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Measurement of LBE flow velocity profile by UDVP

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Abstract

Measurements of liquid metal lead–bismuth eutectic (LBE), flow velocity profile were realized in the spallation neutron source target model by the ultrasonic Doppler velocity profiler (UVDP) technique. So far, it has not been done well, because both of poor wetting property of LBE with stainless steels and poor performance of supersonic probes at high temperatures. The measurement was made for a return flow in the target model, which has coaxially arranged annular and tube channels, in the JAEA Lead Bismuth Loop-2 (JLBL-2). The surface treatment of LBE container was examined. It was found that the solder coating was effective to enhance an intensity of reflected ultrasonic wave. This treatment has been applied to the LBE loop, which was operated up to 150 °C. The electro magnetic pump generates LBE flow and the flow rate was measured by the electro magnetic flow meter. By changing the flow rate of LBE, velocity profiles in the target were measured. It was confirmed that the maximum velocity in the time-averaged velocity distribution on the target axis was proportional to the flow rate measured by the electro magnetic flow meter.

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1. Introduction

A liquid metal, lead–bismuth eutectic (LBE) is a potential target for spallation neutron source as well as a coolant material of sub-critical fast reactor in the concept of nuclear transmutation system driven by high-energy proton accelerator [1]. Through the experience with LBE loop operation, it has been found that the corrosion–erosion of materials would be caused by LBE flows [2]. The projected electrode of electro-magnetic flow meter used in the LBE loop was eroded by LBE [3]. Fluctuations of heat transfer were detected in LBE flow of the target window model [4]. Dissolved elements of structural material into LBE at hot leg deposited on cold leg in the form of polycrystals as a result of mass transfer in closed channel [3]. Flow control of LBE is a necessary technique to use materials in MW spallation target systems. Ultrasonic technique is a unique method, which can visualize velocity profile of LBE. Hitherto, the Ultrasonic Doppler Velocity Profiler (UDVP) was used in the mercury flow visualization [5] but no successful experience was reported for LBE flow.

Disadvantage for usage of LBE in comparison with, for example, liquid mercury is that working

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temperature must be over the melting point of 124.5 °C, higher than mercury. In this study the UDVP is adopted to measurement of LBE flow. It has been found that the surface treatment is necessary to receive ultrasonic echo waves. So this technique has been applied to JLBL-2 flowing loop.

2. Experiments

2.1. Lead bismuth loop

The lead bismuth loop named JAEA Lead Bismuth Loop-2 (JLBL-2) was used for flow measurement by UDVP. Fig. 1 illustrates JLBL-2 loop. The loop consists of a double walled tube, an electromagnetic pump, an electromagnetic flow meter and a surge tank. The total LBE volume is $0.025\ \mathrm{m}^3$. Argon gas covers the free surface of LBE in the surge tank. The loop was operated at 150 °C in the experiment. Measuring area of velocity profile is located at closed hemispherical cap at the end of loop where LBE returns to the opposite direction from annular to tube channels. The thickness of cap is 3 mm. The size of annular channel is 69 mm and 63 mm in the outer and the inner diameters, respectively. The diameter of tube channel is 35.5 mm. The length of cylindrical part is 1.5 m. The ratio of average velocity of annular channel flow to tube flow is 1/0.63. *Re* number will be 2.69×10^4 and 1.0×10^5 for annular and the tube channels, respectively, for the case that an average velocity of LBE in annular channel is 1 m/s, a density of LBE is $10.453\ \mathrm{g/cm}^3$ and a viscosity of LBE is 2.33×10^{-3} Pa s.

2.2. Ultrasonic doppler velocity profile

The measurement of the LBE flow was made using the Ultrasonic Doppler Velocity Profile (UDVP) method [6]. The Principle of method is to detect the Doppler shift frequency of the ultrasound pulsed wave, which hit a small particle in flowing liquid. Part of the ultrasound energy scatters on the particle reflectors and echoes back to the ultrasonic probe. UDVP probe for 4-MHz frequency with 5 mm in diameter was used in the experiment. Typically measurement depth range was 5–70 mm, sampling time was 49 ms for acquisition of one velocity profile, a channel distance was 0.44 mm. The measurement depth start at the internal surface of hemispherical cap, $X = 0$ (Fig. 1). It took a several microseconds to switch UVP monitor from transmitting to receiving mode. So there was no data acquisition in the range of $X = 0$–5 mm. The probe was put on the surface of hemispherical cap normal to the surface plain with matching material between the probe and the container materials. As a diameter of probe is 5 mm and ultrasonic field divergence is 2.2° from the centerline, a source of potential echo volume is very narrow.

