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On-Line Measurement of Liquid Metal Level by Change of Static Gas Pressure*)

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On-line measurement of liquid metal level is an essential technique for the coolant systems of fusion reactors to keep their safety operation and to recognize accidents such as a coolant leakage and a coolant blockage. The purpose of the present study is to propose a static gas type level meter which is widely applicable in various coolant systems. This level meter consists of a differential pressure meter and a measurement compartment which is inserted into fluids. The change of the liquid level is measured on-line by the change of the differential pressure between the filler gas in the level meter and the cover gas. The experiments were performed with three fluids: water, viscous fluid (PVA starch) and liquid metal PbBi. The output of the level meter indicated good linearity and reproducibility. The meter output obtained in the experiments was slightly larger than that estimated by theory since the meter output was influenced by surplus gas which was unintentionally involved in the insertion procedure of the level meter. This technical issue was improved by the use of the measurement compartment with several slits, which can release the surplus gas through the slits.

Keywords: level meter, liquid metal, molten salt, liquid blanket, coolant loop

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1. Introduction

Liquid metals and molten fluoride salts are candidate liquid breeders of fusion blanket systems [1]. Heavy liquid metals (Pb and PbBi) are promising coolants of fast reactors [2]. The on-line measurement of liquid level is required for the safety operation and the prevention of accidents such as a coolant leakage and a coolant blockage in the coolant systems. Therefore, the level meter is an essential instrument for the coolant loops. Several types of level meters are being developed and used in the coolant systems with high temperature fluids such as liquid metals and molten salts as follows:

- A conductive type level meter is schematically illustrated in Fig. 1 (a). This level meter which based on a simple principle has been used for the liquid metal coolant loops. However, this level meter cannot continuously measure the liquid level.
- A pulse radar type level meter [3] and an ultrasonic type one [4] are schematically illustrated in Figs. 1 (b) and (c), respectively. These level meters were studied for the use in liquid metal coolant systems. These level meters are hard to be installed in a small tank since they require certain distance between the sensor and the free surface of fluids to obtain adequate reflection time.
- A mutual inductance type level meter is schematically illustrated in Fig. 1 (d). This level meter was designed and used for the liquid level measurements of liquid LiPb [5] and liquid sodium [6]. However, this level meter needs a complicated electrical circuit.
- A gas-purge type level meter is schematically shown in Fig. 1 (e). This level meter has a simple structure. However, this level meter requires gas purging all the time during the measurement and can be installed only in open tanks.

The coolant systems with high temperature fluids require the level meter which can continuously measure the

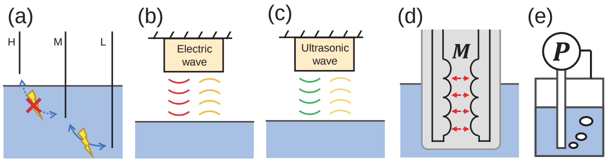

Fig. 1 Schematic diagrams of conventional liquid level meters for liquid metals and molten salts: (a) conductive type level meter, (b) pulse radar type level meter, (c) ultrasonic type level meter, (d) mutual inductance type level meter and (e) gas-purge type level meter.

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Table 1 Experimental conditions.

Fluids	Cover gas	Temperature in measurement compartment T_1 [K]	Temperature at differential pressure meter T_2 [K]	Cover gas pressure P [Pa]
Water	Air	296	296	1.01×10^5
PVA starch	Air	296	296	1.01×10^5
PbBi	Air	473	296	1.01×10^5

Table 2 Hydrodynamic properties of fluids at test temperatures [7–9].

