INVESTIGATION OF RELAP CAPABILITY TO SIMULATE THE LBE COOLING SYSTEM THERMAL-HYDRAULIC

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Abstract

The paper subject regards the validation of the RELAP5/Mod3.2.2β, the best estimate code modified to deal with fluids of interest for the XADS (eXperimental Accelerator Driven System), a Lead Bismuth Eutettic alloy (LBE) cooled ADS design set up at Ansaldo Industry. The validation will be made exploiting the experimental program carried out on support of XADS design and MEGAPIE experiment, at the ENEA Research Centre of Brasimone (Italy), making use of CHEOPE and CIRCE facilities.The comparison between experimental results and post test calculation allows the check of the code capability in simulating the 1Dym fluid-dynamic of heavy metal. In particular, CHEOPE tests have provided data for the validation of the new heat exchange correlations introduced in RELAP5 and the first experimental campaign on CIRCE facility allows the assessment of the code capability to simulate the LBE T/H both in single-phase and in two-phase flow conditions.

Introduction

Nowadays the interest of the scientific community on Accelerator Driven Systems (ADSs) is considerably growing up due to the possible contribution to supply an adequate answer to the problem of the closure of nuclear fuel cycle [1]. ADSs are subcritical nuclear systems coupling a proton accelerator and a subcritical fission core by means of a spallation target, where the additional neutrons necessary for the criticality are produced. Among the alternatives proposed to the international attention, it is worth of note the LBE (Lead-Bismuth Eutectic) ADS. In fact, this eutectic alloy couples a suitable neutronic behaviour with favourable physical and chemical properties: poor reactivity following the contact with air or water, operative pressure near atmospherical one and significant thermal transport even at relatively low values of fluid velocities.

An extensive R&D program is in progress in order to maximize the safety of the LBE ADS plants and to optimise the layout. In this framework, a lot of facilities have been build up in the world to support preliminary experimental plant designs such as the Ansaldo XADS (eXperimental Accelerator Driven System), a 80MWth facility [2], in which the LBE circulation is enhanced by a gas lift device insuffling argon in the bulk of primary coolant. Besides, several experimental programs are in progress to investigate different component concepts; among these we cite the MEGAPIE (MEGAwatt Pilot Experiment) initiative, a collaboration between European and Japanese research centres aimed at testing LBE spallation target technology at 1 MW beam power.

Moreover, in the last decades, the growing importance of predicting the behavior of nuclear power plant gave rise to a new approach (best estimate), which applies either on safety studies or on support of design. This approach requires so called best estimate codes containing the analytical models necessary to simulate the phenomenology involved in nuclear plant accidental transient. The best estimate calculations have to be validated by experimental tests to determine the calculation uncertainties.

The paper subject regards the validation of the RELAP5/Mod3.2.2β, the best estimate code modified to deal with the LBE fluid in the frame of TRASCO (TRASmutazione SCOrie), the Italian research project, which foresees the collaboration between Universities, research centres (ENEA, INFN) and Ansaldo Industry, on the design proposed by Ansaldo [3]. The validation will be made exploiting the experimental program carried out on support of XADS design and MEGAPIE experiment, at the ENEA Research Centre of Brasimone (Italy).

Two series of tests have been taken into consideration. The first tests have been performed making use of a CHEOPE (CHEmical OPErational transient) configuration, an experimental rig that has been built in order to measure the thermal exchange characteristics between the lead-bismuth eutectic alloy and the heat removing fluid. The tests carried out on the plant aim at simulating the behavior of a single element of the 12 heat removal elements foreseen for the experimental installation MEGAPIE. The second series of tests have been carried out by CIRCE (CIRCuito Eutettico), the largest facility for heavy liquid metal technology development. It will provide experience on thermal-hydraulic and material behavior in a pool configuration, as well as full-scale tests of the critical components of the spallation target and the XADS LBE option.

