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Testing and qualification of CIRCE instrumentation based on bubble tubes

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Abstract

The paper is focused on the development and the qualification of the instrumentation suitable for the level and the differential pressure measurements in the experimental facility CIRCE. This large-scale facility is installed at the ENEA Brasimone Centre for studying the fluid-dynamic and operating behavior of ADS reactor plants. This a rather challenging objective since the facility adopts the molten lead bismuth eutectic (LBE) alloy as a coolant and, at present, instrumentation qualified for operating under such conditions is scarce or does not exist. Bubble tubes have been installed in CIRCE to transfer pressure signals from the LBE to differential pressure cells operating with gas at room temperature. The bubble tube is a simple measuring device, but its use in LBE must be carefully assessed. Therefore, preliminary tests of bubble tubes in representative conditions have been carried out in a smaller test section. Experimental tests were performed at several temperatures, with LBE in stagnant conditions. The results obtained in these tests, aiming at checking the performance of the bubble tubes adopted in measuring pressure, differential pressure and level in the CIRCE facility, are discussed here. The obtained information will allow to calibrate the related measuring systems and to verify the accuracy and repeatability of the measurements, as a function of the injected gas flow rate, the tube diameter and the geometry of the tube exit section.

1. Introduction

Presently proposed Accelerator Driven Systems (ADS) are subcritical nuclear reactors in which the fission reaction chain is maintained in steady conditions by the injection of neutrons generated in a target material through the spallation reaction by a high energy proton beam produced in an external accelerator. The neutronic characteristics of the reactor are conceived as to efficiently incinerate long lived fission product by transmutation, in order to reduce the need for very long term geological disposal of nuclear wastes produced in the nuclear reactor fuel cycle [1–3].

The lead bismuth eutectic (LBE) alloy is proposed as one of the most promising coolants for the reactor.

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Natural circulation as well as gas-injection enhanced circulation will be adopted to assure the required core cooling in the different operating conditions. In particular, the injection of argon in the riser channels above the core will increase so efficiently the circulation flow in the reactor as to safely remove the heat produced by the fission reaction chain.

An extensive experimental research program has been undertaken in order to investigate the phenomena at the basis of ADS reactor operation. CIRCE (Circulation Experiment) [4,5] is a large-scale test facility designed for studying key operating principles of the 80 MW experimental Accelerator Driven System (XADS) currently being designed in Italy [6]. The experimental activities planned to be performed by this facility will investigate the hydraulic, chemical and mechanical issues related to the development of the LBE-cooled XADS in a pool configuration.

In the CIRCE plant, tubes injecting argon below the molten metal level, in short 'bubble tubes', have been installed to transfer pressure signals from the LBE alloy to differential pressure cells operating with gas at room temperature. In particular, the Level Measurement System and the Differential Pressure Measurement System make use of the above instruments to perform their tasks. This measuring system has different advantages:

- it includes only a few components, which are all of standard design;
- since there is no material included to separate the gas region from the molten metal alloy, there is no additional problem of compatibility with the coolant;
- the pressure transducers are located sufficiently apart from the molten coolant, as to be preserved from any possible thermal or chemical interaction with it.

On the other hand, possible drawbacks of this technique may come from its intrusive character, mainly consequent to the injection of argon in the coolant, which might disturb the flow, and from possible delays in the transmission of the pressure signals along the injection gas lines.

In the aim to investigate the characteristics of such devices and to optimise their configuration, tests were first carried out in an auxiliary experimental facility; the obtained experimental data are useful to verify and calibrate these measurement systems, in view of their use in CIRCE's first experimental campaign, devoted to calibrating a Venturi flow meter adopted for measuring flow rate during the gas-injection enhanced circulation tests.

In this paper, the main characteristics of the experimental apparatus are presented and the obtained experimental results are discussed, in order to provide the necessary background to understand and correctly process the measurement signals from the CIRCE experimental tests.

2. Experimental facility

The experimental apparatus adopted in these tests [7] consists of a cylindrical inner vessel made of AISI 304 stainless steel, filled with molten LBE; this is in turn immersed in diathermic oil contained in an outer carbon steel vessel. The oil is heated by electric heaters located at the bottom of the outer vessel. The oil heats up and melts the lead–bismuth eutectic in the inner vessel, then keeping it at constant temperature during the test.