Fluids	Fluid temperature in experiments [K]	Density ρ [kg/m^3]	Viscosity [mPa·s]	Surface tension [N/m]
Water	296	997	0.93	0.073
PVA starch	296	1015	4×10^2	-
PbBi [7]	473	10470	2.4	0.406
Flibe [8]	<Reference>	2184 at 823 K	1.1×10^1 at 823 K	0.20 at 823 K
LiPb [9]	<Reference>	9326 at 723 K	1.2 at 723 K	0.44 at 723 K

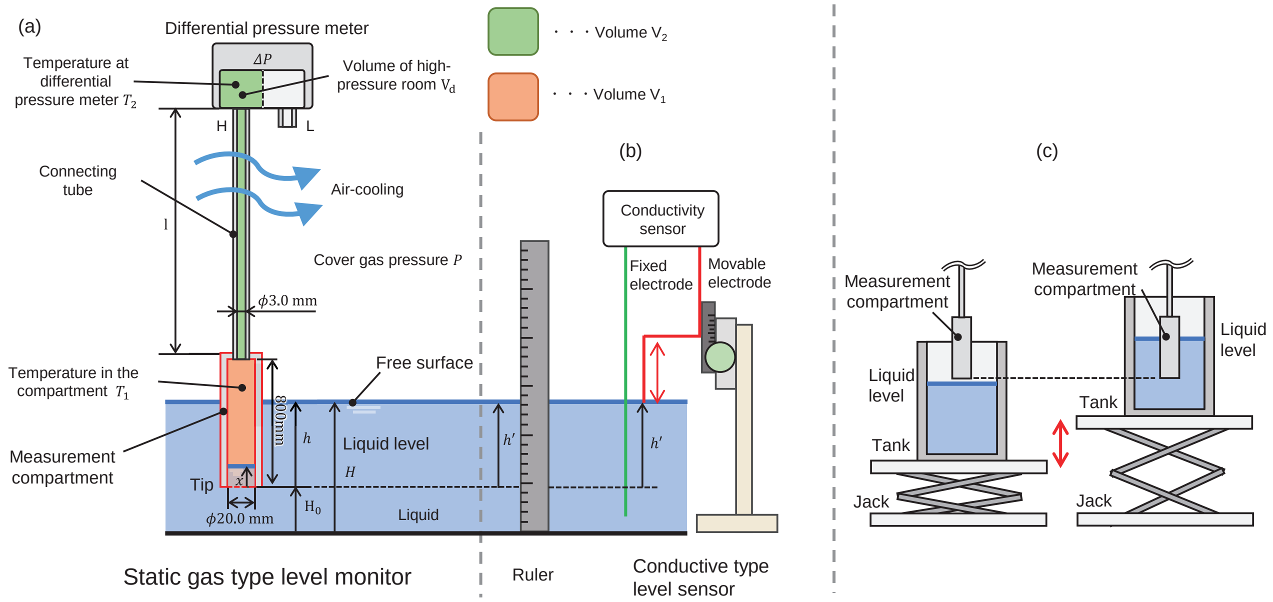

Fig. 2 Schematic diagrams: (a) static gas type level meter, (b) ruler and conductive type level sensor and (c) experimental set ups for tests of liquid level meter.

liquid level. The installation and the performance of the level meter should not be limited by the scale and structure of facilities.

The purpose of the present study is to design a static gas type level meter which has a simple structure and is available regardless of installation conditions in various coolant systems. The fundamental performance of the static gas type level meter in water, viscous fluid and liquid metal was experimentally studied.

2. Experimental Details

2.1 Experimental conditions

Table 1 presents the experimental conditions. The experiments were performed with water, viscous fluid (PVA starch) and liquid metal PbBi. The hydrodynamic properties of test fluids are presented in Table 2. PVA starch was used to investigate the influence of its high viscosity on the level meter performance. The hydrodynamic properties of liquid PbBi are similar with those of liquid LiPb.

The tests of the level meter in water and PVA starch were performed with the tank made of plastic. The temperature of water and PVA starch was room temperature. The test in liquid PbBi was performed with the tank made of stainless steel. The temperature of liquid PbBi was controlled at 473 K by the ribbon heater wound on the outer surface of the tank and the thermocouple inserted into the melt. The cover gas was atmospheric air at room temperature in all the experiments.