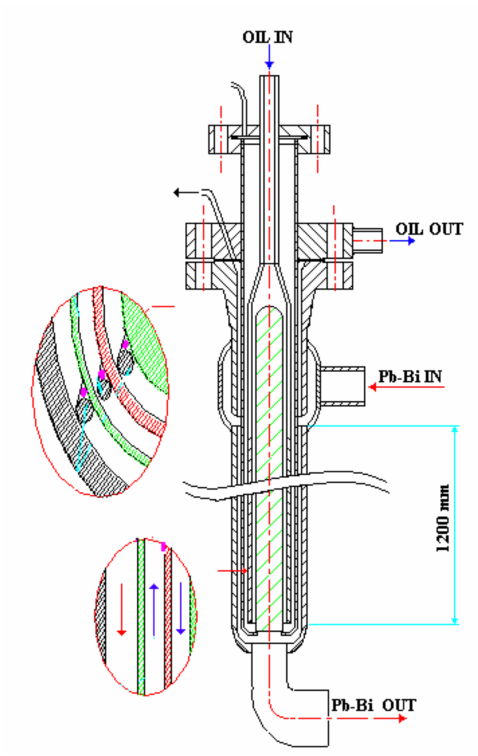
In both cases the comparison between experimental results and post test calculations allows the check of the code capability in simulating the 1Dym fluid-dynamic of heavy metal. In particular, for CHEOPE facility we want validate the code with regard to the heat exchange correlations introduced in the modified version of the RELAP5 code; for CIRCE facility, the comparison allows the validation of the models adopted for single components and the check of the code performance towards the LBE T/H in presence of gas.

CHEOPE tests for MEGAPIE

The CHEOPE facility was built at the ENEA Centre of Brasimone within the framework of the research program on ADS to furnish thermal fluid dynamic data on Lead-Bismuth-Eutectic (LBE). The device was employed in cooperation with PSI and the others European research organizations for thermal exchange and thermal instability studies for the MEGAwatt PIlot Experiment (MEGAPIE) [4].

To this aim a prototype of oil-LBE heat exchanger analogous to the devices foreseen in MEGAPIE was implemented in the facility. The experimental equipment (Figure 1) consist of two circuit inside of which the diathermic oil and the LBE flow separately, and a cooling pin just reproducing one of the 12 oil-LBE heat exchangers. The LBE heating, due to the spallation reactions in MEGAPIE, is simulated by means of electric heaters. The cooling pin is a bayonet heat exchanger with three coaxial cylinders (see particular in Fig. 1). The Pb-Bi enters from the top and, flowing down along the eternal cilindrical shell, gives to the oil, swimming against the tide, the power absorbed in the heater and, finally, goes out from the bottom and comes back to the pump. The oil comes in from the top, flows along the heat exchanger and, at the bottom, goes back up flowing through the internal annular gap. Finally the oil rejects the absorbed power through an air-cooler to the environment.

Figure 1. **CHEOPE cooling pipe: scheme and nominal operative conditions**



Heat exchanger high	1200 mm
Thermal power	55 kw
LBE mass flow rate	0.33 l/s
Oil mass flow rate	0.83 l/s
LBE inlet temperature	350°C
Oil inlet temperature	140°C
LBE Reynolds number	40660
Oil Reynolds number	6386

In order to gather the temperatures, the test section has been equiped with 18 thermocouples, suitable located. Moreover flow and differential pressure meters have been inserted with the aim to check the heat exchange phenomena involved parameter. It is worth to note that, on the basis of preliminary heat exchanger considerations, a metallic spiral has been welded on the external surface of the most internal cylinder with the aim to increment the turbulence of the oil rising the annular gap.

Post-test simulation of the CHEOPE tests

A complete model of the facility has been developed for the RELAP5 code (see Fig. 2). This model, which is also suitable for transient simulation, has been used for the reconstruction of two steady state tests in order to assess the heat exchange coefficient calculated by the code. The tests have been chosen on the basis of some considerations on the measurement uncertainties, among the test matrix produced for the MEGAPIE-TEST project [4]. The RELAP5 calculations have been performed imposing the oil inlet conditions (mass flow rate and temperature) in the cooling pin, the LBE mass flow rate and the thermal power.

