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LBE–water interaction in sub-critical reactors: First experimental and modelling results

A. Ciampichetti [a,b,*], P. Agostini [a], G. Benamati [a], G. Bandini [c], D. Pellini [d], N. Forgione [d], F. Oriolo [d], W. Ambrosini [d]

[a] *ENEA FPN-FIS ING, C.R. Brasimone, 40032 Camugnano (Bo), Italy*
[b] *Politecnico di Torino, DENER, Corso Duca Degli Abruzzi 24, 10129 Torino, Italy*
[c] *ENEA FPN-FIS NUC, Via Martiri di Monte Sole 7, 40129 Bologna, Italy*
[d] *Università di Pisa, DIMNP, Via Diotisalvi 2, 56100 Pisa, Italy*

Abstract

This paper concerns the study of the phenomena involved in the interaction between LBE and pressurised water which could occur in some hypothetical accidents in accelerator driven system type reactors. The LIFUS 5 facility was designed and built at ENEA-Brasimone to reproduce this kind of interaction in a wide range of conditions. The first test of the experimental program was carried out injecting water at 70 bar and 235 °C in a reaction vessel containing LBE at 1 bar and 350 °C. A pressurisation up to 80 bar was observed in the test section during the considered transient. The SIMMER III code was used to simulate the performed test. The calculated data agree in a satisfactory way with the experimental results giving confidence in the possibility to use this code for safety analyses of heavy liquid metal cooled reactors.

1. Introduction

In order to extract the thermal power from the main vessel, the design of XT-ADS and EFIT reactors foresees the presence of steam generator modules placed in direct contact with the liquid metal [1,2]. Taking into account the large number of the required cooling tubes and the severe working conditions, the probability of water leakage due to a tube rupture is not negligible. Although the choice of the liquid metal coolant (lead–bismuth or pure lead) excludes the presence of elements having strong chemical reactivity with water, the interaction between hot pressurised water and heavy liquid metals (HLMs) represents an important concern because influences the safety, the design and the maintenance of these reactors. In particular, the interaction leads to propagation of pressures waves which could damage the structures of the main vessel, causing an escalation of the accident. In addition, the steam generated in the interaction could flow through the core, causing reactivity changes.

In the frame of the EUROTRANS Project, ENEA-Brasimone is studying the interaction between LBE and water caused by a cooling tube rupture inside the steam generator of XT-ADS [3,4]. The work includes an experimental program, using the LIFUS 5 facility, and a related modelling activity. The first test of the experimental program was successfully carried out injecting pressurised water at 70 bar in the reaction vessel of LIFUS 5 containing LBE at 350 °C.

The SIMMER III code has been chosen as the reference code to simulate the experiments. It is a two-dimensional, three velocity-fields, multicomponent, multiphase, Eulerian fluid-dynamics code coupled with a neutron kinetics model [5,6]. It is a flexible tool which can deal with various problems consistent with his modelling framework such as

* Corresponding author. Address: ENEA FPN-FIS ING, C.R. Brasimone, 40032 Camugnano (Bo), Italy. Tel.: +39 0534 801277; fax: +39 0534 801225.
E-mail address: andrea.ciampichetti@brasimone.enea.it (A. Ciampichetti).

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safety analyses in advanced fast reactors up to the new accelerator driven systems [7,8], steam explosions, fuel coolant interaction problems [9–11] and, more generally, multiphase flow problems [12–14].

The aim of the present study is to examine the thermo-hydraulic phenomena involved in the interaction and to verify the capabilities of the SIMMER III code to reproduce this phenomenology.

2. Experimental activity

2.1. Description of LIFUS 5 facility

Fig. 1 shows a schematic P&I of LIFUS 5 plant. It mainly consists of:

- A reaction vessel S1 where the interaction between LBE and water takes place. Its volume is 0.1 m^3 and it is filled with the liquid metal alloy. S1 contains a mock-up of U shaped cooling tubes made by 10 tubes of 16.5 mm of external diameter and about 0.7 m in length.

