Flow Measurement of Lead Bismuth Eutectic in Spallation Target Model Loop

Hironari Obayashi and Kenji Kikuchi
Nuclear Transmutation Technology Group, Japan Atomic Energy Agency,
2-4, Shirane, Shirakata, Tokai-mura, Ibaraki-ken, 319-1195 JAPAN
E-mail: obayashi.hironari@jaea.go.jp

Yasushi Takeda
Laboratory for Flow Control, Division of Energy and Environmental System,
School of Engineering, Hokkaido University,
N13 W8, Kita-ku, Sapporo, 060-8628 Japan
E-mail: yft@eng.hokudai.ac.jp

Measurement of Lead Bismuth Eutectic (LBE) flow velocity profile was successfully realized in the spallation target model loop of Accelerator Driven System (ADS) by the Ultrasonic Velocity Profiler (UVP) technique. UVP is a powerful tool to measure an instantaneous space-time velocity profile especially on a velocity measurement of an opaque liquid flow, such as liquid metal. However, it has not yet been done well because both of its poor wetting property with stainless steel and of the difficulty in manufacturing probe at high temperature. At lower temperature, wetting of LBE to stainless steel that is a material of target loop is too poor. Therefore, the surface of the test section was treated by polishing, flatting and finally coating with nickel and solder. And we performed velocity measurement along the centerline of the loop and confirmed basic performance of the loop. It was found that there were periodical releases of eddy from the re-circulation region formed near the wall surface of the inner cylinder. We made then a measurement for non-parallel directions with the centerline and observed 3-dimensional structure of LBE flow configuration.

Keywords: Liquid Metal, LBE, high temperature, Ultrasonic Velocity Profiler, space-time velocity profile

1 INRTRODUCTION

1.1 Liquid metals as a flowing medium

In the industrial processes, metals are treated and processed in liquid state and they are mostly flowing. For instance, in the steel making, a flow of liquid iron plays an important role in determining its operational efficiency of manufacturing processes and also for designing the molten pot and process channels, especially from the thermal insulation point of view. It is also observed for molten metals to play an important role in welding processes. Flow velocity in such situation becomes unexpectedly large due to a high surface tension and low viscosity of liquid metals.

On the other hand, in active examples of industrial applications, various liquid metals are used as a flow medium for coolant or reacting materials. Typical one is Sodium for fast breeding nuclear reactor (FBR). Other liquid metals are also used in various situations in industry. Among these liquid metals, mercury was convenient since it is in liquid state under room temperature but it is not any more usable due to its toxicity. Sodium is also convenient but as it is reactive with water; its handling requires very careful preventive measures against fire. Gallium is also low melting temperature metal, and it reacts with oxygen in air very radically and a price is too high to use it in a large quantity.

Lead-Bismuth Eutectic (LBE) has advantage to use because its melting temperature is not very high and its chemical state is relatively stable comparative with sodium.

1.2 Measurement method of liquid metal flow

It is of utmost importance to investigate flow structure and behavior of liquid metals when it is used in an active manner not only in heat transportation but also a flowing medium, as is the case for any kinds of situations of fluid flow is involved, and as such, fluid mechanics is applied.

It is obvious that any optical method of flow measurement cannot be applied since all the liquid metals are opaque. This meant that non-invasive flow measurement was not possible until the ultrasonic measurement has been established. A single way is to use radiation such as X-ray [1] [2] or neutron [3-6] to visualize the flow. These methods, however, have no sufficient resolution in space and time for making qualitative evaluation of the flow behavior. Furthermore, apparatus for them are inconveniently large, expensive and difficult to use so that they were used only under some special conditions and configurations. Hot-wire/film [7] anemometer, thermal sensor [8] [9] and magnetic probe [9] [10] are all invasive and point wise measurement methods. This is especially disadvantageous for liquid metal flow measurement because high *Pr* number and low viscosity causes a

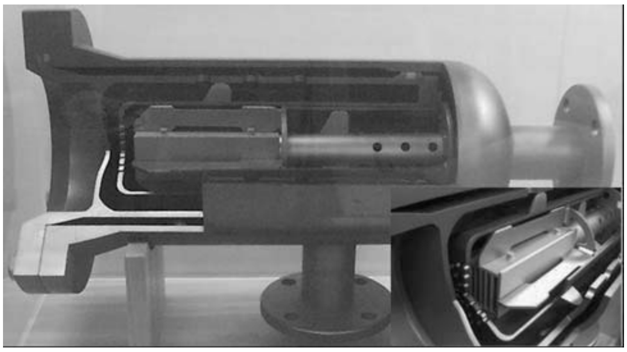

Fig.1: Photograph of LBE spallation target model

very different behavior of momentum and thermal boundary layer around the probe compared with conventional non-metal liquids such a water flow.