The apparatus includes the instrumentation required for measuring pressure, level and temperature (see Table 1 and Fig. 1), and is connected to the argon gas feed

Table 1
Bubble tubes installed on the experimental apparatus

Bubble tube ID	Inner diameter (mm)	Use	Characteristics
P00	6	Cover gas pressure – reference value to perform level measurements	Horizontal pipe
PV1	8	Level measurement	Vertical pipe
PV2	4	Level measurement	Vertical pipe
P11, P12, P13, P14	18	Differential pressure measurement	Horizontal pipe – pipe ends flush with the wall of the inner vessel
P21, P22, P23, P24	6	Differential pressure measurement	Horizontal pipe – pipe ends flush with the wall of the inner vessel
P31, P32, P33	8	Differential pressure measurement	Horizontal pipe – pipe stick out 30 mm into the inner vessel
P41, P42, P43	4	Differential pressure measurement	Horizontal pipe – pipe stick out 30 mm into the inner vessel
P51, P52, P53	4	Differential pressure measurement	Horizontal pipe – pipe ends flush with the wall of the inner vessel

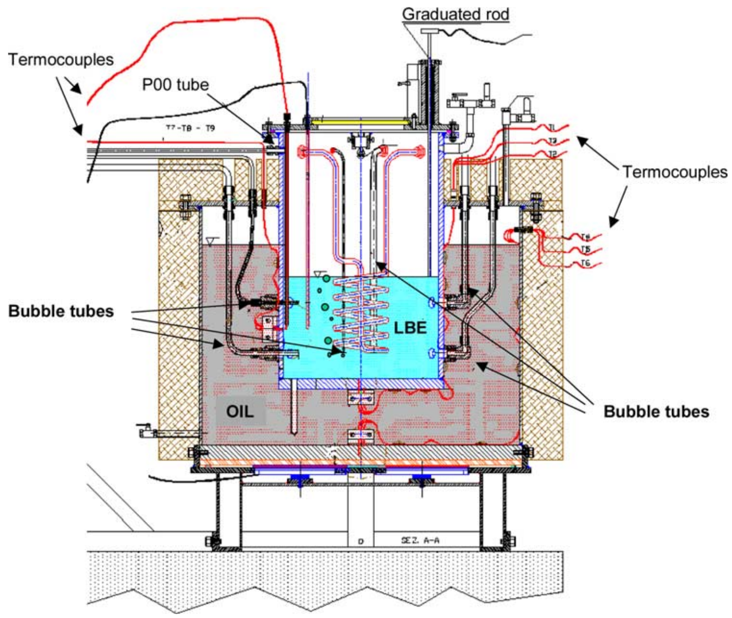

Fig. 1. Assembly drawing of the apparatus.

system, including the gas flow meters [7]. The data acquisition system is the same adopted for the CIRCE plant and includes all the equipments required to transmit, display and store the signals generated by the instrumentation.

Both 'level measurement tests' and 'differential pressure tests' were performed in stagnant LBE, operating under isothermal conditions at temperatures in the range from 160 to 260 °C and using different argon injection flow rates, in the range 0.02–0.92 l/h [8].

Differential pressure tests were carried out using five different types of horizontal gas injection tubes, with different diameters and end nozzle shapes, as shown in Fig. 2. Type 1, consisting of a 18 mm diameter tube, is representative of the CIRCE differential pressure measuring devices, whilst type 2, consisting of a 6 mm diameter tube, is representative of the arrangement adopted in the CIRCE Venturi flow meter, that will be calibrated during the first experimental campaign in the large-scale facility. The other types of injector tubes shown in Fig. 2 represent alternative solutions whose study is considered of possible interest.

3. Results and discussion

3.1. Level tests

Level measurements were obtained on the basis of the differential pressure Δp between the gas flowing through a vertical injection tube and the cover gas, measured by means of a differential pressure meter (DPM) [9]. The differential pressure is then converted to a level by using the relationship:

$$h = \frac{\Delta p}{\rho g}, \tag{1}$$

where g is the gravitational acceleration and ρ is the density of the molten alloy at the test temperature, evaluated according to Ref. [10]. The resulting level is then compared with a reference value, obtained by detecting the position of the liquid surface by means of a graduated rod used (±1 mm precision). The rod is electrically insulated from the vessel cover and an electrical resistance meter is used to detect the position of the molten alloy surface, identified by the closing or the opening of the related electrical circuit.

Continuous data recording shows that the level measured by the differential pressure between the outlet section of the tube and the cover gas fluctuates around an average value for both tested injection tubes (see e.g., Fig. 3); in particular, the 8 mm tube shows a higher level of fluctuation. These fluctuations are related both to the dynamics of bubble formation and detachment and to the electrical noise in the measuring chain, and show a slight increase at lower gas flow rates; however, the amplitude of these fluctuations is usually in the order of 0.2 mm, but it can reach about 1mm at low gas flow rates. For this reason, use of gas flow rates higher than 0.1 l/h is suggested for CIRCE's level measurement system.