In Table 1 the relevant parameters calculated for the two tests are compared with the experimental data. As one can see, the temperatures comparison shows a code overestimation of the LBE inlet and outlet temperatures due to an evident underestimation of the total heat exchange coefficient. As the heat transfer coefficient LBE side is about three times larger than the heat transfer coefficient oil side, this latter has much more influence on the total heat exchange coefficient value.

Figure 2. **CHEOPE nodalisation**

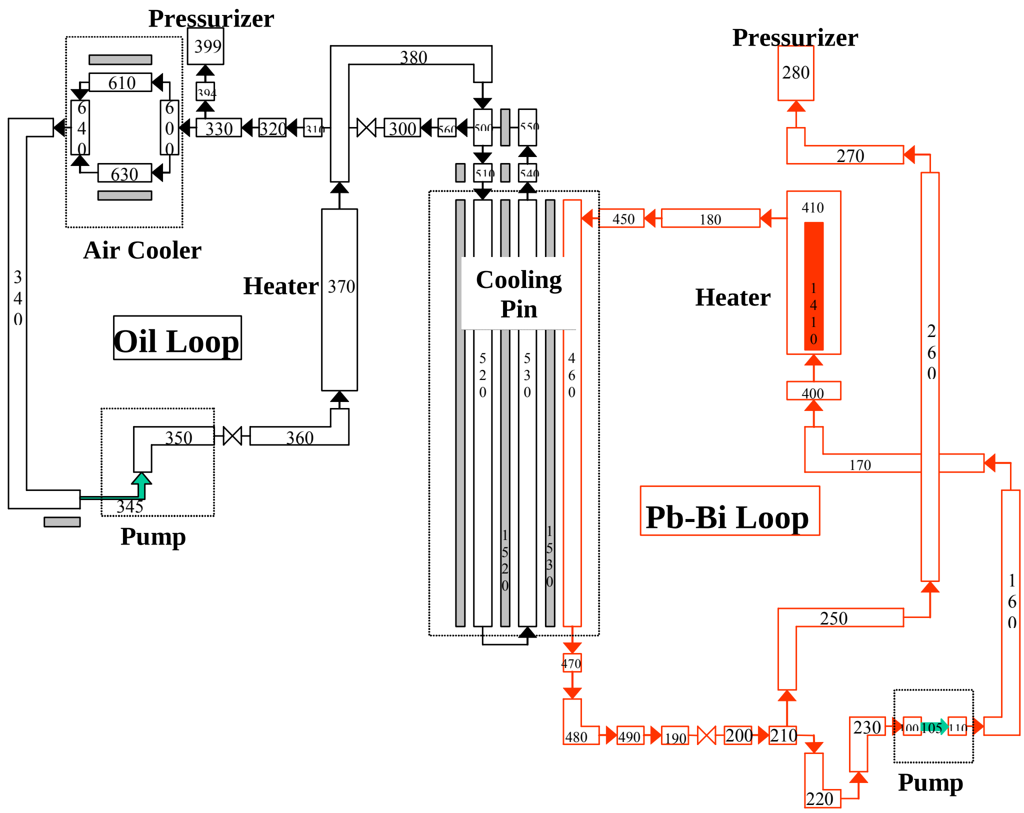


Table 1. **RELAP5 standard calculation**

	E1		E2	
	experim.	**RELAP5**	**experim.**	**RELAP5**
LBE inlet T [K]	579.05	592.31	537.25	550.82
Oil inlet T [K]	410.15	410.50	409.35	409.64
LBE outlet T [K]	455.95	473.19	445.85	462.64
Oil outlet T [K]	436.65	436.90	430.25	430.79
Thermal power [W]	27430	27423	21590	21593
global H [W/(m^{2}K)]	1794.99	1407.62	1835.41	1368.48

Further consideration regards the RELAP5 code one-dimensionality, which does not allow simulating the oil 3D effects due to the spiral introduction. This leads to a substantial underestimation of the Reynolds number, and consequently of the oil side heat exchange coefficient calculated with the Dittus-Bölter ($Nu = 0.023\, Re^{0.8}\, Pr^{0.4}$) correlation. So the Dittus-Bölter correlations seems inadequate in a 1-D model to simulate the convective heat exchanger, improved implementing the spiral.