1.4 ADS target model loop

Accelerator Driven System (ADS) has been developing in Japan Atomic Energy Agency (JAEA). In the present investigation, a given flow configuration is related to a LBE flow in an ADS target loop mock-up which is described below in some detail. Fig.1 is a photograph of the LBE spallation target model. LBE is enclosed as a neutron source and a coolant in this loop. It is impossible to confirm the cooling performance of the target model loop without knowing of the LBE flow. Furthermore, the flow structure and erosion of the materials of the loop are closely related. Therefore, it is most important work to measure actual LBE flow. Thus, the objectives of this study are to measure LBE flow in this loop, and to investigate the flow structure and the cooling performance. However, as shown in Tab.1, lead bismuth alloy has a high melting point, about 125 degrees centigrade. Because flow temperature of LBE is very high, the measurement is more difficult than other liquid metals flow at room temperature. Therefore, we made a trial measurement and probe the flow structure near a target window sphere.

2 EXPERIMENTAL APPARATUS AND CONFIGRATION

2.1 JAEA Lead Bismuth loop-2 (JLBL-2)

JAEA Lead Bismuth Loop-2 (JLBL-2) is a model of the spallation target. It is a closed-loop driven by an electro-magnetic pump. Flow rate of the working fluid driven by this pump is constant and it is observed by an electro-magnetic flow meter. This model loop has coaxially arranged annular and tube channels. The radius of the outer cylinder tube is 63 mm and inner cylinder is 35.5mm. The gaps between the two coaxial cylinders are 3 mm. And the total length of the loop is 1504.5 mm. In operating ADS, the temperature of the LBE is expected to reach 500 degrees centigrade. In consideration

Table 1: Physical properties of liquid metals

Physical properties*	Symbol	Unit	Sodium	LBE	Mercury
Melting point	T_m	°C	97.8	125	-38.9
Density	ρ	kg/m^3	860.2	10236	13.53
Thermal conductivity	k	W/mK	72.3	11.86	8.34
Specific heat capacity	C_p	kJ/kgK	1.30	0.147	0.14
Temperature diffusivity	$\alpha\times10^5$	m^{2}s	6.48	0.790	0.60
Prandtl number	Pr	-	0.0051	0.189	0.015

*Sodium and LBE: measured at 371 °C
Mercury: measured at 25 °C

of the durability and heat-resistant temperatures of high temperature transducers, we set the temperature of LBE to 150 degrees centigrade. Because the surface tension of LBE is very high in the temperature range in the neighborhood of the melting point, the wetting conditions with the stainless steel pipe wall surface and LBE are very poor. This insufficient wetting condition does not erode the solid surface, but some problems occur in UVP measurement [11].Therefore, the inner surface of the measurement section was treated by polishing, flatting and finally coating with nickel and solder. As a result, wetting condition is improved markedly.

2.2 Experimental set-up

The temperature of the loop and the LBE are monitored by a plural thermocouple, and kept uniformly at 150 degrees centigrade. The LBE flow passes the gap between the two cylinders, turns over and then forms the reverse direction flow in the inner cylinder. UVP Monitor model-Duo (Met-Flow) was used for the velocity measurement. A high temperature transducer (Japan probe) undertakes the emission and the reception of the ultrasonic burst signals. We used argon gas bubbles rolled up at the free surface in the LBE tank as reflectors for the ultrasonic burst signal to be able to trace the LBE flow. The velocity measurement was performed at the edge of the loop end of the window sphere where a proton beam was incident to the target. This window sphere has a spherical shape and is 3.5 mm thick. Fig.2 (b) is a front view of the measurement window. As shown in the figure, the measurement position is located at the center of the window sphere, and eight points on an arc have this point as their center. The radius of this arc is 14mm, and measurement positions are located at every 45 degrees. As well, the ultrasonic transducer is installed perpendicular to the surface of the window