2.3. Surface treatment of cylindrical container

Fig. 2 illustrates the measurement apparatus of the ultrasonic echo intensity. The container is made

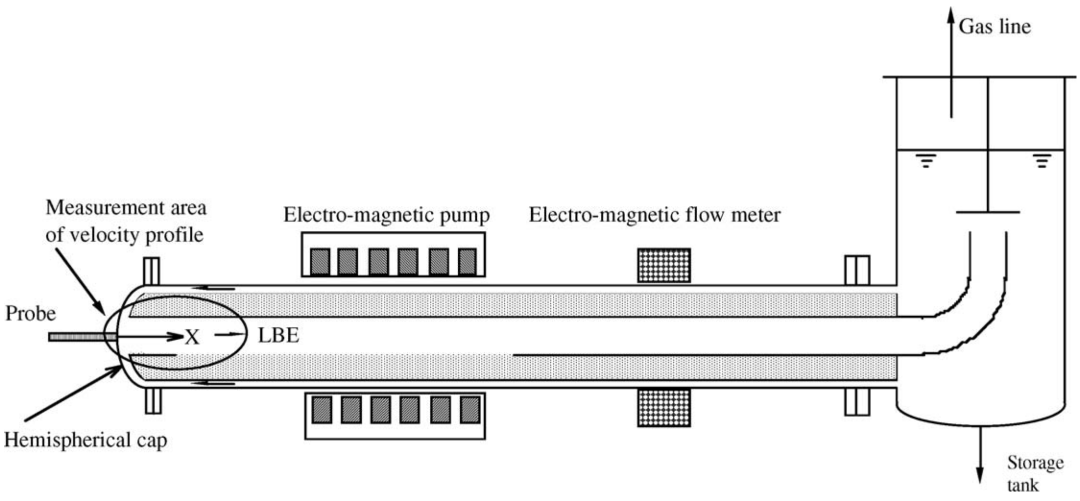

Fig. 1. JAEA Lead Bismuth Loop-2 (JLBL-2).

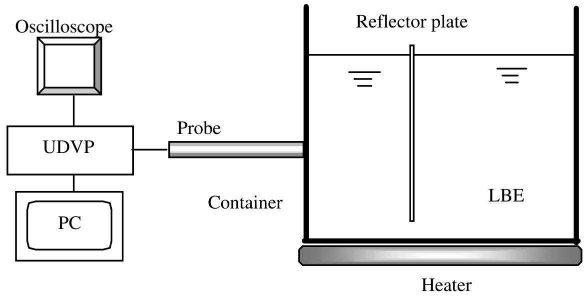

Fig. 2. Measurement apparatus for ultrasonic echo intensity.

of SS316 with 80 mm in diameter and put on electric heater in air. A temperature of LBE is kept to 140 °C, monitored by a thermocouple. The effect of contacting condition among the ultrasonic probe, steel wall and LBE, the interfacial surface treatment of cylindrical container was tested as indicated in Table 1. The ultrasonic probe was attached on the container with using matching medium. The reflector plate made of stainless steel was set up in LBE in order to scatter the energy of ultrasonic waves. As a reference case a probe was submerged into the water of container at room temperature. The ultrasonic probe was also submerged directly into the LBE of container at 140 °C. The outside surface of container was flattened in order to avoid mismatching of the face-to-face contact. The internal surface of container was coated with Ni. The coating is expected to cover the surface roughness after the machining of manufacturing process and to keep the surface from oxidation. The internal surface of another container was coated with the SnPb solder. Pb is common to LBE and solder.

Table 1
Influence of surface treatment of cylindrical container on the measured UVDP values

Case	Container	Surface treatment	Fluid	Echo wave height[c]	Temperature, °C
1	None[d]	None	Water	1	RT
2	None[d]	None	LBE	0.34	140
3	SS316	None	LBE	0	140
4	SS316	Flat[a]	LBE	0.01	140
5	SS316	Ni coating[b]	LBE	0.01	140
6	SS316	Solder coating	LBE	0.06	140

[a] Outside of vessel was flatten.

