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Ultrasonic Doppler Velocimetry Experiment of Lead-Lithium Flow

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The lead-lithium eutectic alloy (PbLi) is a promising coolant for nuclear fusion reactors. Although PbLi flow and heat transfer in a nuclear fusion reactor condition needs to be comprehended, no velocity profile measurement techniques have been developed yet. Since PbLi is a high-temperature liquid metal, ultrasonic Doppler velocimetry (UDV) is a promising method. In the present paper, a series of investigations regarding the UDV measurement of PbLi flows are overviewed, and a UDV experiment of a laminar PbLi circular pipe flow is described. One of new findings is that naturally-contained particles as flow tracers differs by their alloying processes, and this difference influences the PbLi UDV measurement.

Keywords: Lead-lithium, high-temperature liquid metal, ultrasonic Doppler velocimetry

1. Introduction

A liquid metal is expected to be in use as a coolant since it has a low value of Prandtl number. For an example, a nuclear fusion reactor is expected to employ a liquid metal as a coolant. One of liquid metal candidates for the fusion reactor is lead-lithium eutectic alloy (PbLi) [1]. In a magnetic confinement fusion reactor, a plasma confining magnetic field exists even in a blanket region. Because of this, a liquid metal flow, such as PbLi flow, is reconstructed by the strong magnetic field, which is known as magnetohydrodynamic (MHD) flow. In order to design a fusion energy conversion system of the fusion reactor, we need to comprehend a complex fluid flow in a fusion reactor environment, where the lead-lithium flows under an influence of a magnetic field. The fluid flow needs to be known if the heat and mass transfer in the blanket has to be evaluated. Although, no flow velocity profile measurement techniques had been developed. Therefore, we employ ultrasonic Doppler velocimetry (UDV) in the present study.

Since the UDV was developed by Takeda [2], it was successfully applied to various kinds of liquid metals, such as mercury (Hg) (e.g., [2,3]), gallium-indium-tin eutectic alloy (GaInSn) [4,5], and molten gallium (Ga) [6] by using a regular transducer. Molten sodium (Na) [7], molten lead-bismuth eutectic alloy (PbBi) and molten bronze (CuSn) were measured by using an acoustic wave-guide [8]. As just described, the UDV is capable of measuring flow velocity profiles of room-temperature liquid metals and high-temperature liquid metals.

The UDV requires the following prerequisites:

1) Sound speed in a target fluid; generally, a sound speed depends on medium temperature.

2) Ultrasonic transmission at an interface between a tip material of a transducer and the target fluid. When the target fluid is a high temperature liquid metal, wettability influences the interfacial ultrasonic transmission. Besides, acoustic impedances determine ultrasound reflection and transmission at the interface.

3) Ultrasound reflecting particles dispersed in the target fluid. They play a role as flow tracer particles.

Sometimes the technology and knowledge which solve problems of one liquid metal cannot be applied to another liquid metal. In other words, each liquid metal needs each research and development. It is because different liquid metals have quite different physical and/or chemical properties. For an example, although PbLi and PbBi have majority content of Pb in themselves, corrosion behaviors are quite different. PbBi corrosion is an oxidation-type, but PbLi corrosion is a dissolution-type [9]. It is empirically known that liquid metal corrosions influence the interfacial ultrasonic transmission [10, 11]. Based on this, to comprehend characteristics of the target liquid metal is necessary for successful UDV measurement. Studies of the prerequisites for PbLi are described in the following chapters.

2. Acoustic Properties of PbLi

The sound speed in the target fluid is necessary for UDV, since it is necessary for evaluating depth of each of interrogation volumes that UDV examines, and flow velocity of each of the interrogation volumes. Another physical property related to UDV is acoustic impedance. The acoustic impedance, Z, is a product of sound speed in a medium, C, and density of the medium, ρ. This physical property characterizes ultrasound transmission, reflection, and refraction at a medium interface.

Ueki et al. experimentally evaluated the sound speed in PbLi as a function of temperature [10]. Figure 1 is a plot of measured values of the sound speed in PbLi, together with those in Pb, PiBi [12], and Li [13] From this figure, it can be noticed that Li content in PbLi hardly contributes to determine the sound speed in PbLi. It is valid since the weight percent of Li in PbLi, which is less than 5 wt%. Table 1 is a summary of acoustic properties of PbLi, PbBi, Pb, Li, and Ti. Ti is a wetting material of the transducer employed for the present study.

Table 1: Sound speeds and acoustic impedances.