This pipe bundle is located in one of the four sectors in which the vessel has been divided by two AISI 316 plates. The two plates are welded on the top flange and develop in the vertical direction up to 5 cm from the bottom of the vessel so that the four sectors are communicating each other. On one side, the introduction of the tube bundle mock-up has been done in order to evaluate if an enhanced mixing between water and eutectic alloy may produce relevant interaction effects. On the other side, on the plates and the tube bundle are placed different thermocouples useful to detect the evolution of the water jet and interaction zone.

On the bottom of S1, in the sector containing the tube bundle, the water injection device is placed. It is constituted by an orifice and a protective cap or membrane that is broken by the water jet at the beginning of the injection phase.

- A pressurised water vessel S2 containing the water that has to be injected in S1. During the test the pressure in S2 is kept fixed by connecting directly this vessel to an Ar bottle charged at the test pressure.
- A safety vessel S3 which allows to collect the gaseous and aerosol reaction products from S1 and S5 at the end of the test.
- A storage tank S4 for melting the liquid metal and filling the reaction vessel S1 and, in case, a part of the expansion vessel S5.

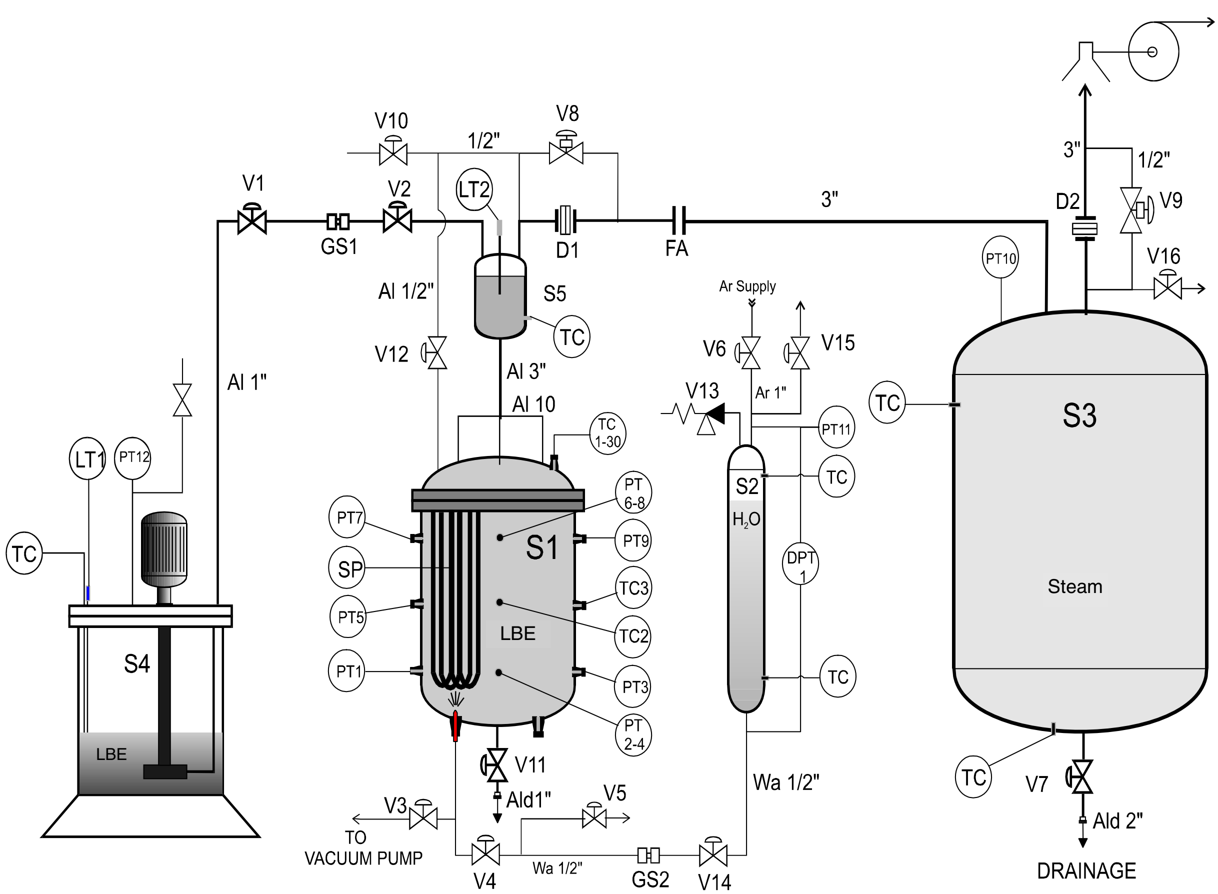

Fig. 1. P&I of LIFUS 5 plant.