The Table 2, set up on a different evaluation of the Dittus -Bölter correlation parameters, which takes into account the better heat exchange conditions by decreasing the hydraulic diameter oil side, shows a good agreement between the experimental results and the results such obtained using the RELAP5 code. In particular, the LBE inlet and outlet temperatures are a few far from the experimental values with a difference lower than 1%.

The implementation in the code of a suitable correlation for the convective heat transfer on oil side will be the subject of a future activity. Concerning the correlation used in the modified version of RELAP5 for the convective heat transfer on LBE side appears sufficiently adequate, in spite the uncertainties affecting the experimental data.

Table 2. **RELAP5 revised calculation**

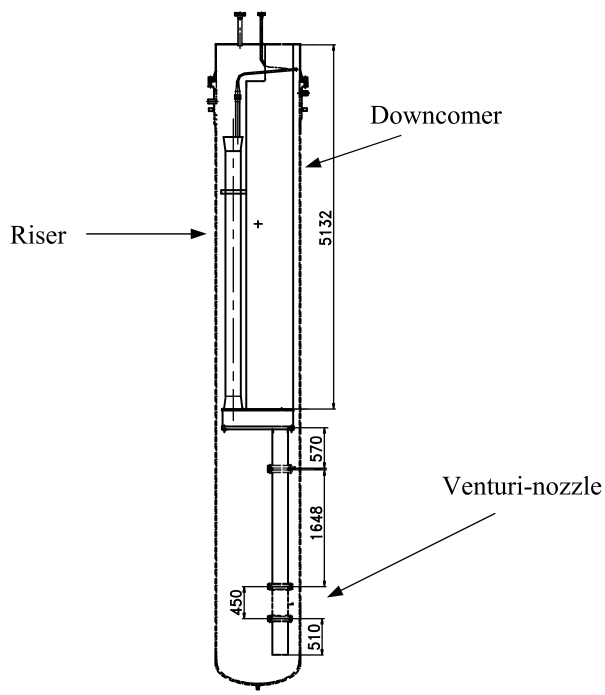
	E1		E2	
	experim.	**RELAP5**	**experim.**	**RELAP5**
LBE inlet T [K]	579.05	578.721	537.25	536.512
Oil inlet T [K]	410.15	410.522	409.35	409.662
LBE outlet T [K]	455.95	460.211	445.85	448.839
Oil outlet T [K]	436.65	436.899	430.25	430.795
H LBE [W/(m^{2}K)]	11265.28	9445.13	11857.07	9328.40

Experimental campaign conducted on the CIRCE facility

The CIRCE facility [5], located at the Brasimone ENEA laboratories, is a large-scale test facility operating with lead-bismuth eutectic (LBE) that was built for verification of key operating principles of an 80 MWth Experimental Accelerator Driven System (XADS) coinceived within the framework of the italian research program TRASCO. It basically consists of a full-height reduced diameter (1:5 the XADS vessel diameter) cylindrical vessel filled with about 90 tons of molten LBE and designed to house several test sections for separate-effect and integral testing.

The first experimental campaign carried out aimed at the performance verification of the LBE circulation enhanced by Argon gas injection that is one of the main peculiarity of the design. The circulation operating principle in the CIRCE facility, like in the XADS, consists of gas injection into the riser (see Figure 3) of the relevant test section. This principle [2] uses a closed-loop recirculating cover gas system. The gas, at nearly atmospheric intake pressure, is fed by compressors via a submerged sparger into the bottom part of the riser. The rising LBE-gas mixture two-phase flow slows down at the top of the riser, where LBE reverses its velocity and flows downwards, whereas the gas separates at the interface with the cover gas plenum because buoyancy prevails over entrainment. The two-phase LBE-gas mixture in the riser, being lighter than LBE alone in the downcomer by the amount corresponding to the mean void fraction in the riser, creates the driving force for the coolant circulation.