2.2 Static gas type level meter

Figure 2 (a) shows a schematic diagram of the static

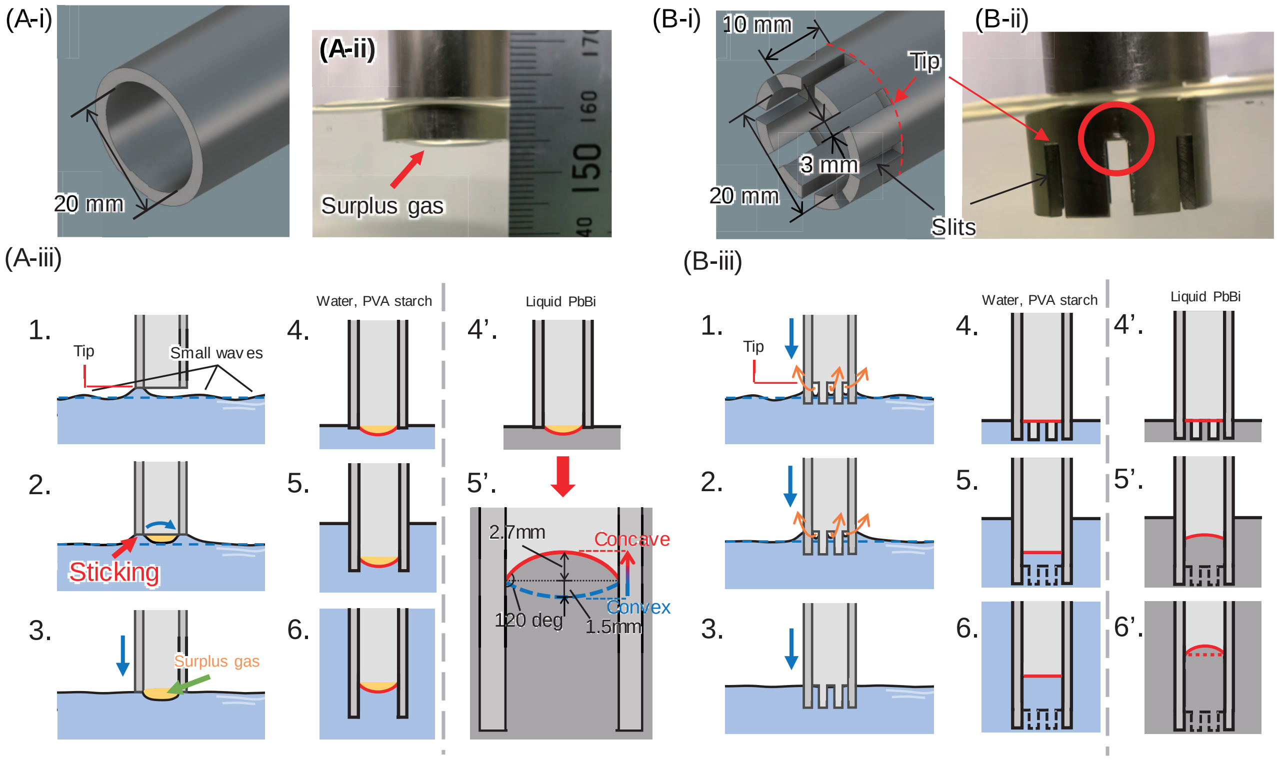

Fig. 3 (A-i) Schematic illustrations of normal type measurement compartment of static gas type level meter, (A-ii) normal type compartment after the insertion, (A-iii) possible behavior of gas filled in compartment. (B-i) Schematic illustrations of measurement compartment with 8 slits, (B-ii) slit type compartment after the insertion, (B-iii) possible behavior of gas filled in compartment.

gas type level meter. The measurement compartment is made of 316L austenitic steel. Figure 3 (A-i) shows the tip of the normal type measurement compartment. The compartment connects to the high-pressure side of the differential pressure meter. The low-pressure side is open to the cover gas. The differential pressure meter is kept at room temperature due to air cooling of the connecting tube.