[b] Inside of vessel was coated.

[c] Arbit. unit.

[d] Probe was submerged directly into water or LBE.

3. Numerical LBE flow simulation

Flow simulation of LBE in JLBL-2 loop was done by using Star-CD code [7]. Fig. 3 shows a calculation model, which consists of a part of annular channel downstream after electro magnetic pump outlet and tube channel. The boundary condition of LBE flow is setup to 1 m/s at an inlet of simulation model. Meshes for calculation was divided by the concept of high *Re* number, which used a wall function at boundary layer, and a k–ε model was used for simulating turbulent flow [7]. The total number of meshes is over a million. Temperature of LBE is kept 200 °C.

4. Results

4.1. Measurement of ultrasonic echo intensity

Table 1 summarizes the results of the echo wave height measurement. Echo wave heights were normalized by the height for the case of 1 where probe was submerged directly into water. Measurement by submerging probe into LBE shows sufficient echo wave height to detect. Insufficient echo wave height, however, was obtained for the case 3. It means that probe could receive echo for the case 1. Flatness of outer vessel could not enhance echo wave height, nor Ni coating of inside the vessel. In both cases measurement of ultrasonic wave was very poor. Only the case 6 showed sufficient enhancement for getting echo wave height as shown in Fig. 4. Fig. 5 shows observation of internal surface of the container before and after immersion into LBE. Probe was attached on the coated area from the opposite side. It is found that ultrasonic echo wave can transmit through solder-coated area but not through uncoated area. We will adopt this surface treatment to measurement JLBL-2 loop.

4.2. Velocity profile measurement

The internal surface of the hemispherical closed cap of JLBL- 2 loop was coated by SnPb in air.

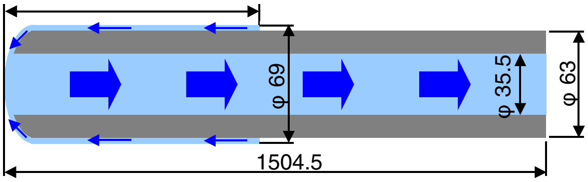

Fig. 3. Concept of the simulation model for JLBL-2.

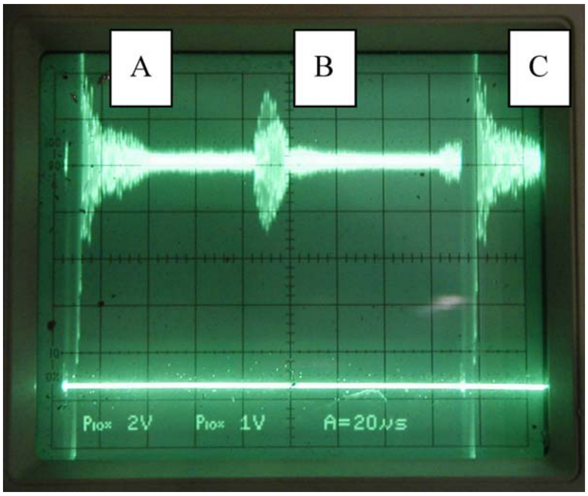

Fig. 4. Measurement of echo wave. (A) Input ultrasonic wave, (B) echo wave from reflector and (C) echo wave from opposite side of container.

The cap was connected to the double walled tube and the whole loop was heated to 150 °C. Air in the loop was evacuated by vacuum pump. LBE at the same temperature with the loop was pumped up by vacuum force into the loop through auxiliary by-pass tube. An electric current of induction coils in the electro magnetic pump was controlled to produce a driving power to the LBE of the annular channel for average flow velocities of 0.25, 0.5, 0.75 and 1.0 m/s, respectively. Flow rates were measured by the electro magnetic flow meter. Fig. 6 shows a result of instantaneous LBE velocity profile during 49 ms. The flow rate at electro magnetic flow meter (V) corresponded to average linear velocity 0.5 m/s of annual channel. The position of closed cap surface is defined $X = 0$ mm. Data acquisition started near $X = 5$ mm. Velocity indicted negative value in the range of 5–10 mm where a circulation might occur. Velocity achieved highest at $X = 25$ mm and reduced gradually with fluctuating. Fig. 7 shows average velocity profile during 20 s for $V = 0.25$, 0.5, 0.75 and 1.0 m/s. Each of case was average value of 500 profiles, respectively. UDVP showed that the highest velocities were proportional to the flow rate.

