Experimental and RELAP5-3D results on IELLLO (Integrated European Lead Lithium LOop) operation

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The experimental facility IELLLO (Integrated European Lead Lithium LOop) was designed and installed at the ENEA Brasimone Research Centre to support the design of the HCLL TBM.

This work presents the results of the experimental campaign carried out within the framework of F4E-FPA-372 and which had three main objectives. First, to produce new experimental data for flowing LLE (Lead-Lithium Eutectic) for an analysis of the loop and the characterization of its main components. Then, to evaluate performances of commercial instrumentation as available instrumentation is not designed for use in LLE. Lastly, to use the data for validation of the model developed with the system code RELAP5-3D. The data collected could prove helpful to analyze the behavior of the LLE loop of ITER and DEMO in accidental conditions.

The results show that the regenerative countercurrent heat exchanger has an efficiency ranging from 70 to 85 %, mainly depending on the LLE mass flow rate. It was verified that the air cooler has the capability to keep the cold part of the loop at 623 K, even in the most demanding situation (700 rpm and maximum temperature of the hot part). The instrumentation tested showed good accuracy, with the exception of the turbine flow meter. Nevertheless, specific limitations in the upper operative temperatures were found for the LLE direct contact pressure transducer. RELAP5-3D simulations fit very well the associated experimental results achieved.

Keywords: TBM, ITER, IELLLO, Lead-Lithium-Eutectic, RELAP5-3D

1. Introduction

The present work was carried out within the framework of the F4E-FPA-372-SG01 contract, which aims to support R&D activities for the conceptual and preliminary design of the European test blanket systems. To deal with the development of Breeding Blankets for future fusion reactors, ENEA designed and built a lead lithium loop, named IELLLO.

This activity was conceived to analyze the behavior of the facility and its main components. Some of these components are candidates as main or back-up solutions for the LLE loop of the HCLL TBS [1]. Moreover, the ability to run a large LLE loop, together with the lessons learned, will be useful for the design and operation of the final LLE loop of ITER.

Commercial measurement devices are not designed to work with LLE. Therefore, the second aim of this activity was to test new instrumentation for LLE. Many experimental analyses have been conducted on hydrogen sensors in LLE (e.g., [2]), while reliable devices to control key operative parameters, such as pressure, flow rate and level, are still under development. Previous analyses on flow meters and pressure transducers were performed by [3].

The third objective was to assess the capabilities of RELAP5-3D system code to work with LLE, in parallel with the work on He performed by Barone et al. [4]. RELAP5-3D [5] is a thermal-hydraulic system code developed at the Idaho National Laboratory on the advice of the US Department of Energy. It derives from RELAP5/MOD3, from which it distinguishes for a fully integrated, multi-dimensional thermal- hydraulic and kinetic modelling capability. It also includes the working fluids (lead-bismuth, lead-lithium, helium, …) and the magneto-hydrodynamic model that were introduced by the ATHENA configuration of the code.

2. Description of the facility

With respect to the loop described in [6], IELLLO underwent a few modifications in 2015. In particular, the permanent magnet pump substituted the mechanical one and the expansion tank S02 was removed. The new configuration of the loop is shown in Fig. 1.

IELLLO is an eight-shaped loop with a temperature ranging from 623 K in the cold part up to 823 K in the hot part. The loop is loaded by means of an increasing pressure of Argon in the storage tank S01, which is located in the lowest part of the facility (as shown by the P&I in Fig. 1). After the loading, S01 is isolated by closing the EPV04 valve.

The LLE is circulated by the permanent magnet pump located above the storage tank S01 and increases its temperature going through the economizer E01, which is a counter-current pipe in pipe regenerative heat exchanger. Then the alloy can pass through the 40 kW electrical heater S05 or it can maintain its temperature constant by means of a bypass line. Regardless of the path chosen for the operation, the LLE passes through the test section and it cools down in the economizer and

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in the air cooler E02, before returning to the permanent magnet pump.

