with argon.

Figure 7 shows the time-trend results for the velocity of the fluid inside the manometer and the displacement of the free level obtained from the ATHLET code and the analytical model. It must be pointed out that the level tracking has not been activated in ATHLET for these simulations.

The velocity time trend (Figure 7, left side) overlaps the corresponding analytical trend, showing a good agreement, especially concerning the frequency.

Similar analogies are exhibited in the free-level displacement during the first 40 s, too. Similarly to what was observed for RELAP5/ASYST simulations in Section 3.1, without the level tracking activation, the oscillation dampens faster with respect to the analytical model and minor differences are highlighted in the free level displacement values, which range from about 1 to 3 mm.

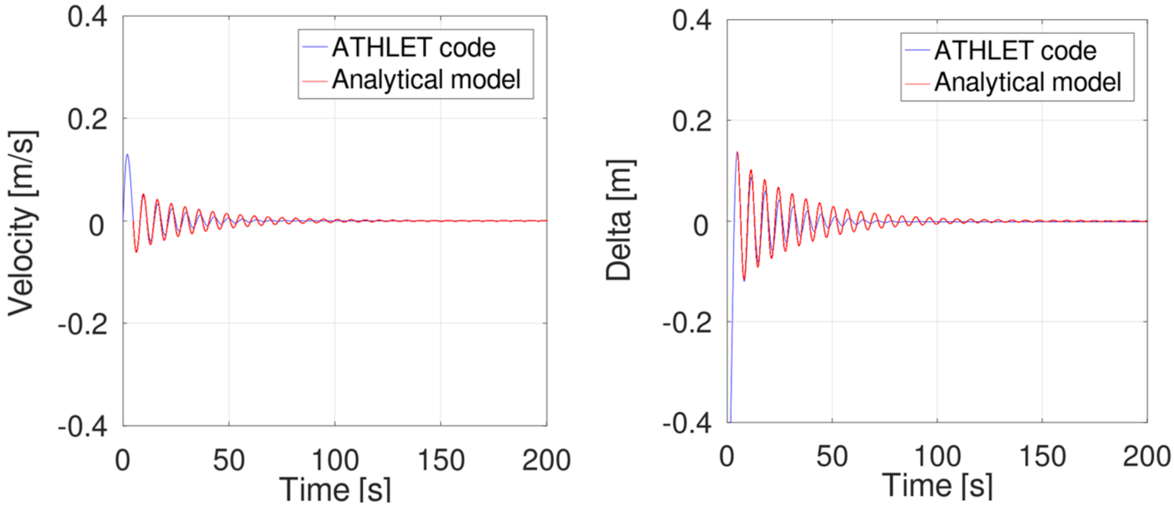


Figure 7: Comparison between ATHLET results and analytical model: velocity (left) and free level displacement (right)

5. CONCLUSIONS

A U-tube manometer has been chosen as a reference test case for validating different system codes against the problem of the lead-argon interface, whose correct evaluation can affect the simulation results in LFRs. Two test cases have been developed based on this reference case.

The first test case had the goal of investigating the influence of important parameters on the simulations carried out with RELAP5/Mod3.3 version beta, developed by the University of Pisa and with ASYST-LM. The comparison among the results has shown a full agreement between the two codes, thus assessing their capability to simulate the dynamic motion of the manometer.

The sensitivity analysis has highlighted the dependence of the results from the activation of the mixture level tracking model and their independence from time step, numerical scheme and hydraulic diameter. The comparison between the results from the simulations carried out with RELAP5/Mod3.3v.beta and ASYST-LM and from the analytical model developed with MATLAB has shown full agreement.

A preliminary assessment of the test case has also been performed with ATHLET Code. The simulation results agree with the dynamic behaviour described by the analytical model.

However, further investigations are needed to complete the analysis, in order to deepen the effects of the level-tracking activation.

REFERENCES

[1] B. Calgaro, et al., “Waste Management Through Transmutation in an ADS Reactor”, Science and Technology of Nuclear Installations, pp. 1-6, 2008.