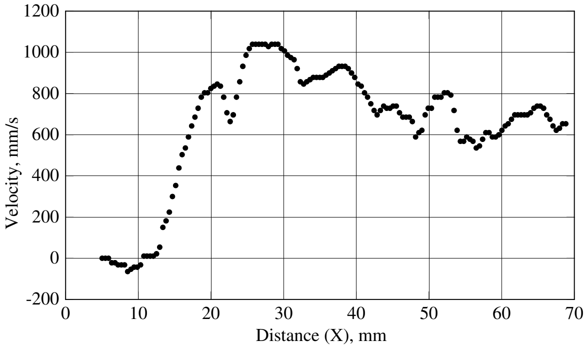

Fig. 6. Instantaneous LBE velocity profile during 49 ms.

4.3. LBE flow simulation

Fig. 8 shows a result of LBE velocity mapping for $V = 1$ m/s. The results must be compared with averaged velocity profile as shown in Fig. 7. Calculation showed velocity was accelerated over 5 mm and achieved highest at a depth of 20 mm. This distance is not so far compared with measurement. Maximum velocity was about 1.4 m/s less than the value shown in averaged velocity profile, 1.7 m/s.

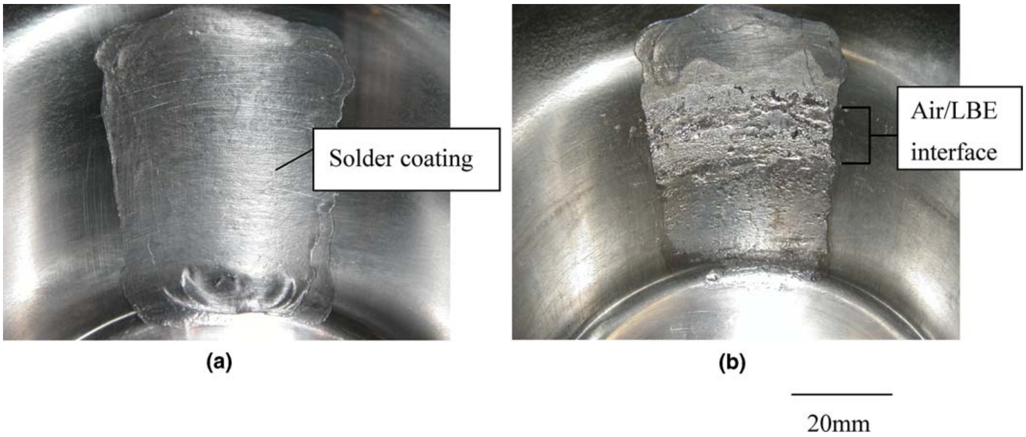

Fig. 5. Observation of the solder-coated internal surface of the vessel for case 6. (a) Image before test and (b) image after test.

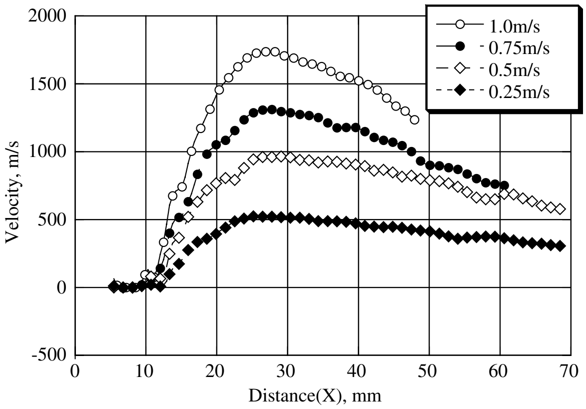

Fig. 7. Averaged velocity profile during 20 s.