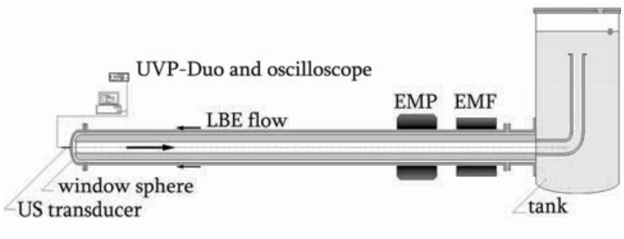

Fig.1: Experimental set-up and schematic illustration of JLBL-2.

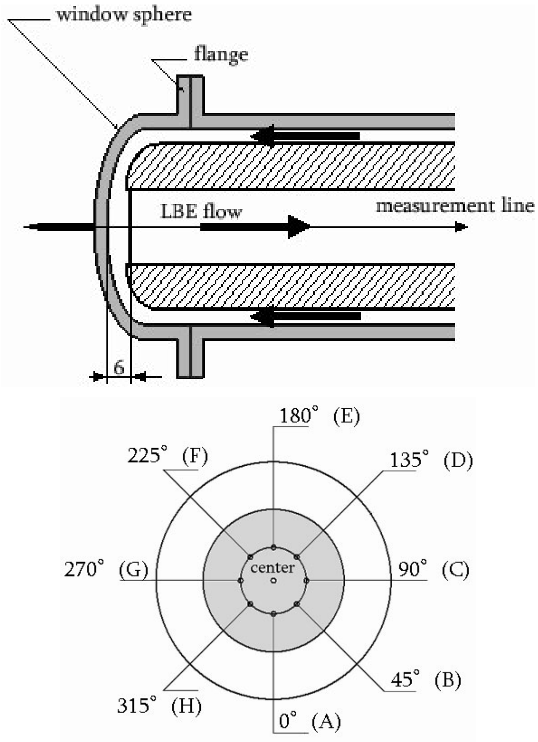

Fig.2: Experimental configuration of the measurement line on the window sphere

(a) Side view of the test section with measurement line

(b) Window sphere and installing position of an ultrasonic transducer

sphere as a countermeasure to prevent the refraction phenomenon of an ultrasonic pulse beam that is caused at the wall surface of the window sphere.

3 EXPERIMENTAL RESULTS

3.1 Velocity profiles along the centerline

We changed the flow rates flowing through the loop and measured the velocity profile at the center line of the inner cylinder. Experimental results are shown in Fig.3, which presents the velocity profiles of each flow rate at the centerline of the inner cylinder of the loop. In this figure, the horizontal axis represents the measured position and corresponds to the distance on the centerline assuming the edge of the loop as the origin. The vertical axis represents averaged velocity data; that is, the number of averaged velocity profiles is 512. In this experiment, the averaged velocity (*U*) in the annular region of the loop was changed, and then measured with an electro-magnetic flow meter installed in the upstream side of the loop. The velocity conditions were set to four phases (*U*= 0.25, 0.50, 0.75, and 1.00 m/s). Under all velocity conditions, in the averaged velocity profiles provided by this experiment the velocity data shows zero data from the starting position of the measurement to a neighborhood distance of 15 mm. At the inner wall surface of the target window sphere, the LBE flows coming from annular channels collide with each other. Therefore, a local dead region is formed for the LBE flow near the center of the edge of the loop. It is thought that this result represents a dead region of the LBE flow that extends to the neighborhood a distance of 15 mm from the inner wall surface at the center of the loop. Even if the LBE flow rate of in JLBL-2 increases, the formation of this dead region cannot be avoided. When a proton beam is incident in the JLBL-2, countermeasures apart from increasing the LBE flow rate are necessary; further, it is thought that this dead region interferes with the cooling of the target model loop.