The buffer tank S04 with a volume of 0.45 m^3 has the task to compensate the volumetric changes of the LLE and to remove any trace of inert gas from the loop. As IELLLO can be coupled with the helium facility HEFUS-3 [7], the expansion tank S03 was connected both to the test section inlet and outlet by means of two rupture disks for each side to prevent the dangerous consequences of a LOCA.

The pump can work at different speeds and, together with a dedicated bypass, can provide a maximum mass flow rate of 2.41 kg/s, when the bypass is completely closed.

The piping is made of AISI316L Sch. 40 with a nominal diameter of 1", with the exception of the test Section inlet and outlet (1-1/2" Sch. 80). The piping is equipped with heating cables, thermal insulating concrete with a thickness ranging from 6 to 12 cm and aluminum sheets.

IELLLO is equipped with a vortex flow meter (capable to measure from 0.93 to 2.49 kg/s), a mini-turbine flow meter (from 0.2 to 1.0 kg/s) and an absolute pressure transducer supplied by GEFRAN. Level sensors and cover gas pressure gauges are installed in all the tanks.

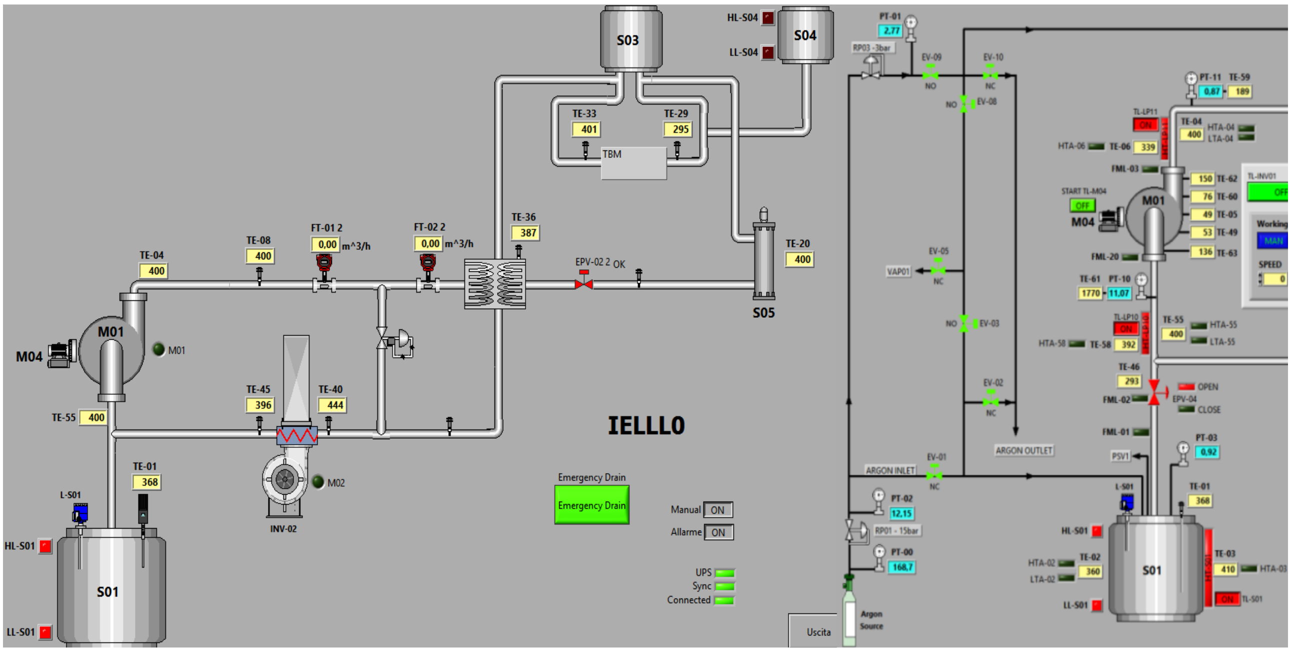

Fig. 1. Layout of IELLLO (left) and detail of the lower part of the loop (right).

