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Experiment and analysis on flow rate and temperature of liquid PbBi in PREKY

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Abstract Flow rate and temperature are important parameters for design and operation of liquid lead–bismuth (PbBi) experimental loop. The PREKY facility was designed to study test technique of flow rate and local temperature of PbBi loop. In this work, flow rate monitoring of molten PbBi was performed, and temperatures of the PbBi and pipe surface were measured. The results show that the flow rate of the venturi-nozzle flow meter had an uncertainty of ±5 % in the range of 0.6–2.0 m/s, and the maximum temperature difference between the PbBi and pipe surface was about 8 °C.

Keywords Lead–bismuth · PREKY loop · Flow rate · Temperature measurement

1 Introduction

For advanced reactors, the use of molten metal or alloy is an attractive choice [1–3]. Heavy liquid metal (HLM) such as lead or lead–bismuth (PbBi) is proposed as a promising candidate coolants for next-generation reactors due to their favorable properties of good neutron properties, heat transfer performance, chemical inert, and security features, etc. [4, 5]. It can also be used as a spallation target for accelerator-driven systems (ADS), which has been proposed for the transmutation of nuclear waste [6].

The KYLIN-II, a multi-function liquid lead–bismuth eutectic (LBE) experimental platform with liquid PbBi loops, has been built at Institute of Nuclear Energy Safety Technology (INEST) [7]. The planned experimental activities will be focused on compatibility of structure materials, thermal hydraulic characteristics of HLM, fuel assembly testing, and safety study, etc. [8, 9]. In addition, measurement technology for liquid PbBi can be studied on the platform.

A high-temperature liquid PbBi experimental facility, PREKY, was established to study key techniques and construction technology of liquid metal loop, such as flow meters with high precision for input reference of thermal hydraulic analysis and thermocouples with long-term lifetime for local temperature, etc. Besides the heavy density, corrosiveness, and opaqueness, direct measurement of flowing PbBi would face temperatures of 200–450 °C or even higher [10–12]. So, the measurement components should have the following features.

(1) Operator safety shall be of top priority in the experiment;
(2) Experimental data shall be repeatable and their accuracy and repeatability can be verified; and
(3) Each sensor can be independently calibrated and easily replaced.

In this paper, main characteristics of the PREKY loop are presented and the experimental results are discussed. The results can evaluate feasibility of the instrumentations.

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2 The PREKY facility

PREKY was designed to study and evaluate feasibility of measurement instruments, which include thermocouples, flow meters, level meters, and differential pressure transducers. They were commonly used in standard industrial applications.

The scheme of PREKY is shown in Fig. 1. It consists of the storage vessel and calibration tank, electromagnetic pump, heaters and heat exchanger, electrical system, data acquisition, and control unit. Table 1 lists the main design parameters, which cover completely the thermal measurement requirements in KYLIN-II loop.

The PREKY loop under operation conditions of <1 MPa and <450 °C includes the following four tests:

(1) Flow meter performance test relative to level meters;
(2) Local temperature comparative experiments for both the pipe and flowing molten PbBi;
(3) Electromagnetic pump (EMP) performance for the coupling curve of power/efficiency and flow rate; and
(4) Pressure drop test of valves at different flow rates.

Tests (1) and (2) will be described in detail in this paper.

3 Results and discussion

3.1 Flow rate test

Owing to the opaque nature of liquid PbBi, especially under high temperature and chemical reaction conditions, traditional measuring technology for water or other flowing medium cannot be applied to the PREKY loop. Therefore, the flow meter should be calibrated in advance. Based on previous experience and test results, the venturi-nozzle flow meter (VNFM) was chosen for flow rate test of the PREKY loop.