- An expansion vessel S5 connected with the reaction tank through four pipes, one per sector. Depending on its filling level, the compressibility of the whole volume can be varied, giving the possibility of evaluating the different responses of the system in terms of pressure evolution.

The instrumentation adopted for Test n.1 is described below.

- Seven pressure transducers have been placed in S1, two in the tube bundle sector in different vertical positions and the remaining five in the three other sectors, and one in S5. All these sensors are located on the reaction and expansion vessel wall. One pressure transducer was placed on the water pipe (Wa ½″) before its entry in S1.

Water-cooled high precision piezometric pressure transducers have been used. They have time constants in the order of 0.1 ms able to follow the rapid pressure evolution in the system under a time scale of a few seconds.

- 18 K-type quick response thermocouples have been placed into the tube bundle sector of S1 and fixed on the tubes at different height. Three thermocouples per tube have been placed, spaced of 20 cm each other in the vertical direction starting from 50 mm above the lowest point of U-tubes. A socket thermocouple with a low response time is also placed in S5.

A fast data acquisition system with a dedicated software in LABVIEW environment acquires the main test parameters during all the phases of the experiment.

A detailed description of LIFUS 5 and of the operational phases during the test is reported in Ref. [3].

2.2. Operating conditions and main results

A set of preliminary operating conditions, and in particular a water injection pressure of 70 bar, were selected at the beginning of the EUROTRANS project in order to arrange the facility for Test n.1. They were chosen taking into account the first indications about the working parameters of XT-ADS [2].

The operating conditions adopted for Test n.1 are:

Thermodynamic parameters

- Liquid metal temperature: 350 °C.
- Initial pressure on the liquid metal free level: 1 bar.

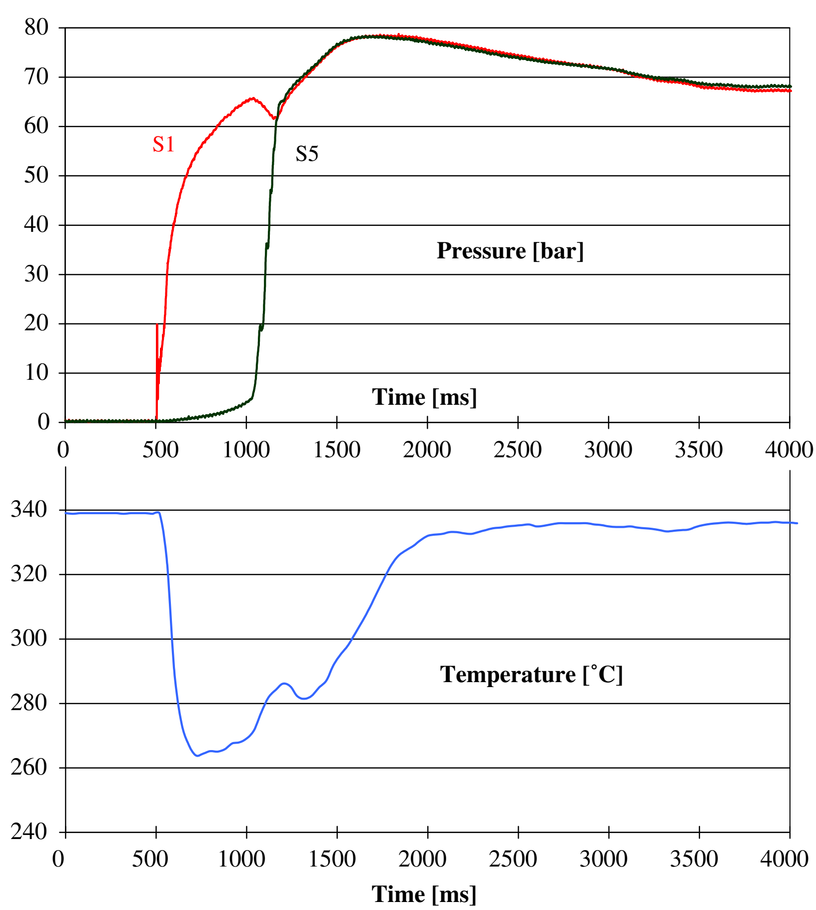

Fig. 2. Pressure evolution in the reaction (S1) and expansion (S5) vessel and temperature evolution near the water injector.