Figure 3. **Gas lifting test section**

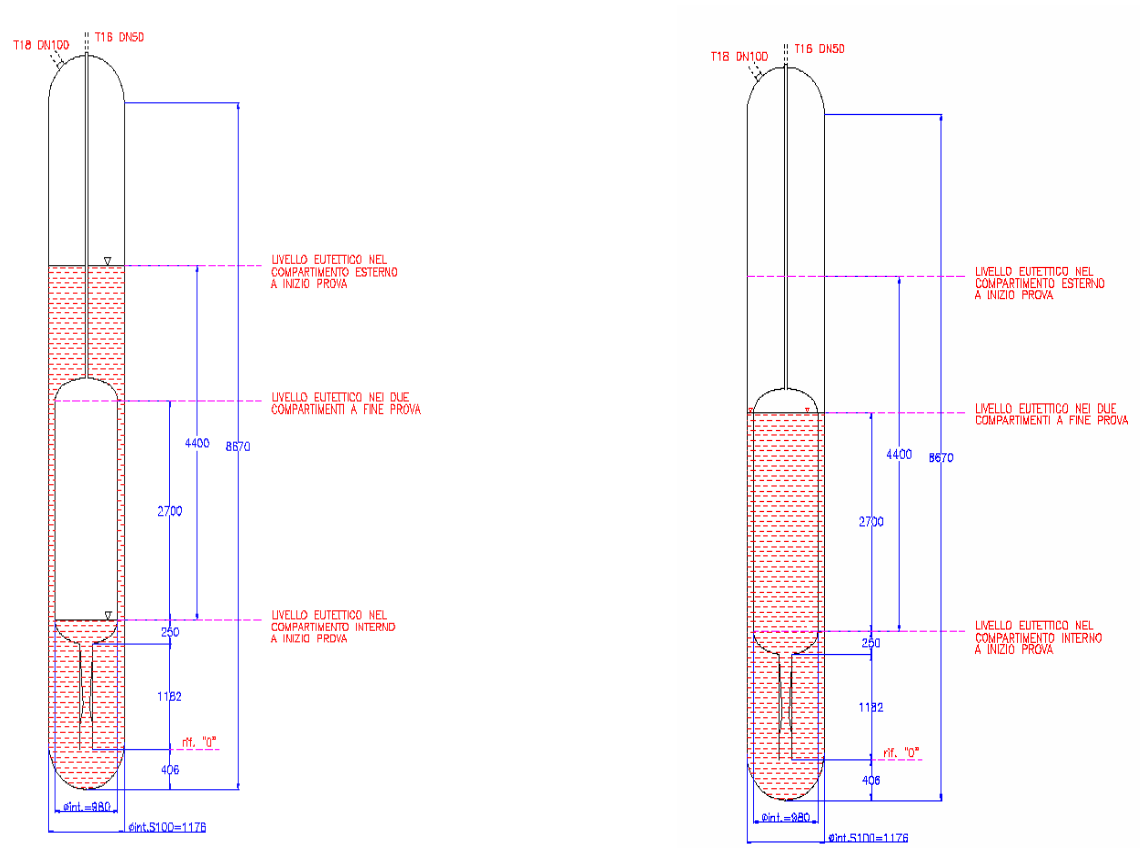


The experimental loop characterization, in term of Argon mass flowrate injected-LBE mass flowrate entrained, was previously supported by a test for calibrating the device chosen for the LBE mass flowrate measurements (Venturi-nozzle). The test section used for this test (Fig. 4) consists of two LBE cylindrical tanks connected with a vertical duct where is implemented the Venturi-nozzle. At the beginning of the test, the cover gas (argon) plenums at different pressures created a different LBE level in the two tanks. Subsequently, the plenums were connected by opening a valve, thus provoking the chocking flow of argon from the inside tank to the outside one, and consequently the LBE flow in quasi-steady conditions. The test was performed in a wide range of LBE mass flowrate (50-350 kg/s) and at three different LBE temperatures (200, 300 and 385 °C). The measurement of the Venturi-nozzle differential pressure and the simultaneous evaluation of the LBE mass flowrate by means of the tank level variation made the calibration of the device possible.