The measurement compartment is immersed into fluids. The gas filled in the compartment is then separated from the cover gas outside of the compartment as shown in Fig. 3 (A-iii-1~3), when the tip of the compartment touches with the free surface of fluids. The pressure of gas filled in the compartment changes according to the liquid level as shown in Fig. 3 (A-iii-4~6). The differential pressure between the gas filled in the compartment and the cover gas also changes in these procedures. The liquid level from the bottom of the tank H [m] is then obtained from the insertion depth of the measurement compartment h [m] and the known distance H_0 [m] between the tip of the measurement compartment and the bottom of the tank as shown in Fig. 2 as follows:

$$H = \mathrm{H}_0 + h. \tag{1}$$

The insertion depth is obtained from a pressure equilibrium equation and a combined gas law as follows:

$$h = \left[1 - \frac{\mathrm{P}}{\mathrm{P} + \mathit{\Delta P}}\right] \frac{\mathrm{T}_2\mathrm{V}_1 + \mathrm{T}_1\mathrm{V}_2}{\mathrm{T}_2\mathrm{S}_\mathrm{m}} + \frac{\mathit{\Delta P}}{\rho g}, \tag{2}$$

where V_1 [m^3] and V_2 [m^3] are the volumes of the measurement compartment and the high-pressure side of the differential pressure meter which includes the volume of connecting tube, respectively. S_m [m^2] is the cross-sectional area of the compartment. T_1 [K] and T_2 [K] are the temperatures in the measurement compartment and the differential pressure meter, respectively. P [Pa] is the cover gas pressure. $\mathit{\Delta P}$ [Pa] is the differential pressure between the compartment and the cover gas. ρ [$\mathrm{kg/m}^3$] is the liquid density. g [$\mathrm{m/s}^2$] is gravitational acceleration.

The level meter output was slightly influenced by surplus gas which was unintentionally involved in the measurement procedure as described in the latter chapter. Therefore, the tests were also performed with a slit type measurement compartment, which could release the surplus gas through the slits as shown in Fig. 3 (B-i). The measurement compartment had 8 slits. The width and depth of the slits were 3 mm and 10 mm, respectively. The root of the slits was defined as the tip of the compartment in the measurement of a liquid level as shown in Fig. 3 (B-i). The tests with the slit type compartment were performed with water and liquid PbBi.

The differential pressure between the gas filled in the compartment and the cover gas was measured by the differential pressure meter SDP-133D (0 - 5 kPa, ± 0.1% F.S.) in the water and PVA starch experiments, and the differential pressure meter SDP-11 (0 - 60 kPa, ± 0.1% F.S.) in the liquid PbBi experiment.

2.3 Conductive type level sensor

The calibration curve of the static gas type level meter in liquid PbBi was obtained by the simultaneous use of a conductive type level sensor as shown in Fig. 2 (b). This level sensor could discontinuously measure the liquid level by the detection of the electrical conduction between the movable electrode and the electrode inserted to the liquid metal.

2.4 Experimental procedures

The position of the measurement compartment was fixed during the experiments. The vertical positions of the tank filled with fluids were then changed to vary the apparent liquid level as shown in Fig. 2 (c). Then, the insertion depth was changed in the range between 0 mm and 160 mm. The actual insertion depth h' [m] was measured by a ruler in the experiments with water and PVA starch. The liquid level was measured by the conductive type level sensor in the experiment with liquid PbBi. The actual insertion depth h' [m] in the experiment with liquid PbBi was obtained as the interval between the liquid free surface and the tip of the fixed measurement compartment.

3. Results and Discussions

3.1 Water experiment

Figure 4 (a) shows the differential pressure measured by the static gas type level meter in the water experiment. Red open circles in the graph indicate the experimental values and a red solid curve indicates the theoretical values by Eq. (2) with the actual insertion depth h'. Multiple measurements were conducted in the experiment. However, the measurement tests were not repeated at the same condition exactly, since the insertion depth of the compartment was manually controlled. Therefore, the data points are not described by the mean values and their errors. The differential pressure measured by the level meter agreed well with the theoretical curve. The insertion depth of the level meter obtained by Eq. (2) agrees well with the actual depth which is indicated by the solid line as shown in Fig. 4 (d). Thus, the insertion depth measured by the static gas type level meter agreed well with that measured by a ruler. The coefficient of determination R^2 of the level meter output indicated that it had excellent linearity and stability. The 95% confidence interval of the level meter output was obtained within ± 0.4 mm.