5. Discussion

In order to know an interface property where solder was coated, reflector plates with a thickness of 1 mm, made of SS316, was coated by solder and submerged into LBE at 150 °C during 10 and 60 h. Fig. 9 shows optical microscope images of three plates. Fig. 9(a)–(c) shows the plates coated by solder. Figs. 9(d) and (e) show the plate (b) submerged into LBE during 10 h and the plate (c) during 60 h, respectively. Surface morphology of (d) and (e) are different from their originated images. Optical microscope observation of cross-section showed that thickness of coated layer was 500 mm but reduced to 10–20 μm after immersion in LBE. Fig. 10 shows cross sections of plate (d) and (e). X-ray analysis showed that SnPb solder was replaced by PbBi as shown in Fig. 11. Conclusively the coated material is so wetted that the supersonic sound can be transmitted at the interface of the steel and LBE.

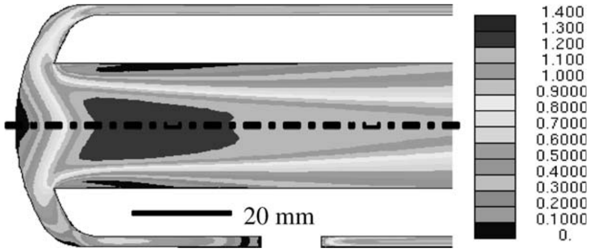

Fig. 8. LBE velocity mapping.

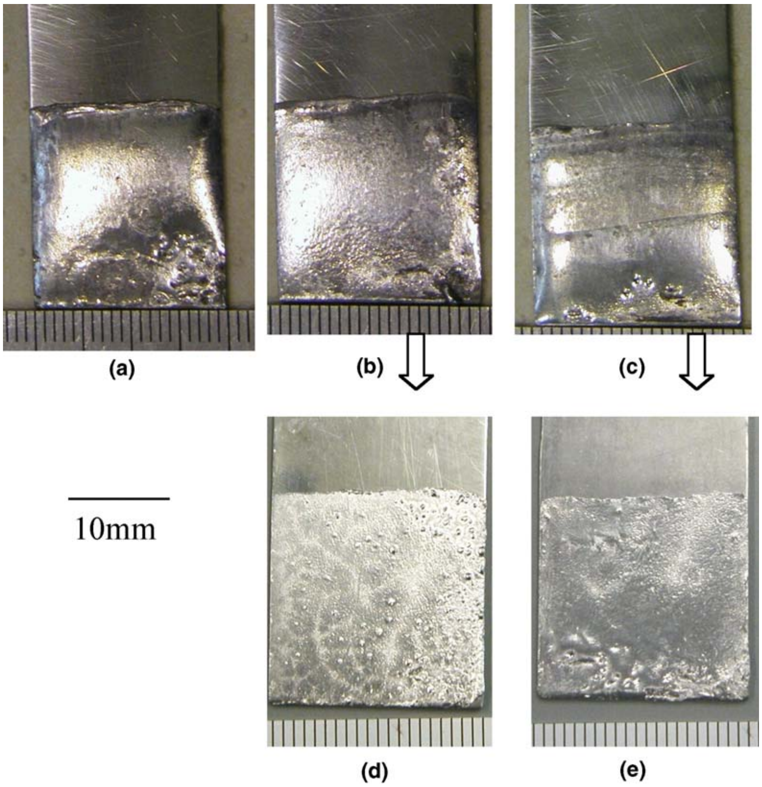

Fig. 9. Immersion test of solder coated plate. (a), (b) and (c) showed before immersion.

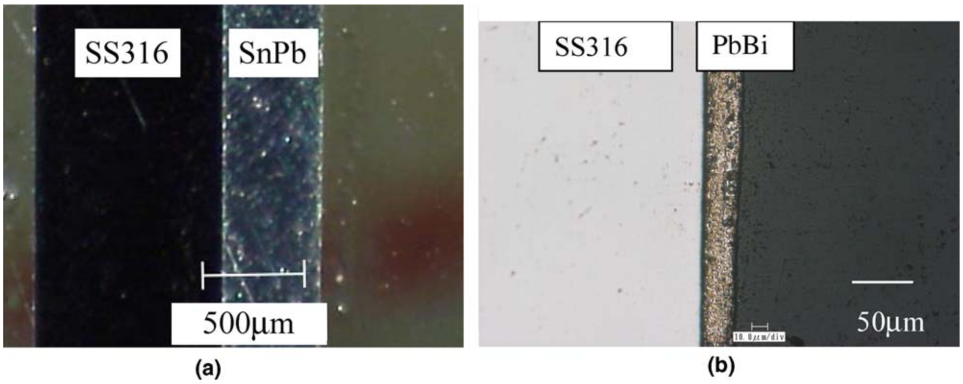

Fig. 10. Cross section of coated plate before and after immersion into LBE. (a) Before immersion; (b) after 60 h test.