- Water injection pressure: 70 bar.
- Water temperature: 235 °C (subcooling of 50 °C).

Reaction system

- Free volume in the expansion vessel: 5 l.
- Liquid metal volume: 105 l.

Injection system

- Duration of the test (V14 open): 10 s.
- Diameter of the injection device (water orifice): 4 mm.
- Water injector device penetration in the melt: 80 mm.

Test n.1 was successfully carried out on March 2006. No problems occurred during all the phases of the experiment and the data acquisition system worked correctly.

In Fig. 2 the pressure evolution detected in the reaction and expansion vessel is shown. It has to be pointed out that all the pressure transducers placed in the reaction vessel detected exactly the same evolution over the time. This is of course correct taking into account that the pressure waves propagate at sound velocity in the liquid metal (about 1700 m/s) and the distance among different sensors is covered in a time lower than the sampling one.

Looking at the pressure evolution it is possible to identify four phases of interaction. During the first phase the expanding jet forces the liquid metal up into the expansion tubes and into the other sectors of the reaction vessel (S1). This phase is characterised by a high pressurisation rate (0.13 bar/ms) due to the initial high water injection rate. The first phase finishes after 500 ms when the pressure reaches a maximum of about 65 bar.

The second phase is characterised by pressure decreases in all sectors of the reaction vessel because of the free flow of steam into the expansion vessel (S5) which is not balanced by an equivalent injection of water. As a matter of fact, the pressure decrease in the reaction vessel takes place when the pressurisation of the expansion vessel starts. When the pressures in the two tanks are balanced the following pressure evolutions in S1 and S5 are joined each other. This second phase lasts about 150 ms.

When the free volume of the expansion vessel has been pressurised the third phase starts. In this one, there is a further pressure increase in both reaction and expansion vessels due to the further water injection and vaporization. This phase lasts about 500 ms until the maximum value of 78 bar is reached and is characterised by a lower pressurisation rate (0.03 bar/ms) with respect to the first phase. Finally, there is the *fourth phase* during which the pressure decreases approaching the injection value of 70 bar.

It is useful to point out that the starting point for the test ($t = 0$ in the graph of the results, Fig. 2) corresponds to the opening signal given to V14 valve. After that, considering the opening of the valve and the time necessary to reach the injector and to rupture the protective cap, about 500 ms are needed to start the water injection in the reaction vessel.

The water injection in S1 is also highlighted in Fig. 2, where the temperature evolution detected by the thermocouple placed just in front of the water injector is reported together with the pressure evolution in the system. As it is possible to see, the thermocouple detects an evident cooling during the water injection time and then goes back to almost the initial value when pressure in S1 overcame 70 bar and, therefore, the injection is stopped.

As far as the general temperature evolution in the system, considering that LBE is practically inert with respect water in the operating conditions of our experiment, a quite considerable cooling was detected along the tube bundle due to the difference between the initial liquid metal temperature (350 °C) and the water temperature (235 °C). The amount of such a cooling depends on the considered position with respect the water injection device. In particular, the lowest temperature (263 °C) was detected at the bottom level of the central part of the tube bundle, while the lower temperature reached in the peripheral part (290 °C) was detected at the top level. The thermocouple placed in the expansion vessel showed during the test a temperature decrease of about 20 °C.