3. Nodalization

The one-dimensional RELAP5-3D nodalization simulates the entire IELLLO loop (Fig. 2). The hydraulic part of the nodalization has 283 nodes and 292 junctions. All hydraulic volumes have a length between 0.15 and 0.6 m to correctly simulate the characteristics and the geometry of the loop but also not to lengthen the calculation time. The axial heat structures are 360, with 5500 mesh points overall. The passive heat structures were specifically modelled by implementing the properties of the thermal concrete and of the stainless steel. In this way it is possible to simulate the heat losses toward the environment. The radial mesh points have a dimension between 2 and 10 mm.

The economizer was represented as two parallel pipes. These pipes are hydraulically separated, but they are coupled by the heat structures.

The expansion of the LLE is allowed by means of a time dependent volume that simulates the action of the buffer tank and it is located above it. The buffer tank was divided in two pipes and a branch to avoid convergence concerns due to the simultaneous presence of non-condensable gas and LLE in the same volumes. The pump was simulated by means of a time dependent junction. The developed mass flow rate is set up according to the experimental data. Table 1 shows the mass flow rates as a function of the pump speed. The reported values were converted from the Vortex flow rate in m^3/h to kg/s by means of the density correlation proposed by Stankus et al. [8].

Table 1. Mass flow rates as a function of pump speed.

Pump speed [rpm]	Mass flow rate [kg/s]	Pump speed [rpm]	Mass flow rate [kg/s]
100	1.28	450	2.06
150	1.45	500	2.15
200	1.55	550	2.20
250	1.69	600	2.28
300	1.80	650	2.33
350	1.88	700	2.41
400	1.98		