	C (10^3 m/s)	Z (10^6 kg/m^{2}s)
PbLi (at 300°C)	1.785	16.9
PbBi (at 300°C)	1.739	18.3
Pb (at 330°C)	1.773	18.9
Li (at 300°C)	4.48	2.3
Ti (room temperature)	6.070	27.3

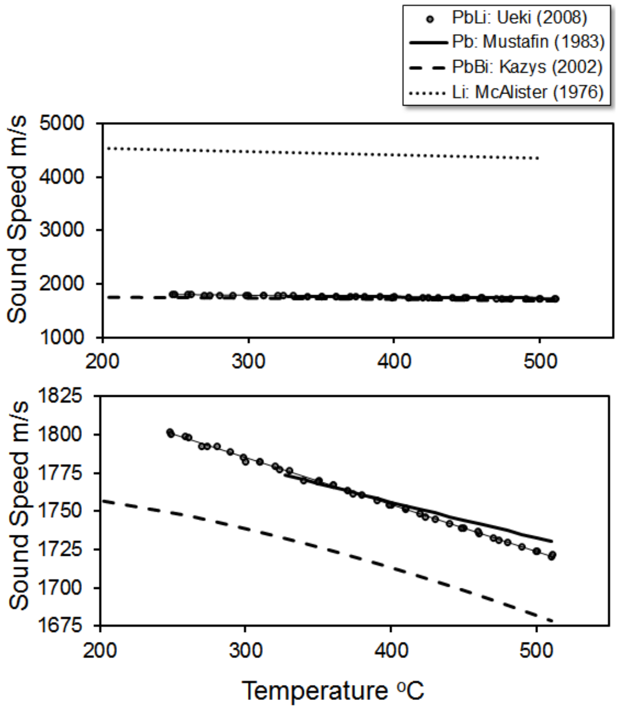

Figure 1: Sound Speed in molten PbLi, PbBi, Pb, and Li.

3. Ultrasonic transmission at interface

The ultrasonic transmission at the interface between the tip material of the transducer and the PbLi needs to be high for successful UDV measurement. We employ high-temperature transducers, the tips of which are made of Ti. The transducers (JAEA-type transducer) are capable of working up to at 500°C. Hereafter, the ultrasonic transmission at the interface between Ti and PbLi is discussed.

In general, ultrasonic transmission at an interface is expressed by the following relation:

$$TE = \frac{2Z_2}{Z_1 + Z_2} \qquad (1)$$

Here, *TE* is the transmission coefficient that is the ratio of the pressure amplitude of a transmitted wave over that of an incident wave. Z_1 is the acoustic impedance of a medium of the incident wave, and Z_2 is that of the transmitted wave. Calculated from Table 1, *TE* of Ti and PbLi at 300°C is 0.765. Based on this, ultrasound transmission is dominant over reflection, and Ti is considered to be a suitable material for PbLi.

It was experimentally observed that the ultrasonic transmission at the interface is sensitive to an oxygen concentration of an inert cover gas in contact with the PbLi. In case that the oxygen concentration is low enough, that is less than 1 ppm, the ultrasonic transmission is high enough for the successful UDV [10,14]. On the other hand, in case that the oxygen concentration is not low enough, that is tens of ppm, the ultrasonic transmission is almost zero. Under this condition, the Ti interface changes from its pure material, which is speculated to be oxidation (see Figure 2 left and center photograph). Gibbs free energy can explain the Ti oxidation in contact with the PbLi [11]. Based on them, it is concluded that the oxygen concentration sufficiently low of less than 1 ppm is necessary to have sufficient ultrasonic transmission at the Ti-PbLi interface.

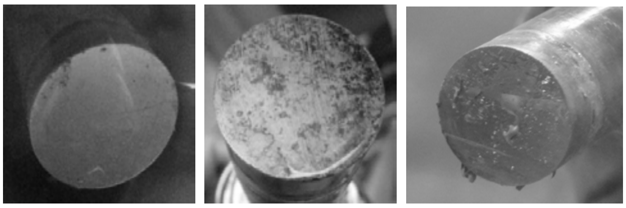

Figure 2: Photographs of transducer tip: (left) after initial immersion at oxygen concentration of tens ppm; (center) approximately 290 hours after the initial state; (right) after 1-hour immersion at oxygen concentration of less than 1 ppm [11].

4. Flow tracer particles for PbLi

Ultrasound reflecting particles, which plays a role as flow tracer particles in the target fluid, are necessary for UDV. Some liquid metals contain natural oxide particles. The particles may play a role as the flow tracer. However, it was unknown whether or not PbLi contains oxides. X-ray diffraction analysis was performed for PbLi. The analysis showed that PbLi in a bulk region contains lead-oxide (PbO) [15]. X-ray photoelectron spectroscopy also detected PbO in the PbLi [16]. PbO has high melting point of 886°C, and density close to PbLi. Based on them, PbO particles are expected to work as the flow tracers.