3. Numerical simulation

3.1. Computational model

The overall computational domain for SIMMER (see Fig. 3) is subdivided into 10 radial and 26 axial meshes. The facility components which have been addressed in the domain are: the interaction vessel S1, the expansion

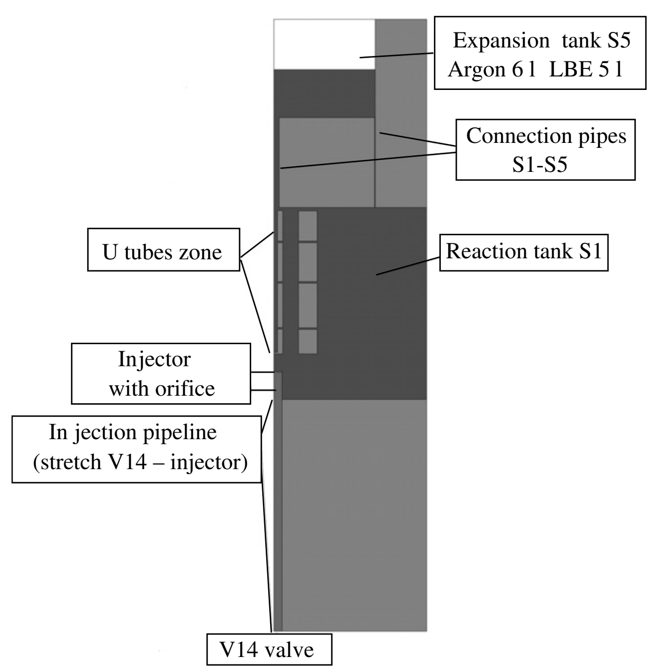

Fig. 3. LIFUS 5 computational domain.

vessel S5, the connection tubes between S1 and S5 and the water injection pipeline between the V14 valve and the injector device.

In the S1 tank, the U-tubes bundle and separating plates are represented by 10 'no calculation' regions. Needless to say, the strong asymmetry due to U-tube shape and position cannot be adequately accounted for. For this reason, U-tubes are simulated by annular elements assuming the following simplifications:

– the overall volume is conserved;
– the tubes are simulated by two groups of annuli, which are axially divided into four parts;
– the annuli are coaxial with the injector device;
– a little circular plate over the injection device avoids the LBE going up directly to the connection tube between S1 and S5.

The model of the connection tubes between S1 and S5 consists of a central tube and an annular region placed at the left end of the S5 tank. These simplifications are based on the assumption that the overall volume of the four tubes is conserved even though the S1 subdivision into four parts has been removed.

The S5 tank is represented by eight radial cells (from 1 to 8) and 4 axial cells (from 22 to 26). Inside it, the argon

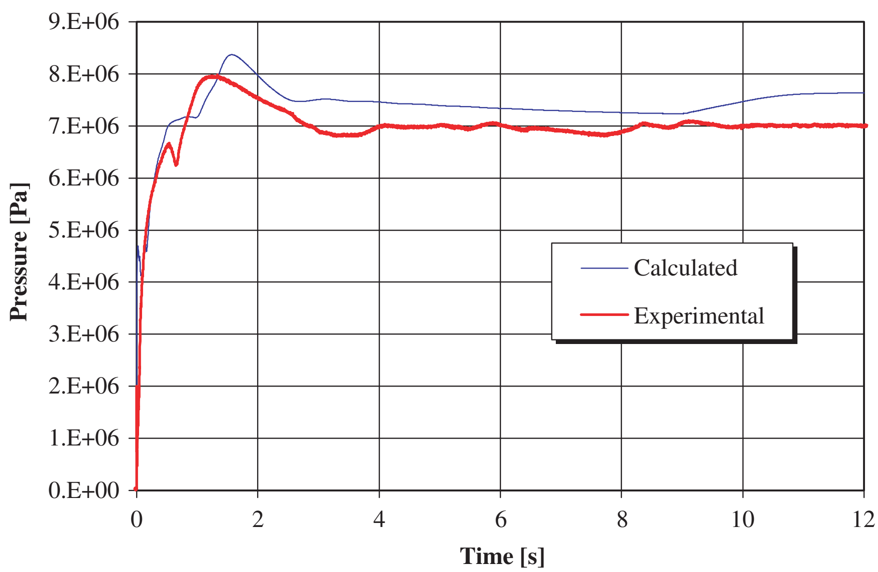

Fig. 4. Comparison between experimental and calculated pressure in S1.