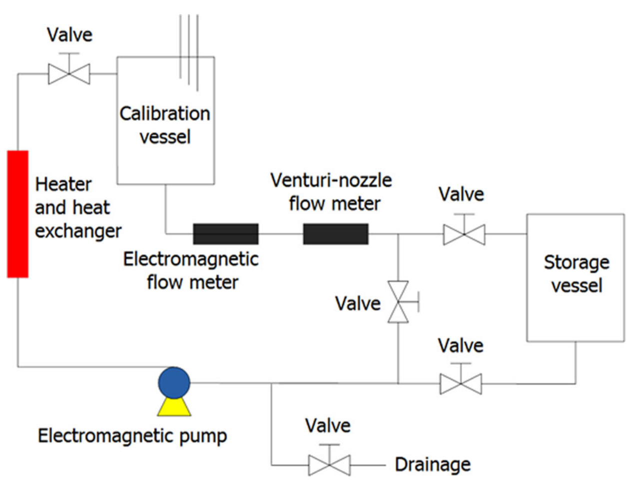

Fig. 1 Scheme of PREKY

Table 1 Main parameters of PREKY

Parameters	Values
Working temperature (°C)	200–500
Working pressure (MPa)	0.5–1.0
Velocity (m s^{-1})	0.5–2.0
Maximum flow resistance (MPa)	0.25

The scheme of VNFM is shown in Fig. 2. In principle, VNFM can be used in a wide range of flow rates based on the measuring principle of differential pressures. The flow rate (Q) of VNFM is calculated by Eq. (1) [13]:

$$Q = \mu \cdot K \cdot \sqrt{\Delta h}, \tag{1}$$

where μ is flow coefficient of the VNFM, Δh is the pressure loss between pressure ports located at the entrance 1–1 and throat 2–2 (see Fig. 2), and K is a constant, determined by Eq. (2) [13]:

$$K = \frac{\pi d_2^2}{4} \cdot \frac{\sqrt{2g}}{\sqrt{1 - \left(\frac{d_2}{d_1}\right)^4}}, \tag{2}$$

where d_1 and d_2 are inner diameters of the pipe at the entrance and throat (see Fig. 2), respectively, and g is the acceleration of gravity.

The flow coefficient μ is determined by Eq. (3):

$$\mu = \sqrt{\frac{1 - (d_2/d_1)^4}{a_2 + \zeta - a_1 \cdot (d_2/d_1)^4 + \lambda \cdot l/d_2}}, \tag{3}$$

where (see Fig. 2) l is the length between the 1–1 and 2–2; λ is the drag coefficient; a_1 and a_2 are the correction coefficients of kinetic energy at the 1–1 and 2–2, respectively; and ζ is the local head loss coefficient from 1–1 to 2–2. In this experiment, the μ is evaluated at 0.9316.

Calibration experiment of the VNFM was implemented to obtain the relationship between flow rate Q and pressure loss $\triangle h$. The measurement data were compared with the calculation results using the above equations. At beginning

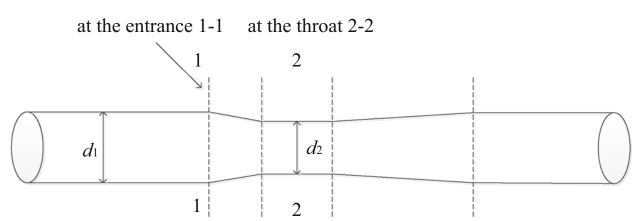

Fig. 2 Schematic diagram of VNFM

of the experiment, the output signal under differential pressures was unstable and changed due to the less wetting of internal surface of the flow channel [14, 15]. This, however, can be sufficiently improved by flowing liquid PbBi at large flow rate and high temperature for tens of hours before the calibration experiment [16].

The flow rate calibration was carried out at different flow rates. Gravity was the driving force of liquid PbBi flow, and different flow rates were obtained by adjusting the valve opening at the calibration tank exit. The calibration procedures are as follows:

(1) The system is fully preheated, and evacuated for at least 3 times;
(2) Liquid PbBi is driven to the safety level in the calibration tank; and
(3) Open the valve quickly to a certain degree, and record the experiment data.

