Heat-Pulse Flowmeter for a Liquid Breeder Blanket*)

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Liquid metals Li, Pb-17Li and Sn-20Li are candidate liquid breeders in fusion reactors. The development of a flowmeter that can be applied to high-temperature liquid metals is an important issue. A heat-pulse flowmeter is proposed in the present study. Its basic performance was investigated by means of a loop experiment with Pb-17Li and a numerical simulation. The temperature distribution in flowing Pb-17Li was obtained by local transient heating of the outer surface of a loop tube. The temperature distribution gradually changed and resembled the movement of a hot spot, which had a higher temperature than its surroundings. This hot spot moved along the flow and passed through the tips of the thermocouples. The change in temperature distribution with the movement of the hot spot was monitored by three thermocouples exposed to the Pb-17Li flow. The results of the loop experiments were numerically simulated by assuming a certain flow rate, and the temperature profile obtained in the loop experiment was in agreement with the simulation results. The time taken by the hot spot to pass through the tips of the thermocouples was measured and simulated, and the correlation between this time and the average flow velocity was evaluated. The results indicated the average flow velocity can be obtained using the heat-pulse flowmeter proposed in this study.

Keywords: liquid breeder blanket, flowmeter, natural convection loop, Pb-17Li

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1. Introduction

Liquid metals Li, Pb-17Li and Sn-20Li are candidate liquid breeders in fusion reactors. The temperature of the liquid metals at an outlet of the liquid breeder blanket was higher than 773 K [1–4]. The compatibility of the liquid metals with some candidate structural materials at this high temperature is a critical issue. The studies on this compatibility have been performed with some small-scale natural convection loops in France (1990) [5] and the University of Tokyo (2007) [6] and with middle- or large-scale forced convection loops in FZK [7] and SCK-CEN (1986) [8], respectively. The structures and operation of the small-scale natural convection loops are more simple and advantageous compared to those of the large-scale loops. However, most natural convection loops do not consist of a flowmeter, which is essential to evaluate the flow velocity and mass transfer phenomenon in the loop. In addition, the loss of flow by loop plugging from the deposition of the corrosion products [9] cannot be detected. Although the flow velocity of Li in a natural convection loop was measured in the Oak Ridge National Laboratory [10], the method was not analyzed in detail. An inexpensive and a simple-structure flowmeter that can be applied to the natural convection loop must be developed. Simultaneously, the development of a flowmeter that can be applied to a liquid blanket is also an important issue. An electromagnetic flowmeter (EMF) has been developed for high-temperature liquid metals [9]; however, it does not function easily when the temperature is extremely high since its magnet needs to be cooled.

In the present study, a heat-pulse flowmeter has been proposed for its application to the liquid metal loop. This flowmeter could determine the average flow velocity through the measurement of the temperature change of a flowing liquid metal by local transient heating of the loop tube. It has simple structure and can be applied to evaluate the flow direction and flow velocity in small-scale natural convection loops. It can cross-check the flow rate by the simultaneous use of another flowmeter in a large-scale device. The purpose of the present study is to investigate the basic performance of the heat-pulse flowmeter by means of an experiment with a Pb-17Li natural convection loop and a three-dimensional numerical simulation.

2. Experimental Apparatus

2.1 Thermal convection loop

Figure 1 shows the natural convection loop made of Fe-12Cr ferritic steel. The loop was developed by the National Institute for Fusion Science to investigate the mass transfer phenomenon in a steady-state liquid metal flow. The loop consists of a high-temperature region, a cooling region, a low-temperature region, a heating region, two expansion tanks, and a dump tank. The loop was installed on