In order to confirm that naturally-contained particles work as flow tracers in PbLi, a swirl flow experiment was performed in the Ar-gas glovebox where the oxygen concentration was maintained to be less than 1 ppm [14]. It is known that suitable tracer particle size is 1/4 -1/2 of the ultrasound wavelength, that is approximately 100-200 μm in the present study. PbLi ingots employed for this experiment were from Atlantic Metals and Alloys, Inc. A UDV instrument used was UVP Monitor Model X-1 from Met-Flow SA. Mean velocity profiles measured in the experiment were speculated to be valid since each interrogation volume gave continuous velocity profiles. This result indicated that reflected ultrasounds from each of the interrogation volumes was sufficiently high for evaluating flow velocities. Under a condition similar to the above, it was confirmed that another kind of UDV instrument, that is DOP2000 from Signal-Processing SA, also successfully worked as well as the Met-Flow instrument.

5. UVP experiment in PbLi loop

The swirl flow experiment was suitable for investigating the flow tracers in PbLi. However, its flow field was 3-dimensional, and complicated. Because of this, the experiment configuration was not suitable for evaluating UDV measurement accuracy. A simple flow field serves for the measurement accuracy evaluation. A steady circular pipe flow is employed in the present study.

Figure 3 illustrates a schematic drawing of a test-section employed in the present study. A main part of the test-section is a straight circular pipe, 1900 mm in length, 41.2 mm in the inner diameter, and made of SUS304. In downstream side of the main circular pipe, the transducers which are the identical model employed in the previous experiments described in Chapter 5. High-temperature pressure sensors are mounted on the test main pipe to measure PbLi gauge pressures. The distance between the upstream pressure sensor and the transducers is more than 40*D*, where *D* is the inner diameter of the main part. That is long enough compared to a flow fully-developed length. Because of this, the PbLi flow is expected to be fully-developed in the region where UDV detects flow velocities.

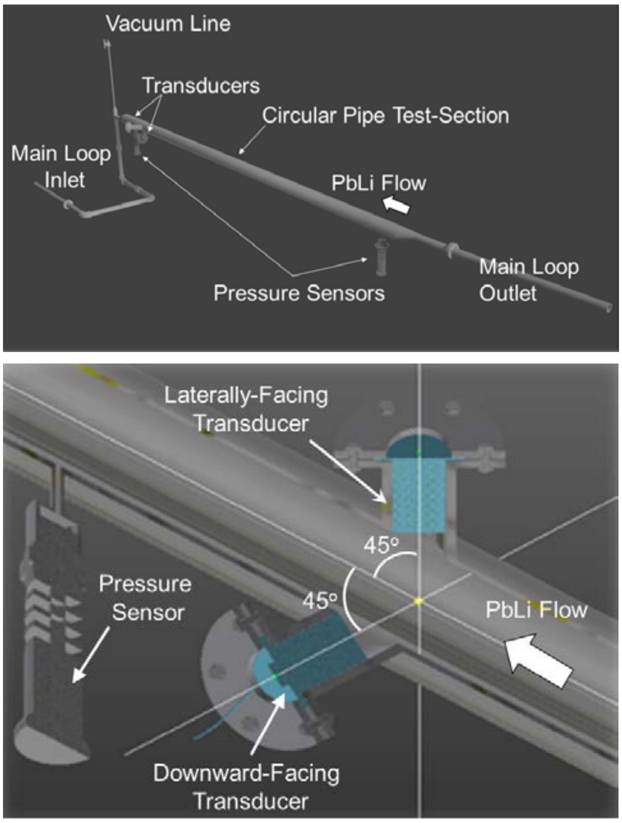

Figure 3: Schematic drawing of test-section; (top) overview; (bottom) Transducer region.

Two transducers (JAEA-type transducers) are mounted on the main pipe of the test-section on its downstream side. One of the two is downward-facing, and the other is laterally-facing, as shown in Figure 3. Those acoustic beam lines cross the straight pipe axis at an angles of 45° with respect to the pipe axis. With this configuration, two velocity profiles are expected to be measured in the fully-developed region. The test-section is installed on a PbLi thermofluid loop, named as Oroshhi-2 loop, at the National Institute for Fusion Science in Japan [17]. The UDV instrument employed in the present study is UVP-DUO from Met-Flow SA. Echo signals of the UDV instrument are monitored and recorded by a digital oscilloscope connected to the UDV instrument.