In the calibration, the calibration vessel and storage vessel were kept at the same gas pressures. To improve the value precision and extend the range of flow rate, the experiment was repeated for seven times. The maximum flow rate was up to 2 m/s, which was about the maximum flow rate of the KYLIN-II loop, for corrosion and thermal hydraulic experiments.

Typically, the experiment was performed at about 350 °C and flow rate of 2.0 m/s. Figure 3 shows that basically, the VNFM data agree with the level meter measurement results. The flow rate of VNFM increases stably each time, while the level meter curve fluctuates a little comparing with the VNFM output, and slope of the level meter curve is a little bigger than that of VNFM.

The relative errors between VNFM and level meter measurement are shown in Fig. 3b. At flow rates of below about 0.6 m/s, the maximum measurement error is about 20 % or even more, so the VNFM is not suitable for measurements at low flow rates. It can also be seen that the flow rate calibration has an uncertainty of ±5 % in the range of 0.6–2.0 m/s. This is because that (1) the driving force for liquid PbBi to flow through the calibration vessel is the gravity, hence the non-steady flowing state between two level electrodes; and (2) changes in diameter and height of the calibration vessel under different temperatures were not considered in the experiment.

3.2 Local temperature test

Temperature controlling and monitoring are of importance for safe, reliable, and stable operation of molten PbBi facilities. Accurate measurement of temperature distribution is an important emergency control for safe operation.

For studying heat transfer characteristics of PbBi in the channel, temperature tests were implemented by two quick response thermocouples of K-type (Table 2; Fig. 4) installed inside and outside the flow channel located at the outlet of air-cooled heat exchanger. The inside thermocouple was directly contacted with flowing PbBi itself under high temperature.

The heat exchanger was used to cool down the PbBi flowing out of the test section. Its inlet and outlet were opened manually. A few minutes were needed to reach stable state of flowing PbBi. The thermocouples were contacted with the pipe surface, and the heating and controlling system would need a thermal response time of over 60 s. In other words, the heat exchanger would start to stop working 60 s later when the temperature of outer surface of flow channel reached the preset value, while the temperature of liquid PbBi had exceeded the preset value at this moment. Therefore, there were temperature difference at the same position and time between flowing PbBi and the outer surface of flow channel.

Thermal response time of the thermocouple, which depends on outer diameter of the measuring terminal, can be defined by Eq. (4) [13]:

$$\tau = \rho V c / h S, \tag{4}$$

where h is heat transfer coefficient; and ρ, V, c, and S are density, volume, specific heat, and surface area of the

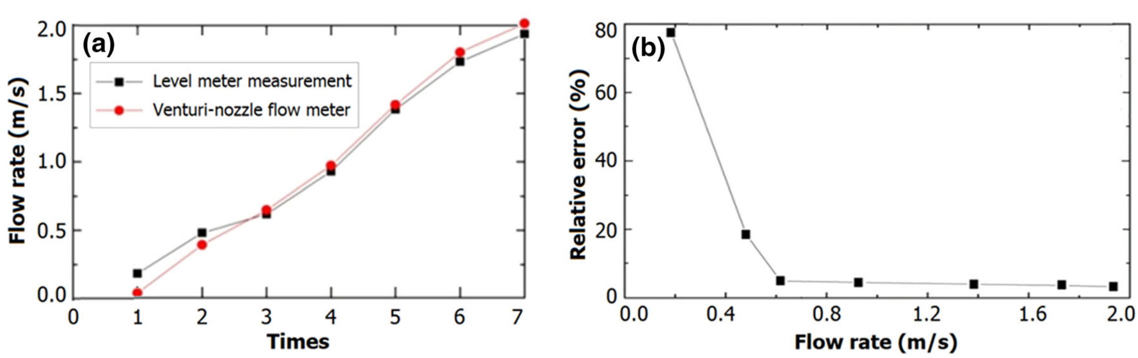

Fig. 3 Calibration results (**a**) of the VNFM and the relative error (**b**)