In the side downstream from the dead region, the velocity profiles are at a maximum in the vicinity of a distance 30 mm, and after having suddenly increased, they gently decrease thereafter. By increasing the velocity conditions, the maximum velocity profiles show a proportional relationship; however, there is no proportional relation in the tendency for a decrease in the velocity after the maximum data is obtained. A re-circulation region of the LBE flow is formed on the cylinder pipe wall near the edge of the inner cylinder of the loop. A shrinking flow occurs for the flow in the main direction at any position in this re-circulation region.

A color density plot of the data set on the space-time domain, as given in Fig.4. In this figure, velocity condition is U_1. Horizontal axis represents the time, and vertical axis represents the distance on the centerline. Color represents the velocity. In this figure, almost velocity data is positive. It is observed that there occurs a space-temporal oscillation in the measured area. In this figure, velocity data shows oblique line and appears periodically in time. These lines show the motion of a fluid volume moving on the measurement line. A moving velocity of this volume that calculated by the inclination of the velocity stripes is about 2.3 mm/s. It is thought that this flow structure is eddies that discharged from the re-circulation region which moved along the centerline.

3.2 Angular velocity profiles

Fig.5 shows the experimental results of the averaged

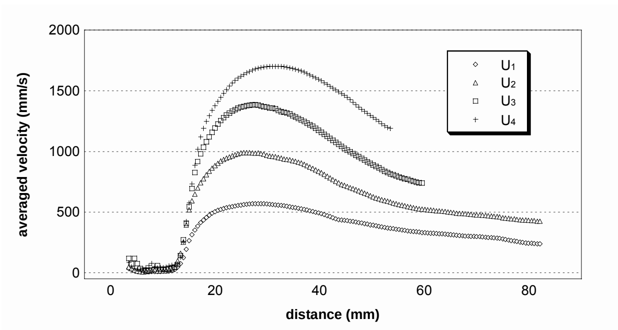

Fig.3: Averaged velocity profile at the centerline of JLBL-2, where velocity conditions are U_1, U_2, U_3, U_4 = 0.25, 0.50, 0.75, 1.00 m/sec

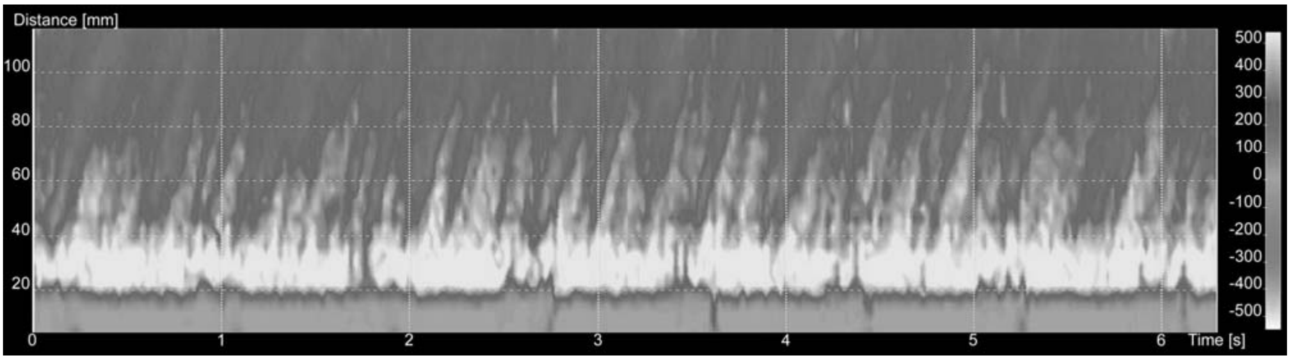

Fig.4: Space-time representation of the time dependent 1D velocity profile, where velocity condition is U_1.

velocity profiles. Each velocity profile (A) to (H) shows a result measured counterclockwise from positions at intervals of 45 degrees. A velocity condition is U_1. This figure represents that the LBE flow is approximately symmetric. In the position near the window sphere, it was observed that the flow of the upper side was fast and the lower side was slow. Furthermore, the velocity profiles of the lower side (A, B, H) changes from negative velocity to positive velocity continually. This shows the possibility that an eddy caused by the characteristic of the equipments is formed in the lower side.

4 SUMMARIES

The measurement of LBE flow in JLBL-2 by using UVP, we can obtain following results.