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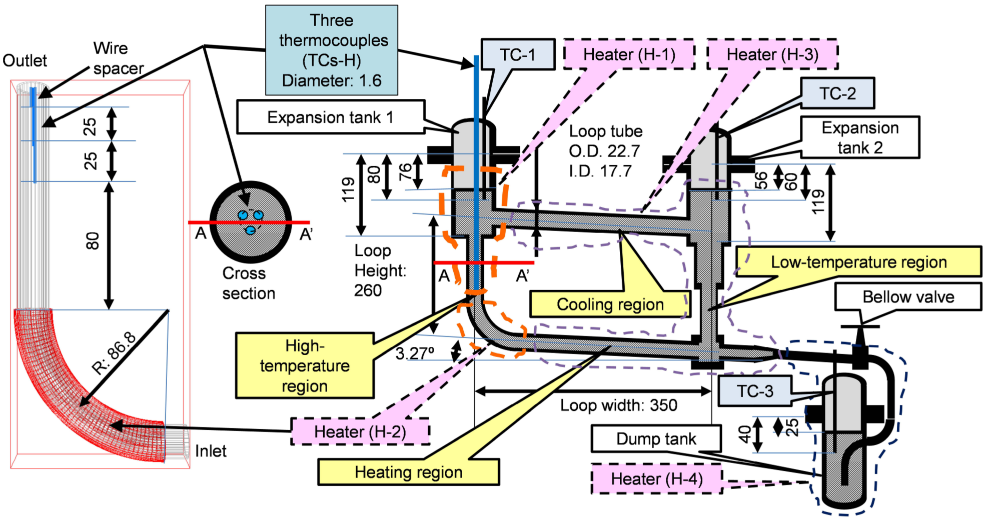

Fig. 1 Schematic view of the thermal convection loop (unit: mm).

the gas line, which was available for the impurity control of the cover gas by means of Ar gas purge and evacuation with a turbomolecular pump. The number of type K thermocouples (TCs) mounted on the surface of the loop tube to monitor and control the temperature was 39 in total. Some thermocouples (TC-1, TC-2, TC-3, and TCs-H) were placed in the liquid metals to monitor the liquid temperature. The thermocouples (TC-1, TC-2, TC-3, and TCs-H) can be used as a level gauge during charging and draining. The inventory of Pb-17Li in the loop was 780 cc, and the system pressure was 0.11 MPa.

The non-metal impurities such as moisture in the loop were removed by baking, in which the loop was heated up to 573 K and maintained for 1 h under an evacuation condition by the turbomolecular pump. Then, the Pb-17Li sticks (Santoku Cooperation, as-received batch, 22 wppm Fe, 0.17 wppm Cr, 0.52 wppm W, and 1.3 wppm Ni), totaling 7.48 kg were loaded into the expansion tank of the loop preheated at 350°C and melted, while high-purity Ar gas (99.999%) was purged into the loop. After the loop operation, Pb-17Li in the loop tube was drained into the dump tank by gravity. The charge procedure from the second operation was performed as the liquid metal was charged from the dump tank into the loop by pressurizing the dump tank.

2.2 Heat-pulse flowmeter

The heat-pulse flowmeter consists of three thermocouples (TCs-H; TC-H(U), TC-H(M), and TC-H(L)) and the loop tube, which was wound by a sheathed heater, as shown in Fig. 1. The three sheathed thermocouples, TCs-H, were immersed in the liquid metals. The diameter of the thermocouples was 0.2 mm. The three thermocouples were fixed using a Mo wire, and the wire acts as a spacer to maintain the distance between each thermocouple. The distance between the tips of the thermocouples in the longitudinal direction was 25 mm, as shown in Fig. 1. The accuracy of the thermocouples was ± 0.2% of rdg + 3.5 K. The thermocouples, TCs-H, were produced in the same rot. The same magnitude of error was observed in the output of these thermocouples when the temperature measured by each thermocouple was almost the same. Therefore, even if the difference in the temperature detected by each thermocouple was small, it could be detected with a negligibly small error although the error of the respective thermocouples was relatively large. The structure of the heat-pulse flowmeter proposed in this study is similar to that of a thermal mass flowmeter [11].