For the following test of gas lifting, the Venturi-nozzle was installed in vertical postion between the downcomer and the riser. The loop coinceved like this is hydraulically equivalent to the XADS plant and the expected total pressure drop of 30000 Pa at nominal LBE flowrate (250 kg/s) is guaranteed by means a calibrated flange.

Pre-test calculations for both tests have been performed with the special version of RELAP5/Mod3.2.2β modified for LBE thermal-hydraulic simulation. The data produced during the experimental campaign enable a first step for the code validation, both in monophase flow conditions and in two-phase flow conditions.

Figure 4. **Initial and final configuration of the calibration test section**



Post-test simulation of the CIRCE tests

The RELAP5 models to simulate both CIRCE tests have been developed in order to represent as well as possible the fluid dynamics phenoma investigated. Particular attention have been payed to the nodalization of the experimental loops, because it strongly influences the code predictions. The post-test calculations allow optimizing it and verifying the real capability of the code to predict LBE fluid dynamics.

This approach is particularly evident in the notalization used for the gas lifting test reported in Figure 5. Even if the nodalization has been costructed respecting the geometrical dimensions of all the components, a special attention has been payed to the riser meshing and to the modelling of braches with the LBE free level. In fact, they represent critical points for the two-phase flow simulation and for assessing the real separation of the gas before the LBE downstream flow in the downcomer. Moreover, the Venturi-nozzle meshing has been verified and optimised through the post-test analysis of the experiments for the Venturi-nozzle calibration.

Concerning this first test, the post-test calculations have permitted the correct dimensioning of the valve connecting the cover gas plenums of the two tanks in order to take into account the flow contraction at the chocking junction. In Figure 6 are reported the post-test results for the experiment conducted at 300 °C and with LBE mass flowrate around 200 kg/s. One can notice that, once the pressure evolution in the gas plenums is well described, the LBE mass flowrate is sufficiently calculated by RELAP5. The calculation repeated at different LBE mass flowrates (50, 100, 150, 200, 250, 300 and 350 kg/s) allows constructing the calibration curve of the Venturi-nozzle, which results in very good agreement with the experimental one (see Figure 7). That leads, on one hand, to confirm the code capability to simulate LBE flow in presence of free level, on the other, to conclude that the RELAP5 model of the Venturi-nozzle can be implemented in the overall model of the gas lifting test.