[2] M. Salvatores, G. Palmiotti, “Radioactive waste partitioning and transmutation within advanced fuel cycles: Achievements and challenges”, Progress in Particle and Nuclear Physics, pp. 144-166, 2011.

[3] International Atomic Energy Agency, “Climate Change and Nuclear Power”, Technical Report, 2022.

[4] M.D. Matthew, “Nuclear Energy: A pathway towards mitigation of global warming”, Progress in Nuclear Energy, Vol. 143, 2022.

[5] F. Delhin, J. Wallenius, S. Bortot, “An analytical approach to the design of passive safe lead-cooled reactors”, Annals of Nuclear Energy, Vol. 169, 2022.

[6] A. Zrodnikov, V. Chitaykin, B. Gromov, O. Grigoryv, A. Dedoul, G. Toshinsky, Y. Dragunov, V. Stephanov, “Use of Russian Technology of Ship Reactors with Lead-Bismuth Coolant in Nuclear Power”, TECDOC-1172. 2000.

[7] P. Domstedt, M. Lundberg,P. Szakalos, “Corrosion Studies of Low-Alloyed Fe-10Cr-4Al Steel in Liquid Pb at very high temperatures”, Journal of Nuclear Materials, Vol. 531, 2020.

[8] G.K. Zelenskii, Yu. A. Ivanov, A.G. Ioltukho, M.V. Leont'eva-Smirnova, I.A. Naumenko, I.A. Shkabura, “Methods for protecting fuel-element cladding from corrosion in lead coolant and the heat transfer sublayer”, Atomic Energy (2008), Vol. 104.

[9] INL, “RELAP5/Mod3.3 Code Manual”, Idaho National Laboratories: Idaho Falls, USA 2003.

[10] C.M. Allison, J. K. Hohorst, “Role of RELAP/SCDAPSIM in nuclear safety”, Science and Technology of Nuclear Installations, 2010.

[11] RHYS User’s Manual v2.2, 2024.

[12] A.Wielenberg, P.Schöffel,T. Skorek, https//user-codes.grs.de/default/files/ATHLET_3.4.0_Program_Overview.pdf , November 2023

[13] G.A. Roth, F. Aydogan. “Theory and implementation of nuclear system codes- Part I: Conservation equations, flow regimes, numerics and significant assumptions”, Progress in Nuclear Energy, Vol.76, 2014.

[14] J. Wang, X. Li, C. Allison, J. Hohorst, “Nuclear Power Plant Design and Analysis Code - Development, Validation, and Application”, Woodhead Publishing, 2020.

[15] V. Ramson, “Numerical Benchmark Test N.22: Oscillating Manometer”, Multiphase Flow and Technology, Vol 6, 1992.

[16] M. Bonizzi, V. Faluomi, P. Andreussi, “MAST: a fine mesh transient multiphase code for geothermal fluid networks simulation”, European Geothermal Congress, Den Haag, The Netherlands, 11-14 June 2019.

[17] MATLAB version: 9.13.0 (R2022b), Natick, Massachusetts: The MathWorks Inc., https://www.mathworks.com

[18] G. Barone, D. Martelli, N. Forgione, “Implementation of Lead-Lithium as working fluid in RELAP5/Mod3.3”, Fusion Engineering and Design, 146, pp. 1308-1312, 2019.

[19] N. Forgione et al”, Simulations of NACIE-UP Experimental Tests by STH Codes”, ICONE 26-81434, 2018.

[20] F. Galleni, G. Barone, D. Martelli, A. Pucciarelli, P. Lorusso, M. Tarantino, N. Forgione, “Simulation of operational conditions of HX-HERO in the CIRCE Facility with CFD/STH Coupled codes, Nuclear Engineering and Design, Vol. 361, 2020.

[21] A. Venturini, M. Utili, N. Forgione, “Numerical Simulations with RELAP-3D and RELAP5/mod3.3 of the second Experimental Campaign on In-Box LOCA transient for HCLL TBS”, Energies MDPI, Vol.14(15), 2021.

[22] M. Eboli, A. Ciampichetti, F. Giannetti, N. Forgione, A. Del Nevo, “The LIFUS5 separate effect test facility experimental programme”, Nuclear Engineering and Design, Vol.411, 2023.