The transient heating was performed locally on the outer surface of the curved tube in the loop. Then, the temperature distribution was obtained for flowing Pb-17Li. The temperature distribution gradually changed and resembled the movement of a hot spot, as described later. After the hot spot was formed in Pb-17Li by the local transient heating of the tube, it moved along the flow. The temperature profile was obtained as the hot spot passed through the tips of the thermocouples.

The heat-pulse flowmeter was installed just before the high-temperature region of the loop to minimize the negative influence of the transient heating on the driving force of the natural convection in the loop.

3. Conditions of Loop Experiments and Numerical Simulation

The conditions of the loop experiments are summarized in Table 1.

After the temperatures of the loop and flowing Pb-17Li became steady, the transient heating on the curved tube was performed for 30 s using the heater H-2. The capacity of the heater H-2 was 170 W. However, it was used not only for the temperature control of the high-temperature region around the curved tube but also for the flowmeter. The transient heating was performed by the un-

Table 1 Experimental conditions.

	Temperature [K]		Input heat flux [W/m^2]	Time resolution [s]	Average flow velocity [m/s] (by eq. (1))
	High-temperature region	Low-temperature region (Temperature difference)			
Tube surface	723	673 ($\Delta T = 50$)	5.5×10^3	0.5	5.6×10^{-2}
Liquid	724	672 ($\Delta T = 52$)			5.8×10^{-2}
Tube surface	723	623 ($\Delta T = 100$)	1.6×10^4		8.0×10^{-2}
Liquid	724	631 ($\Delta T = 93$)			7.7×10^{-2}

used capacity of the heater. The temperature condition had to be adjusted to change the flow rate in the natural convection loop, since the driving force of the flow was the density difference caused by the temperature difference in the loop. Then, the heater input was raised to increase the temperature difference. The unused capacity of the heater H-2 decreased. 75% of the heater capacity was used to maintain the temperature of the loop when the temperature difference evaluated by the liquid temperature was 93 K. The transient heating was performed at 100% of the heater capacity. 25% of the heater capacity was applied for the transient heating. The average surface heat flux for the transient heating was 5.5×10^3 W/m^2. Similarly, the heater capacity of the transient heating was 85% and the average surface heat flux was 1.6×10^4 W/m^2 when the loop was operated with a temperature difference of 52 K. This was the reason for the difference in heat capacity between the two cases.

The flow velocity of Pb-17Li in the loop tube was controlled by the temperature difference in the loop system. The flow velocity was roughly estimated from the balance between the driving force by the density difference of the fluid and pressure drop by the drag force in the loop as

$$(\rho_{\mathrm{L}} - \rho_{\mathrm{H}})gh = \lambda \frac{l}{d}\frac{1}{2}v^2\bar{\rho} + \Sigma\xi\left(\frac{1}{2}v^2\bar{\rho}\right), \tag{1}$$

where ρ_{L} is the density of Pb-17Li in the low-temperature region [kg/m^3], ρ_{H} is the density in the high-temperature region [kg/m^3], $\bar{\rho}$ is the average density, l is the loop length [m], h is the height of the loop [m], v is the cross-sectional average flow velocity in the loop tube [m/s], $\Sigma\xi$ is the sum of the drag coefficients at the entrance and outlet of the tank and the elbow of the loop. λ is the friction coefficient of the tube for turbulent flow. The Blasius equation, which gives the friction coefficient when the Reynolds number (Re) is between 3×10^3 and 10^5, is expressed as

$$\lambda = \frac{0.3164}{\sqrt[4]{Re}}. \tag{2}$$

The average flow velocity obtained when the temperatures of the high-temperature and low-temperature regions were 723 K and 623 K, respectively, was approximately 8.0 cm/s. Similarly, the average flow velocity obtained when the temperatures of the high-temperature and low-temperature regions were 723 K and 673 K, respectively, was approximately 5.7 cm/s.