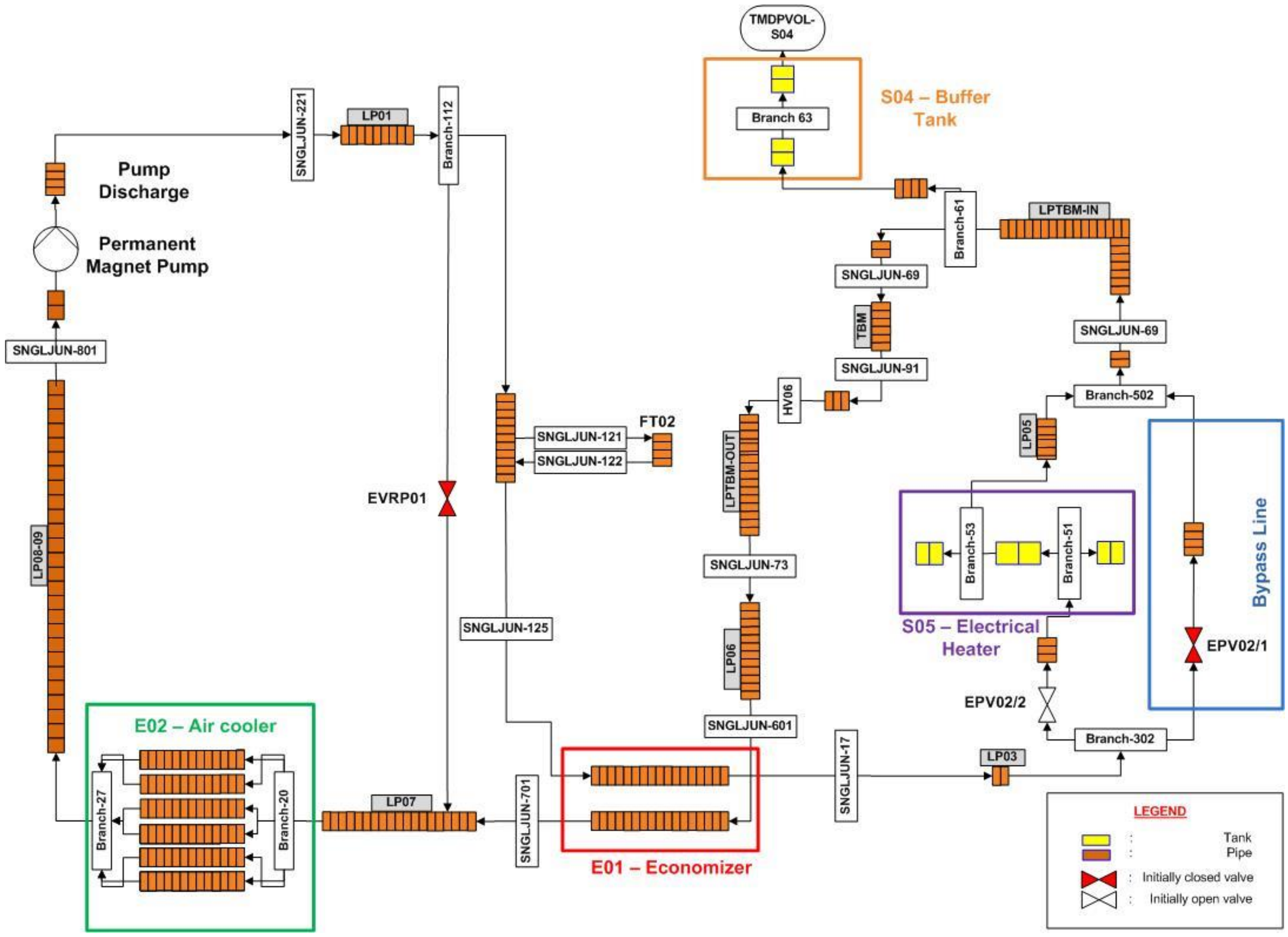

Fig. 2. IELLLO Nodalization.

4. Experimental and numerical activity

4.1 Experimental results vs RELAP5-3D simulation

The data from 77 experimental tests are summarized hereafter. The tests are divided in 6 groups in which the maximum temperature of the loop is varied (673, 723, 753, 773, 788 and 813 K). In each group, the pump speed is varied in steps of 50 rpm from 100 up to 700 rpm, except for the 788 and 813 K groups in which 100 rpm steps were adopted.

Fig. 3 shows the efficiency of the economizer evaluated from the experimental data (circles) and calculated by RELAP5-3D (stars). The tests revealed performances of the LLE heat exchanger higher than those expected after the preliminary theoretical evaluations. In details, measured efficiencies are from 5% to 8% higher than the expected ones. The higher efficiency for lower mass flow rates is intriguing for the ITER relevant mass flow rates which are smaller than the ones that we could analyze (0.2 - 1.0 kg/s), as the mini-turbine flow meter did not worked since the very beginning phase of the experiments. Moreover, the efficiency tends to decrease as the temperature difference across the economizer increases. As far as the numerical simulations are concerned, RELAP5-3D tends to slightly overestimate the efficiency at high flow rates, with an average discrepancy of 2.67 percentage points and a unique maximum discrepancy of 9.90 percentage points.

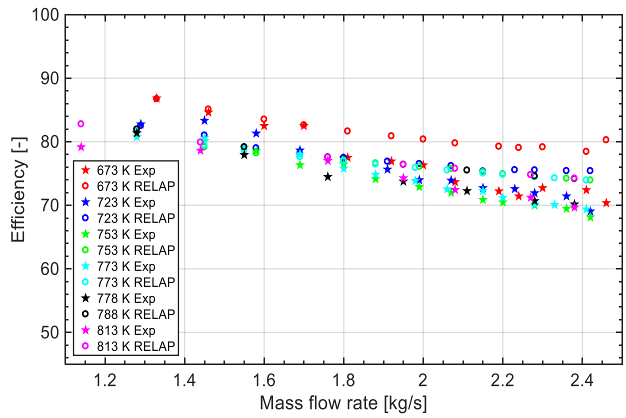

Fig. 3. Efficiency of the economizer as a function of mass flow rate and temperature.

Fig. 4 shows the temperature difference in the LLE across the air cooler. The air cooler can be operated in natural convection, simply opening its shutter, and in forced convection by switching on the blower. Fig. 4 refers to the natural convection mode. As the air cooler was never tested before, experiments were performed only above 753 K to avoid the risk of freezing in the pipes. Similarly to the economizer, the performances of the air cooler in natural convection mode are higher for low mass flow rates. In spite of that, a ΔT of about 70 K at the lowest pump rotational speed can be considered an interesting value, even in prevision of the ITER relevant tests, which will be performed at lower mass flow rates. RELAP5-3D shows a tendency to underestimate the ΔT produced by the air cooler with an average discrepancy of 2.95 K, with three exceptions at 1.28 kg/s where the discrepancy is about 20 K.