For both the considered tube diameters, the measured value exceeds the reference obtained by the rod for all test conditions. The difference between the measured

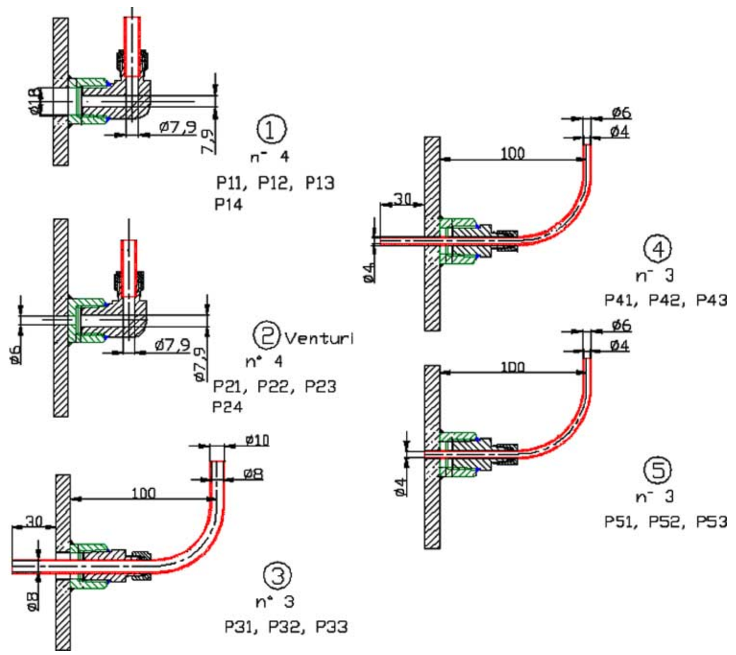

Fig. 2. Tested injector nozzles.

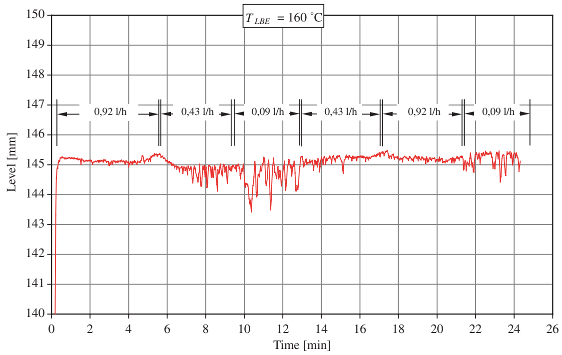

Fig. 3. Measured LBE level above the 8 mm bubble tube using several Ar flow rates.

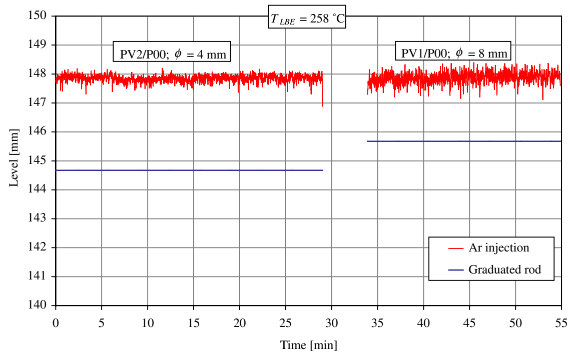

Fig. 4. Test results at 258 °C (Ar flow rate = 0.43 l/h).

and the reference values is mostly in the range 1–4 mm and decreases with increasing temperature. The effect of the surface energy of the liquid metal seems to be not enough to explain the difference noted, so the greatest contribution to this uncertainty is probably due to the procedure adopted for obtaining the reference value by the graduated rod. Notwithstanding the higher 'noise' observed, the 8 mm tube shows better results for all test conditions (see e.g., Fig. 4).

3.2. Differential pressure tests

These tests were carried out by measuring the differential pressure between two injectors of each type, then converting the obtained value into mm of LBE by Eq. (1) and comparing it with the distance between the injectors, known from the 'as built' configuration.

The adopted injectors were aligned at the same vertical position or slightly displaced in the horizontal direction, in order to point out possible effects resulting from bubble plume interaction. Nevertheless, no relevant difference in the results was noted in the two configurations and a similar level was found in the amplitude of signal fluctuations.