The results of the loop experiment were numerically simulated using the three-dimensional thermo-fluid simulation code PHOENICS. The equivalent geometry with the heat-pulse flowmeter installed in the natural convection loop is shown in Fig. 1. A 250-mm long horizontal straight tube (not shown in Fig. 1) was connected to the inlet of the curved tube. In the PHOENICS code, the average surface heat flux by the transient heating cannot be directly applied to the curved tube as input data. Therefore, a 1.9-mm thick sheet was placed on the curved tube for the heat input. Its heat capacity was given as to be equivalent to that of the heater H-2 used in the loop experiment.

The heat transfer in the present study was simulated using a k–ε model. A non-slip condition was applied at the interface between the fluid and inner tube wall. The outer surface of the sheet heater was thermally insulated. The system pressure was 0.1 MPa. The Nusselt (Nu) number for a flowing lead–bismuth eutectic at low-oxygen concentration [12] was expressed as eqs. (3) and (4) and was applied to the present simulation.

$$Nu = 5 + 0.025\, Pe^{0.8}, \tag{3}$$

$$Pe = Re \cdot Pr. \tag{4}$$

The boundary conditions for numerical simulation are as follows:

$$T_{\text{tube wall}} = 723.15\,\mathrm{K} \quad \text{at} \quad t = 0, \tag{5}$$

$$T_{\text{inlet}} = 723.15\,\mathrm{K} \quad \text{for} \quad 0 \le t \le 180, \tag{6}$$

$$v = 0.05 \quad \text{or} \quad 0.1\,\mathrm{m/s} \quad \text{for} \quad 0 < t \le 180, \tag{7}$$

$$q = 0 \quad \text{for} \quad 0 \le t < 60 \quad \text{and} \quad 90 < t \le 180, \tag{8}$$

$$q = 1.6 \times 10^4 \quad \text{or} \quad 5.5 \times 10^3\,\mathrm{W/m^3} \quad \text{for} \quad 60 \le t \le 90. \tag{9}$$

The time resolution of the simulation was 0.5 s.

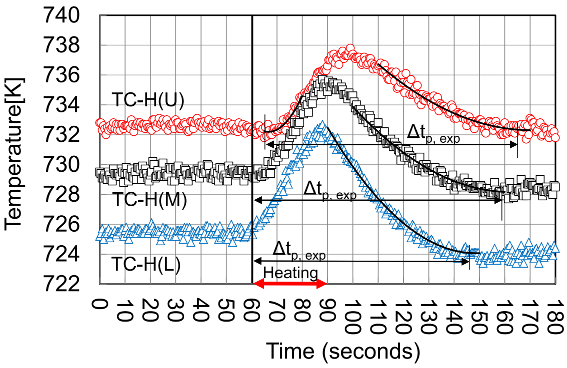

Fig. 2 Response of thermocouples (TCs-H) (Temperature difference in the loop: 52 K).

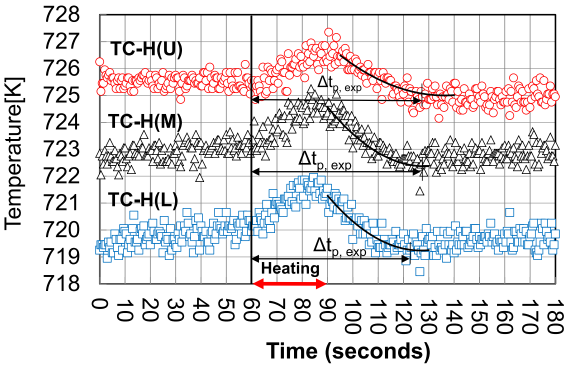

Fig. 3 Response of thermocouples (TCs-H) (Temperature difference in the loop: 93 K).

4. Results and Discussion

4.1 Natural convection loop experiment

The temperature change at the tips of the thermocouples, TCs-H, was obtained by the transient heating for 30 s. The temperature profile is shown in Fig. 2, where the temperature difference evaluated by the liquid temperature in the loop was 52 K. The shape of the temperature profile detected by TC-H (L) was similar to those of the temperature profiles detected by TC-H (M) and TC-H (U). The temperature started to increase soon after the beginning of the transient heating. The temperature increase in the temperature profile due to the transient heating of flowing Pb-17Li was 6 - 8 K, and the time taken by the hot spot to pass through the tips of the thermocouples was 86 s (at TC-H(L))-105 (at TC-H(U)).