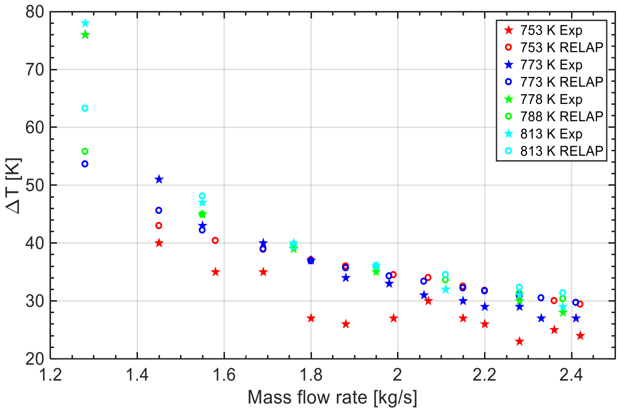

Fig. 4. Air cooler performances as a function of mass flow rate and temperature.

A few tests in forced convection were performed at high values of pump rotational speed (650 and 700 rpm) by setting a temperature at the outlet section of the air cooler. Fig. 5 shows the temperature trends as a function of time for one of the tests at 700 rpm. In this case the outlet temperature was set to 623 K. About 1100 s are sufficient to reach the set point conditions. It can be also observed that the air cooler is very effective at cooling down the loop, as the temperature difference between the inlet and the outlet remains approximately constant during the transient. Similar results were obtained in the other tests at 700 rpm, while a slightly lower time is needed to reach the set point in the cases at 650 rpm.

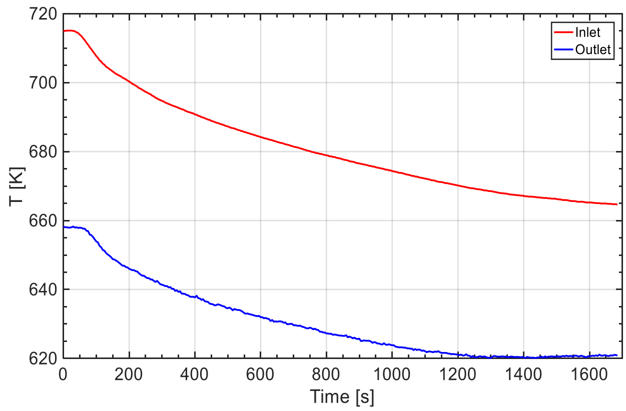

Fig. 5. Temperatures at the inlet and at the outlet sections of the air cooler.

4.2 Instrumentation performances

This first experimental campaign had the objective to evaluate the performances not only of the main components, but also of the commercial instrumentation installed on the loop. Hereafter, the results of the analyses on the Vortex mass flow meter and on the GEFRAN pressure transducer are presented.

The Vortex mass flow meter was firstly calibrated for water and, afterwards, adapted for lead lithium. The aim of the tests was to check if the mass flow meter correctly gauges the LLE mass flow rate in the loop. To qualify the mass flow meter the real mass flow rate is calculated from the power exchanged in the electrical heater by means of the equation:

$$\dot{m} = \frac{P_{S05} - P_{diss}}{c_p (T_{out} - T_{in})} \quad (1)$$

where P_{S05} is the power supplied by the electrical heater, P_{diss} is the power dissipated, T_{out} and T_{in} are the temperatures measured by the thermocouples at the outlet (TE22) and at the inlet (TE18) of the heater. Values of c_p used in the calculations were taken from the work by Schulz [9]. During the experiments the proportional valve EVRP01 was kept closed to drive all the mass flow rate in the electrical heater. LLE mass flow rate is regulated acting on the pump rotational speed and it was kept constant for one hour in each test. The experiments started from 100 rpm, which corresponds to the lower limit of the flow meter range of measure. The obtained results are shown in Fig. 6**Errore. L'origine riferimento non è stata trovata.**. It can be observed that the calculated values lie in a region with a width of 10 % of the experimental values.