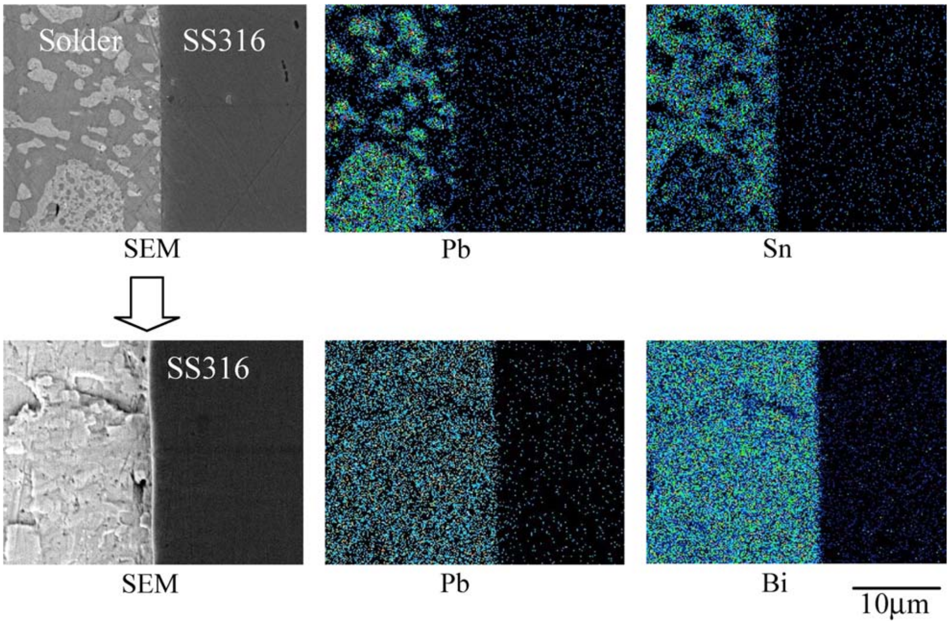

Fig. 11. X-ray analyses of surface materials. Top: solder coated interface; bottom: after 60 h immersion into LBE.

Reflecting particle was not used in flowing LBE test. Micro voids in LBE work at scattering the energy of ultrasonic wave as was done for mercury flow [5]. As shown in Fig. 1 Ar gas filled in the surge tank dissolved into LBE. Micro voids might be generated at electro magnetic pump. Impurity particles in LBE are another potential reflecting particle.

6. Conclusion

A success of UDVP application to LBE depended on surface treatment of austenitic stainless steel at temperatures up to 150 °C. The UDVP monitor could not receive echo wave through stainless steel container. SnPb solder coating inside the container surface could enhance echo wave intensity because coated surface was wet. As a result the LBE velocity profile in JLBL-2 could be measured by UDVP. Instantaneous LBE velocity profile during tens of milliseconds was obtained.

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References

[1] K. Tsujimoto, T. Sasa, K. Nishihara, T. Takizuka, H. Takano, Study of Accelerator-driven System for Transmutation of High-level Waste from LWR, ICONE-7, Tokyo, 1999.

[2] K. Kikuchi, Y. Kurata, S. Saito, M. Futakawa, T. Sasa, H. Oigawa, E. Wakai, K. Miura, J. Nucl. Mater. 318 (2003) 348.

[3] K. Kikuchi, S. Saito, Y. Kurata, M. Futakawa, T. Sasa, H. Oigawa, E. Wakai, M. Umeno, H. Mizubayashi, K. Miura, JSME Int. J. B 47 (2) (2004) 332.

[4] Hayashi et al., Annual Meeting of the Atomic Energy Society of Japan, F38, 2005.

[5] Y. Takeda, H. Kikura, G. Bauer, Flow measurement in a SINQ mockup target using mercury, ICANS XIV, 1998, p. 321.

[6] User's Guide of UVP Monitor Model UVP-DUO, 2002.

[7] Computational Fluid Dynamics Software STAR-CD, Version 3.2, User Guide, CD adapco Group, 2004.