Figure 3 shows the temperature change measured by the thermocouples when the temperature difference in the loop was 93 K. The temperature increase in this case was 1 - 2 K, and was less than that in the previous case. The time taken for the hot spot to pass through the tips of the thermocouples was 62 (at TC-H(L))- 67 s (at TC-H(U)). The time taken by the hot spot to pass through the tips of the thermocouples when the loop temperature difference was 93 K was also less than that when the loop temperature difference was 52 K.

In the present experiment, the temperature after applying the heat pulse decreased because of the following reasons. The temperature of the high-temperature region increased momentarily because of the transient heating for the measurement of the flow rate. When the loop temperature difference was 52 K, the temperature increase in the high-temperature region was approximately 6 K as shown in Fig. 2. The temperature of the low-temperature region was maintained constant, as presented in Table 1, because of the temperature control system. The increase in temperature in the high-temperature region was relatively greater than the temperature difference at the steady-state condition. The temperature difference was the driving force for the flow in the natural convection loop as expressed by eq. (1). Therefore, the flow rate of the low-temperature Pb-17Li, which flowed into the high-temperature region, increased compared to that at the initial condition. Then, the temperature around the thermocouples slightly decreased compared to that at the initial condition for a short time after applying the heat pulse. Therefore, the input heat capacity should be smaller as the heat input does not influence the flow rate in the case of the natural convection loop.

A large noise detected by the thermocouples was not made by an electrical condition, since the noise did not influence the three thermocouples in the same way. The large noise on the output of the thermocouple was due to the temperature fluctuation in the Pb-17Li flow. Therefore, the temperature profile might be affected by the noise if the heat input is not sufficiently large. Hence, the heat capacity must be sufficiently large so as to minimize the effect of the noise on the temperature profile; however, the heat capacity must be adjusted to avoid the influence on the driving force of the natural convection in the loop.

4.2 Numerical calculation by the PHOENICS code

The results of the numerical calculation using the PHOENICS code are shown in Figs. 4 and 5. The shape of the temperature profile obtained by the numerical simulation is similar to that of the temperature profile obtained by the loop experiment. The temperature profile changed according to the positions of the thermocouples, and this result agreed with that obtained in the loop experiment. The initial temperature distribution due to an imbalance of the heat input in the loop as shown in Figs. 2 and 3 was not simulated. In the simulation, the inlet flow rate was constant. The heat supplied by the transient heating remained in the tube wall and thermocouples for a long time. Then, temperature after the transient heating was slightly higher than that before the transient heating; however, it slowly decreased.

Figure 6 shows that the temperature profile due to the transient heating and formation of the hot spot and movement along the flow when the flow velocity was assumed to be 0.10 m/s. Flowing Pb-17Li was locally heated from the outside of the tube. The flow with higher temperature than the other part merged into a single bulk, and then the hot spot was formed. The hot spot passed through the tips of the thermocouples. The shape of the hot spot did not change during the measurement of the flow velocity. The temperature profile of the three thermocouples was obtained as the hot spot moved along the flow.

4.3 Discussion on performance of the flowmeter

A flowmeter must be calibrated to know the flow velocity before the loop operation. However, the heat-pulse

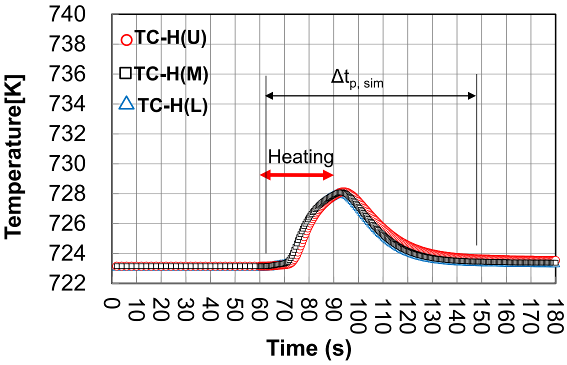

Fig. 4 Response of thermocouples in the numerical simulation (average flow velocity: 0.05 m/s).