The results obtained for all the types of injectors show that the difference between the measurements and the reference values is in the range from 1 to 2 mm; moreover, no evidence of temperature dependence of the measured accuracy was noted.

In addition, the dependence on the gas flow rate appears to be weak, being appreciable only for injectors with a small inner diameter, mounted with the outlet section flush with the wall of the vessel (types 2 and 5). For these injectors, the difference between the measured and the reference values is again in the order of 2 mm when the Ar flow rate is in the range of 0.15–0.43 l/h, whereas an increase in the error was noted for both lower and higher values of the Ar flow rate (see Fig. 5). For this reason use of an Ar flow rate in the above range is recommended for CIRCE's pressure measurement system.

The diameter of the gas feed line seems to have an influence on the results: at the price of a small increase in the noise level, the difference between the averaged measured pressure difference and the reference value seems to slightly decrease at larger diameter feed lines, as can be seen in Fig. 6.

Long-duration tests were performed to check the stability of both the level and the differential pressure measurement systems. It was found that, limited fluctuations in the average signal value occur in some cases, in particular at the start of the tests (see e.g., Fig. 6), though the system mostly exhibits an acceptable level of stability. In any case, on the basis of the above observation, a 30 min waiting period is suggested to be adopted before data acquisition to allow the signal to settle at asymptotic conditions.

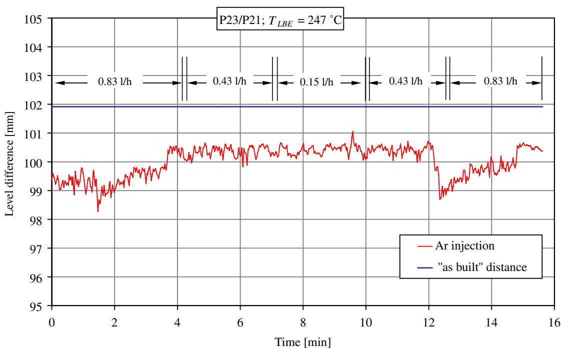

Fig. 5. Measured difference in level between P23/P21 injectors at several Ar flow rates.

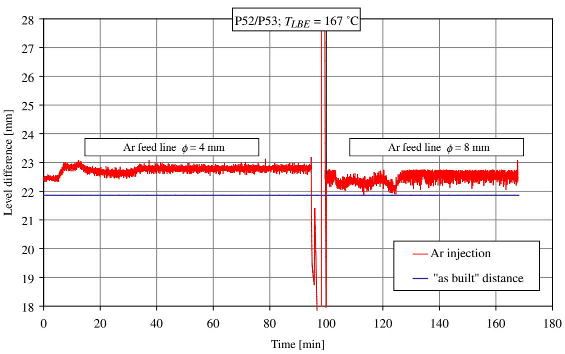

Fig. 6. Long-duration test for the P52/P53 injectors at constant Ar flow rates and using different feed lines.

4. Conclusions

Tests have been performed in a small experimental apparatus, at different temperatures and flow rates of injected argon, to check the reliability and the accuracy of the differential pressure and level measurement systems installed in the CIRCE experimental facility.

The results obtained by the tests indicate that the measuring technique provides reasonable accuracy. The use of a gas injection flow rate in the range from 0.15 to 0.43 l/h seems to be particularly suitable for measuring both the liquid level and the differential pressure.

The error in the level measurements is mostly in the order of 1–4 mm and has been observed to decrease at the highest temperatures considered in the tests. The greatest contribution to this uncertainty is probably due to the procedure adopted for obtaining the reference value by the graduated rod. In all the conditions addressed in the tests, the 8 mm tube seems to provide more accurate results than the others.

On the other hand, the order of the error in the differential pressure measurements is usually equivalent to 1–2 mm of LBE, i.e., slightly lower than observed for the level. This can be anyway considered as an occasional difference and it is reasonable to expect similar error levels for both the measurement systems, as they are based on the same physical phenomena.

Injectors similar to the ones adopted in the Venturi flow meter of CIRCE seem to have a satisfactory behavior in the suggested range of flow and at all the test temperatures.

As the tests provided the indication that fluctuations on the signal might occur at the start of gas injection, an initial waiting time of about 30 min before data acquisition is recommended to allow the measurement system to settle to asymptotic behavior.

The obtained results are intended to provide guidance for interpreting the results obtained by the planned experiments in the CIRCE facility. In this aim, particular attention is presently paid to the behavior of the measuring systems under dynamic conditions [11].

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