Figure 5. **RELAP5 nodalisation of the gas lifting test section**

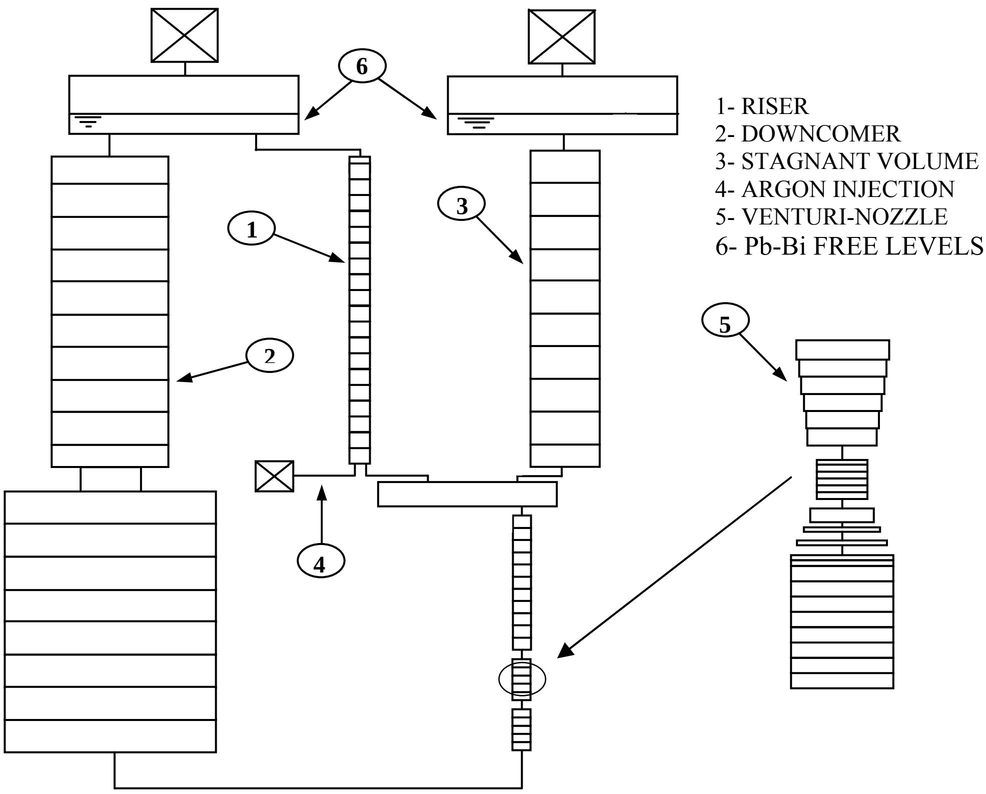


Figure 6. **Numerical and experimental results for Venturi-nozzle calibration test (300 °C and 200 kg/s)**

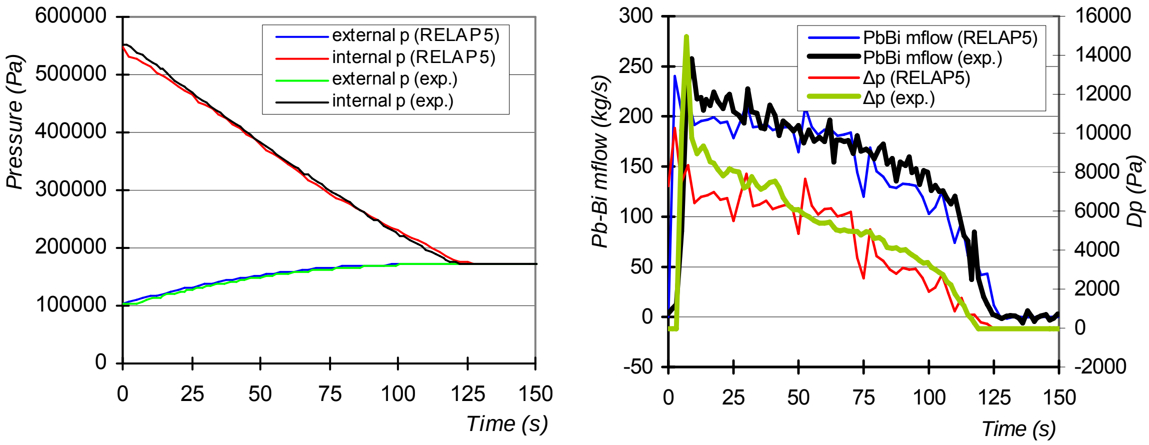
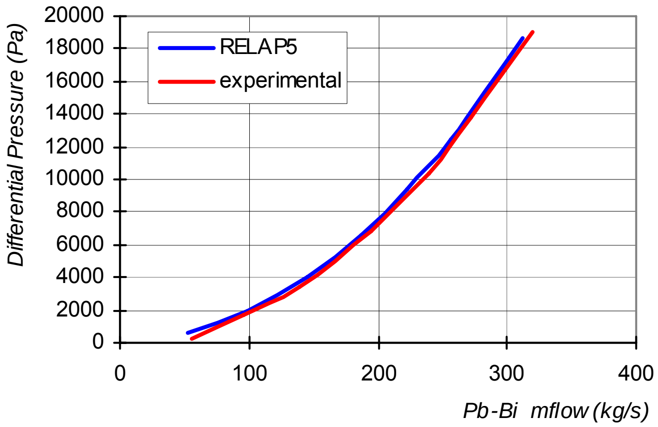