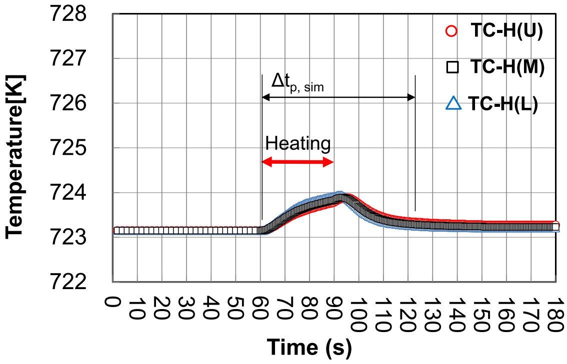

Fig. 5 Response of thermocouples in the numerical simulation (average flow velocity: 0.10 m/s).

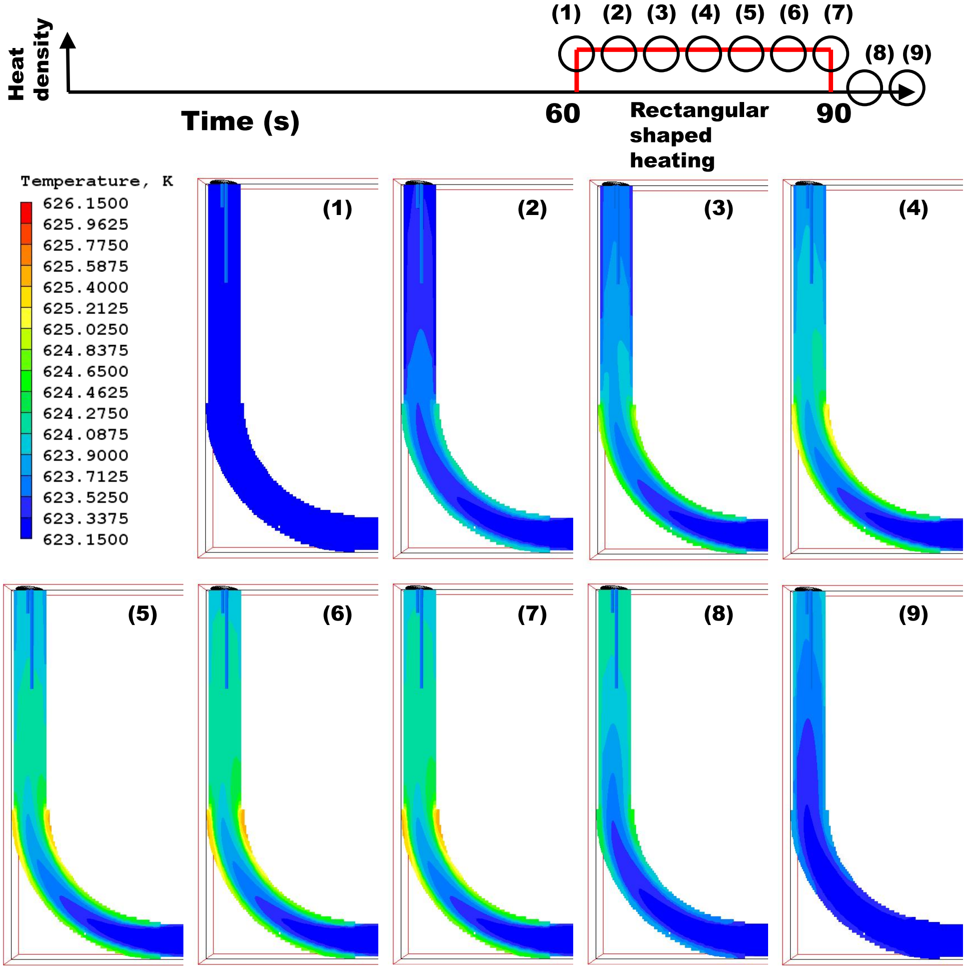

Fig. 6 Temperature profile in the heat-pulse flowmeter (inlet flow velocity 0.10 m/s, inlet temperature: 723 K): (1) at 60 s (beginning of heating), (2) at 65 s, (3) at 70 s, (4) at 75 s, (5) at 80 s, (6) at 85 s, (7) at 90 s (end of heating), (8) at 95 s, and (9) at 100 s.

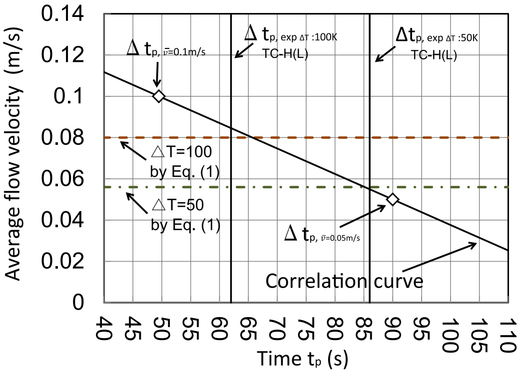

Fig. 7 Discussion on correlation curve of the flowmeter.

flowmeter proposed could not be calibrated in this study because of the absence of another flowmeter similar to an EMF, which could be calibrated as reported in ref. [9]. Therefore, the performance of the flowmeter was evaluated by means of a comparison with the simulation results.

The time taken by the hot spot to pass through the tips of the thermocouples was defined as Δt_p. This time can be chosen as the parameter of the correlation curve, since it is influenced by the flow velocity. In the obtained temperature profile, as shown in Figs. 2–5, the beginning of Δt_p was determined as the instance when the temperature change ratio (K/s) at the tip of TC became larger than 0.01. This ratio indicated the beginning of the temperature change by the transient heating. Δt_p obtained by TC-H(L) in the loop experiment was used in Fig. 7.

In the same way, the end of Δt_p was determined as the instance when K/s < 0.01 after the approximation curve was obtained from the experimental data, as shown by solid line in Figs. 2 and 3. These times were summarized as $\Delta t_{p,sim}$ and $\Delta t_{p,exp}$ in Fig. 7 together with the flow velocity obtained from eq. (1). The solid line in Fig. 7 is the correlation curve obtained by the results of the simulation. These values agreed with each other, although the evaluated time from the experimental data included a relatively large error due to the noise on the output of the thermocouple.

5. Conclusion

The major conclusions of this study are follows:

(1) The natural convection loop made of ferritic steel was developed. Pb-17Li of 780 cc was loaded in the loop, and the loop was operated at 724 K for the investigation of the performance of the heat-pulse flowmeter. The temperature distribution in the Pb-17Li flow made by the local transient heating on the tube surface was measured by the thermocouples exposed to the Pb-17Li flow.

(2) The temperature distribution obtained by the transient heating in the loop experiment was simulated numerically using the PHOENICS code. The inlet flow velocity, which was preliminarily determined as input data for the simulation, was roughly evaluated from the equation of the balance between the driving force and pressure drop according to experimental conditions. The change of the temperature distribution after the transient heating resembled a hot spot, which had a higher temperature than its surroundings and moved along the Pb-17Li flow. The temperature profile in the simulation, which was obtained during the hot spot passing through the tips of the thermocouples, agreed with the experimental results.

(3) The correlation curve of the times taken by the hot spot to pass through the thermocouples and the cross sectional averaged flow velocity was obtained to evaluate the performance of the flowmeter. The results indicated that the average flow velocity can be evaluated by the output of the heat-pulse flowmeter proposed in this study.

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