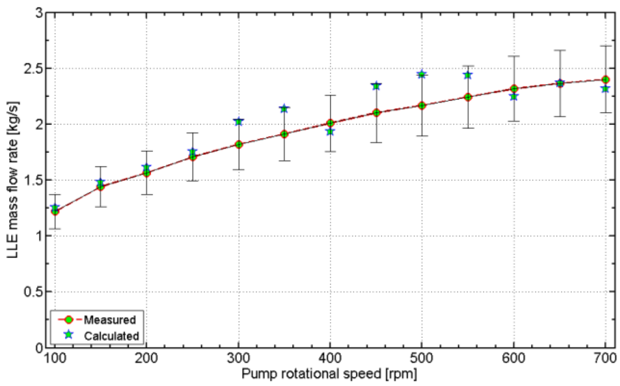

Fig. 6. Results of the flow meter qualification tests.

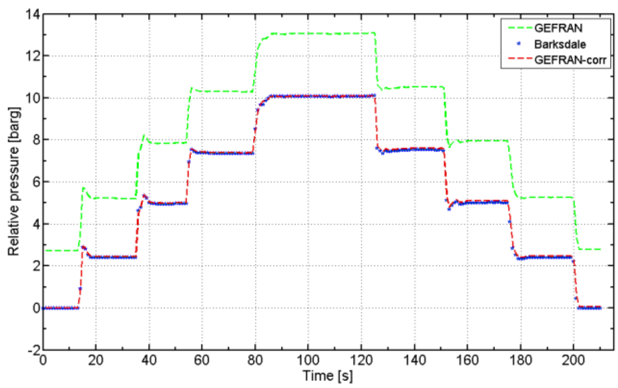

Fig. 7. Measured and corrected pressures at 673 K.

A special device was used to qualify the GEFRAN pressure transducer for lead eutectic alloys. The device contains an eutectic alloy of LLE equipped with heating cables and with an argon injection system in order to control both the temperature and the pressure. A Barksdale transducer is installed to measure the pressure in the gas. Firstly, a test was performed to ensure the seat tightness. Then, the temperature of the facility was raised to 523 K and LLE was loaded. Afterwards, the pressure was gradually increased up to 10 bar and subsequently decreased down to the room pressure. The procedure was also repeated for different temperatures.

As a result, the following equation was determined to correct the measured pressure and to obtain the real one:

$$P_r = 0.975 \cdot \left(P_G - 0.79 - P_h - \frac{T_G}{184 + 0.1 \cdot T_G} \right) \quad (2)$$

where P_r, P_G and P_h are the real pressure, the pressure of the Gefran transducer and the hydrostatic pressure (due to the difference in position between the two transducers, about 0.315 bar), T_G is the temperature measured by the thermocouple of the transducer. After the correction, the pressure measured by GEFRAN transducer follows the one by Barksdale transducer (Fig. 7). The maximum error is around 100 mbar, while the standard deviation lies between 25 and 40 mbar. These values correspond to a maximum error of 0.5 % on the FSO for a 0-20 bar transducer. LLE pressure transducers revealed a good accuracy for temperatures between 523 K and 673 K. The results suggest possible applications for absolute pressures in a LLE system, while the high error will prevent to use the GEFRAN transducer for pressure drops evaluation. A flanged connection was agreed between ENEA and GEFRAN to avoid leakages.

5. Conclusions and future perspectives

In the present work the behavior of the main components of the loop was analyzed, together with the loop itself. A pressure transducer, a regenerative counter-current heat exchanger, a permanent magnet pumping system, a Vortex mass flow meter and an air cooler were tested for the use in LLE systems.

The system code RELAP5-3D was tested against the experimental data obtained.

Further experiments will be carried out at lower mass flow rates, after the replacement of the mini-turbine flow meter. The pressure head of the pump and the pressure drops of the main components will be also measured after the installation of differential pressure transducers. The validation of RELAP5-3D will go on together with the experimental analysis.

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