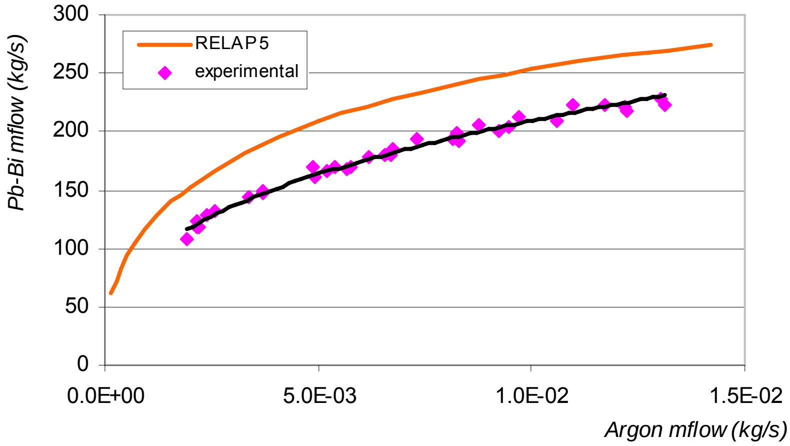
Figure 7. **Comparison between experimental and calculated calibration curve at 300°C**



The main results expected from the second test is the loop characterization in term of Argon mass flowrate injected-LBE mass flowrate entrained as well as the confirmation of the gas separation in the upper plenum. In addition, several pressure taps were implemented along the loop to acquire detailed information on pressure drop total value and distribution, which are essential for the optimisation of the RELAP5 model during the post-test analysis.

For the first experience carried out, the pressure drop measurements were unavailable thus there wasn't evidence about the real separation of the gas. Therefore a preliminary post-test calculation has been performed with the RELAP5 model used for the pre-test calculations. The characteristic curve predicted by RELAP5 is compared with the experimental curve in Fig. 8. From the grapfh one may notice the quasi-constant discrepancy between the LBE mass flowrate calculated by RELAP5 and the experimental data. Due to the lack of information on the real pressure drops in the loop, it is impossible to evaluate the origin of this difference. It may depends whether on the precence of a total pressure drop larger than it was estimated in the pre-test model or, for instance, on a code underestimation of the interphase drag coefficient that brings to overestimate the void fraction in the riser. A previous work [6] has already reported the inadequacy of the Kataoka and Ishii drift flux correlation used by RELAP5 for the calculation of such coefficient; the next phase of the experimental campaign, thanks to the further information on the loop pressure drop, will help to clarify this topic.

Figure 8. **Comparison between experimental data and numerical calculation for the gas lifting test**



Conclusions

This paper has dealt with a first step of the validation path of the RELAP5/Mod3.2.2β special version modified for LBE thermal-hydraulic simulation. This acticity has been performed on the base of the experimental tests conducted on the CHEOPE and CIRCE facilities, located at the ENEA Brasimone centre.

For the first post-test carried out on CHEOPE tests, the RELAP5 code has shown reliable results about the estimation of the LBE side convective heat exchange coefficient, despite the experimental uncertainties.

The interpretation of the experimental campaign conducted on CIRCE has shown a good capability of the RELAP5 code to simulate the single-phase flow of LBE, also in a loop with an interface between LBE and non-condensable gas (calibration test). The lack of information on the real pressure drops in the loop for the gas lifting test prevents in-depth valutations on the effective capability of the code to simulate two-phase flow.

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