Table 2 Main parameters of the K-type thermocouple

Parameters	Values
Dimension (mm)	$\Phi 3 \times 500$
Maximum measuring range (°C)	~1000
Accuracy (°C)	±1.5 (below 400 °C)
Maximum working pressure (MPa)	~1
Response time (s)	10
Material of protection tube	SS 316L

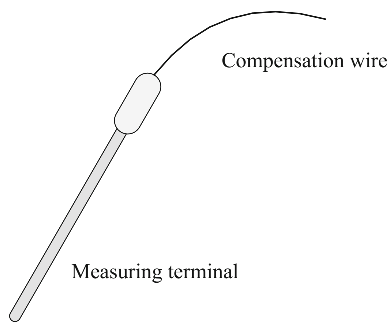

Fig. 4 Schematic diagram of thermocouple

thermocouple, respectively. From Eq. (1), supposed L is the terminal diameter of the thermocouple, the volume $V \propto L^3$, the surface area $S \propto L^2$, similarly the thermal response time $\tau \propto (V/S) \propto L$. Therefore, the thermal response time τ is proportional to L. So, the terminal diameter is 3 mm; thus, response time is about 10 s.

The results of temperature experiments are shown in Fig. 5. It can be seen that (1) the working period of the cooler was about 10 min, and the temperature fluctuations of flowing PbBi and the pipe surface were about 35 and 18 °C, respectively; (2) the maximum temperature difference between the PbBi and pipe surface was roughly 8 °C;

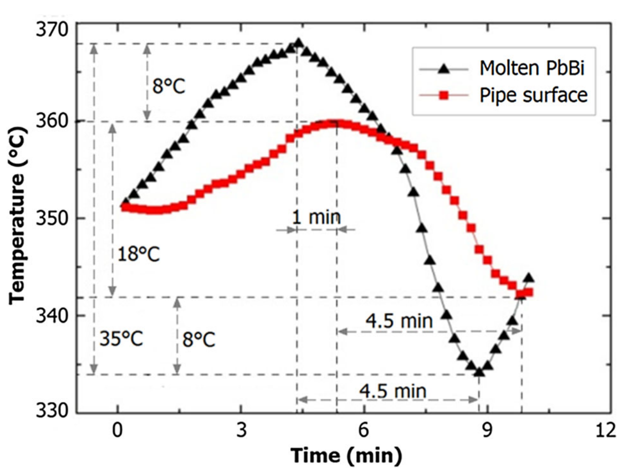

Fig. 5 Curve of temperature measurement

and (3) the temperature peak position of pipe surface was about 1 min later than that of the PbBi, and the maximum and minimum temperatures of PbBi, and of the pipe surface, had a time difference of about 4.5 min.

These can be explained as follows:

(1) The two thermocouples were located at the outlet of the heat exchanger. When the heat exchanger stopped working, output of the two thermocouples increased for a short period of time due to continuous heat release from the electromagnetic pump. After a few seconds, temperature went down quickly by heat exchange in the working state. At this time, a working period for the heat exchanger had been completed.

(2) When temperature of liquid PbBi began to drop, due to heat transfer of liquid PbBi and thermal response time of thermocouples, temperature of pipe surface started to drop about 60 s later. The maximum temperature difference (about 8 °C) between PbBi and pipe surface did not appear in the inflexion of the operating state for the heat exchanger.

Following the above results, thermocouples could be in direct contact with flowing PbBi to obtain the accurate and real-time temperature of liquid PbBi.

4 Summary

The VNFM experiment results indicate that the measuring technique can meet the experiments requirements. VNFM can be used to measure the flow rate of 0.6–2.0 m/s. The uncertainty of ±5 % in the flow rate measurement was probably due to the driving force of liquid PbBi and temperature difference.

The results of temperature monitoring experiment show that the maximum temperature difference between flowing PbBi and pipe surface was about 8 °C. The thermal response time of the thermocouple was about 10 s. These can be considered as an inevitable difference.

These results were intended to provide guidance for the planned experiments in the KYLIN-II facility.

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