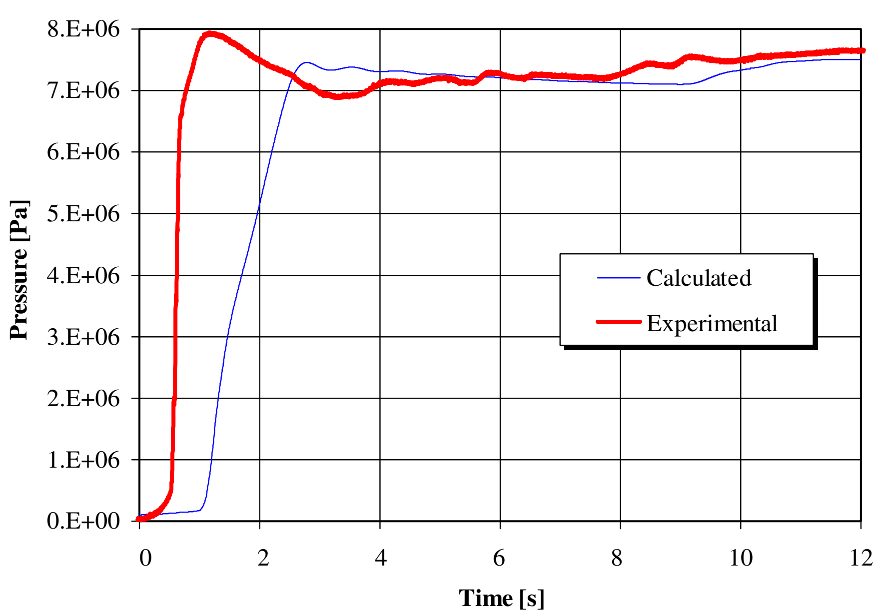

Fig. 5. Comparison between experimental and calculated pressure in S5.

region is about 6 l, in order to account the mass of argon inside the 3″ tube which connects S5 with the rupture disk D1 (see Fig. 3).

3.2. Obtained results

In Fig. 4 the comparison between the experimental and calculated pressure trends in the interaction vessel S1 is reported. The two trends are in quite good agreement, even though the SIMMER III code tends to overestimate the experimental pressure slightly. The calculated pressure trend highlights a little plateau in place of the first peak exhibited by the experimental trend and a little delay of the second peak.

The comparison between calculated and experimental pressure in S5 tank is reported in Fig. 5. In the short term (about 4 s), the two trends are different in slopes and timing. In particular, the calculated pressure rise occurs more slowly than what observed experimentally. This is due to the geometrical features of the test section: in fact, in the experiment the interaction between LBE and water occurs in a quarter of volume while in the SIMMER III model it occurs in the overall S1 vessel, thus involving a greater volume; therefore, the observed delay is mainly due to the greatest fluid inertia present in the model. After the first 4 s, the two trends are anyway in good agreement.

4. Conclusions

Test n.1 was successfully carried out injecting subcooled water at 70 bar in the reaction vessel of LIFUS 5 containing LBE at 350 °C. Even if the geometrical conditions and in particular the compressibility of the system are completely different with respect to the main vessel of XT-ADS or EFIT, the results are important because provide the first information about this kind of interaction and allow to prove the capability of SIMMER III code to reproduce the phenomenology of the LBE–water interaction.

A fast pressurisation of the system, up to a value (78 bar) higher than the water injection pressure (70 bar), has been detected during the test.

Concerning the temperature evolution a quite considerable cooling was detected in the reaction vessel due to the difference between the initial liquid metal temperature (350 °C) and the water temperature (235 °C). The amount of such a cooling depends on the considered position in the system with respect to the water injection device. The lowest detected temperature was 263 °C.

The simulations have highlighted a quite good agreement between the experimental and the calculated results, especially for what concerns the pressure in S1 tank. A slight difference between the experimental and the calculated values of pressure in S5 is also observed only in the short term (4 s). This is due to the geometrical features of the calculation domain, in particular owing to the presence of the S1–S5 connection.

The development of the activity foresees some modifications on the facility, in order to better reproduce a liquid metal pool representative of the reactor vessel, and a new test that will be carried at low pressure (6 bar). Moreover, some improvements in the SIMMER III model of the LIFUS 5 facility are in progress, in order to better reproduce the experimental trends.

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