*There is a space-temporal oscillation that shows the motion of a fluid volume moving on the measurement line near the target window sphere. It is the small eddies that discharged from the re-circulation region which moved along and crossed the centerline.

*LBE flow near the target window sphere is approximately symmetric. However, a standing eddy could be formed in the lower side.

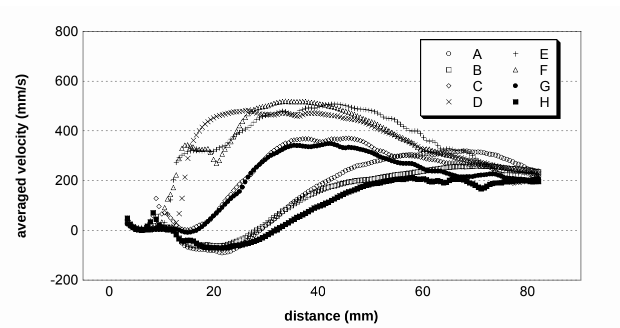

Fig.5: Averaged velocity profiles measured around the centerline of the measurement window at even intervals of angle, where measurement position labeled with A to G are expressed in Fig.2 (b) and velocity condition is U_1.

REFERENCES

[1]H.Sherif, Abdulla, L.Xin, H.Mark, Anderson, B,Riccardo, L.Michael, Corradini, C.Dae: Liquid-Metal/Water Direct Contact Heat Exchange: Flow Visualization, Flow Stability, and Heat Transfer Using Real-Time X-Ray Imaging, . Nucl. Sci. Eng.Vol.150-2 (2005) 182-220.

[2]D.Wildenschild, J.W.Hopmans, M.L.Rivers and A.J.R.Kent: Quantitative Analysis of Flow Processes in a Sand Using Synchrotron-Based X-ray Microtomography, Vadose Zone Journal 4 (2005) 112-126.

[3]Sito, et al.: Visualization and Measurements of Liquid Phase Velocity and Void Fraction of Gas-Liquid Metal Two-Phase Flow by Using Neutron Radiography, Proc. 9th International Symposium on Flow Visualization (2000)

[4]N.Takenaka, et al.: Visualization of Streak Lines in Liquid Metal by Neutron Radiography, Neutron Radiography Vol.4, Gordon and Breach (1993) 355-362.

[5] N.Takenaka, et al.: Liquid metal flow measurement by neutron radiography, Nucl. Instrum. Methods. Phys. Res. A. Vol.377 (1996) 156-160.

[6]H.Umekawa, et al.: Visualization of bed material movement in a simulated fluidized bed heat exchange by neutron radiography, Nucl. Instrum. Methods. Phys. Res. A. Vol.424 (1999) 77-83.

[7]M.Sadjben: Hot-wire anemometry in liquid mercury, Rev. Sci. Instrum. 36 (1965) 945-953.

[8]H.Ji, W.Fox, D.Pace: Study of small amplitude magneto hydrodynamic surface waves on liquid metal, Phys. Plasmas (2005) 012102_1-13.

[9]A.Cramer, S.Eckert, V.Galindo, G.Gerbeth, B.Willers, W.Witke: Liquid metal model experiments on casting and solidification processes, J. Materials Sci. 39 (2004) 7285-7294.

[10]S.Men, C.Resagk, M.Ziolkowski, M.Kuilekov and H.Brauer: Measurement of magnetic flux density on a rotating distorted electrolyte-metal interface, Meas. Sci. Technol. 15 (2004) 1323-1326.

[11]H.Obayashi, Y.Tasaka, M.Morinaga, Y.Takeda and K.Kikuchi: Measurement of Liquid Metal Flow using Ultrasonic Velocity Profiler (1st Report, Flow Measurement of LBE Target), Journal of JSME, 72 (2006) 642-628.

[12]Y.Takeda: Measurement of velocity profile of mercury flow by ultrasound Doppler shift method, Nucl. Tech. Vol 79, (1987)120-124.

[13]H.Kikura and Y.Takeda: Flow mapping using ultrasonic Doppler method, ASME Fluiid Eng. Division Summer Meetig FED-Vol.245 FEDSM98-5084 (1987).