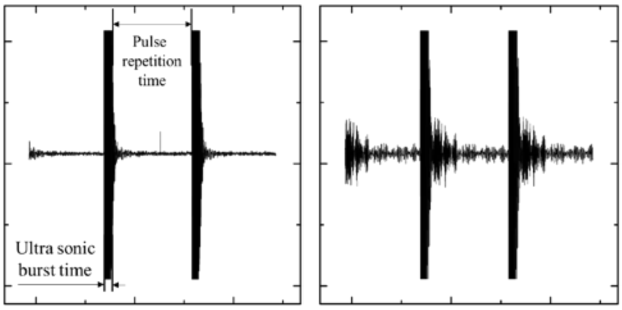

Figure 4: Echo waveforms measured by downward-facing transducer (left); by laterally-facing transducer (right).

Figure 4 is plots of echo waveforms of repeatedly-pulsed ultrasounds measured by the transducers. The left waveform shows that the transducer membrane damping is favorably rapid. On the other hand, the right waveform shows that the damping is slow and not sufficient. These results indicate that the downward-facing transducer is in a well contact with the target fluid, but the laterally-facing one is not. We speculate that the poor damping resulted from that Ar-gas bubbles might have been trapped on the laterally-facing transducer. Hereafter measurement with the downward-facing transducer is described.

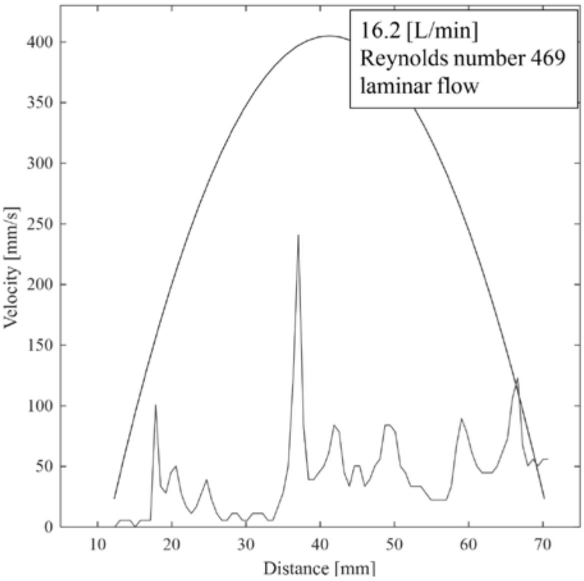

Figure 5: Measurement result of spontaneous velocity profile of PbLi pipe flow, and expected laminar flow velocity profile; it is speculated that insufficient amount of tracer particles arises the flow profile detection deterioration.

The ultrasound frequency is 4 MHz, the number of cycles is 32, and the number of repetitions is 1024. Figure 5 is a measurement result of a spontaneous velocity profile of the PbLi pipe flow when the flow rate is 16.2 L/min, which correspond to Reynolds number of 469. Therefore, the flow regime is laminar. The Hagen-Poiseulle flow is expected to be developed in the transducer region. The

Hagen-Poiseulle flow velocity profile calculated from the flow rate is depicted as well in Figure 5 for the purpose of comparison.

The velocity profile measured with UDV under the above mentioned condition is underestimated with respect to the theoretical prediction. The other result obtained is that the flow velocity profile fluctuates in time, although the flow regime is laminar. We speculate that it is because an amount of flow tracer particles contained in PbLi is insufficient for a successful UDV measurement. Although in the previous measurement described in Chapter 4, an amount of the naturally-contained particles was sufficient. What makes this difference is speculate to be PbLi purity. The PbLi employed in the previous study was from Atlantic Metals & Alloy, that was alloyed in an atmospheric condition [18]. However, the PbLi employed in Oroshhi-2 loop was alloyed in the Ar-gas glove box where an oxygen concentration was extremely low of less than 1 ppm, and also made from high-purity lead and lithium. Based on this process, the PbLi in the Oroshhi-2 loop is expected to have less amount of oxides particles than the commercial PbLi.

UVP-DUO is based on a time-domain algorithm to evaluate a Doppler shift from detected pulsed ultrasounds. Therefore, it is expected that the insufficient amount of the flow tracers results in lack of waveform information in the time-domain algorithm, and then the flow velocity profile underestimation occurs.

Conclusions

In the present paper, a series of investigations regarding the UDV measurement of PbLi flows are overviewed, and a UDV experiment of a laminar PbLi circular pipe flow is described. One of new findings is that naturally-contained particles as flow tracers differs by their alloying processes. In the UDV experiment with the PbLi loop, the flow velocity profile is underestimated, and also fluctuates timewise. From this, it is indicated that the amount of flow tracers in the PbLi employed in Oroshhi-2 loop is insufficient for PbLi UDV measurement. In order to stabilize the measurement, seeding some artificial tracer particles suitable for PbLi is favorable.

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