However, the insertion depth measured by the level meter was very slightly deeper than the actual depth at all the conditions as shown in Fig. 4 (d). The relative error of the output in the experiment was indicated by red open circles in Fig. 5 (a). The tip of the measurement compartment inserted to water was shown in Fig. 3 (A-ii). The surplus gas was involved in the insertion procedure, and this was the cause of the error. The tip of the measurement compart-

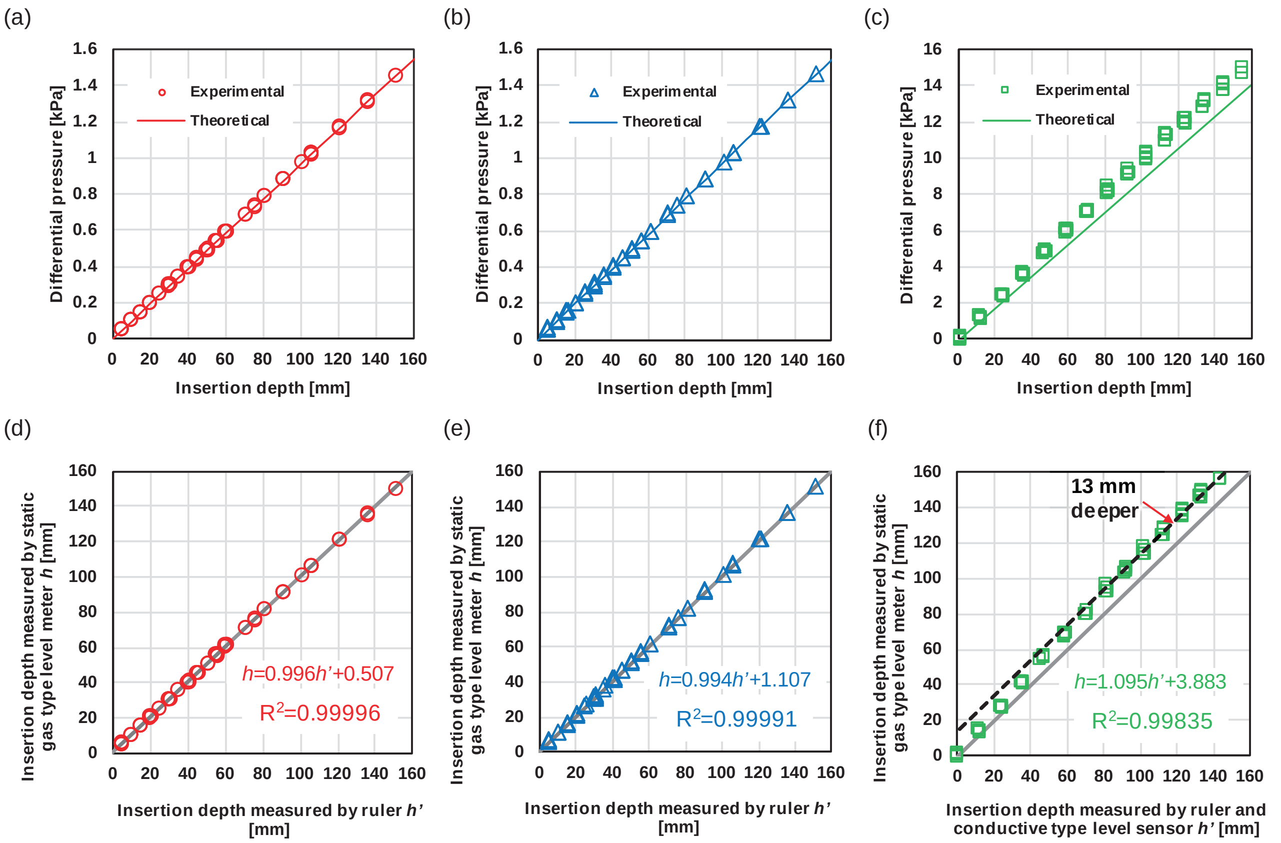

Fig. 4 Differential pressure measured by static gas type level meter, (a) water, (b) PVA starch and (c) liquid PbBi. Insertion depth measured by static gas type level meter, (d) water, (e) PVA starch and (f) liquid PbBi.

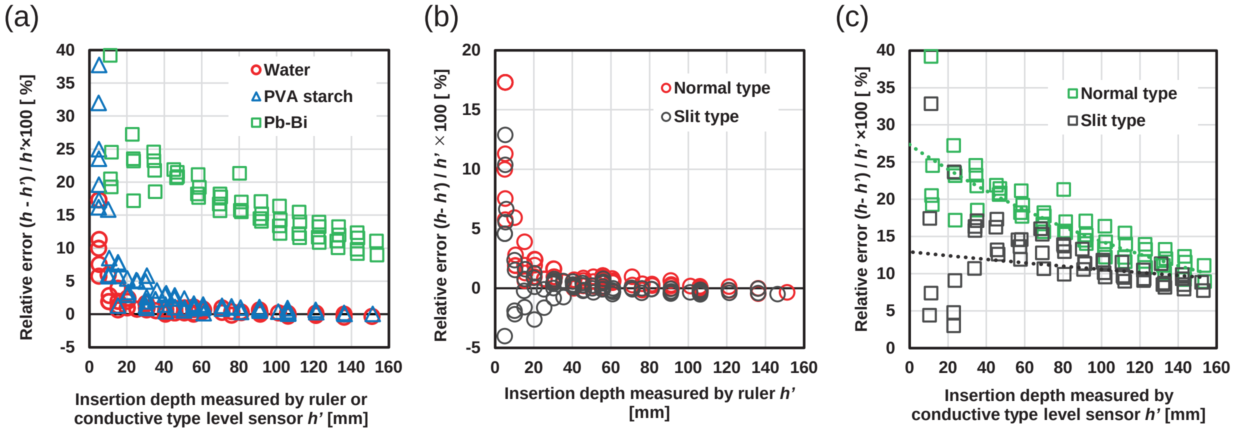

Fig. 5 Relative error of static gas type level meter (a) with normal type measurement compartment, (b) with slit type measurement compartment in water and (c) with slit type measurement compartment in liquid PbBi.

ment could stick to fluctuating free surface, and the surplus gas was unintentionally involved as illustrated in Fig. 3 (A-iii). Therefore, the level meter output became larger than the actual depth by the surplus gas. The insertion depth *h* should be zero theoretically when the differential pressure is zero. However, the differential pressure was not exactly zero even when the insertion depth *h* is zero because of the involved surplus gas.

3.2 Viscous fluid experiment

Figure 4 (b) shows the output of the static gas type level meter in the experiment with PVA starch. Blue open triangles indicate the experimental output of the level meter, and a blue solid curve indicates the theoretical values by Eq. (2) with the actual insertion depth *h*'. Figure 4 (e) indicates the insertion depth of the measurement compartment which was obtained by Eq. (2) with the differential pressure measured in the experiment. The solid line indicates the actual insertion depth. The results were similar to those of the water experiment. The coefficient of determination R^2 of the level meter output indicated that it had excellent linearity and stability. The 95% confidence interval of the level meter output was obtained within ± 0.7 mm.

The relative error of the output in the experiment was indicated by blue open triangles in Fig. 5 (a). The trend was similar to that obtained in the experiment with water. The surplus gas involved was also recognized in the experiment. The high viscosity of PVA starch had little influence on the linearity and stability of the level meter.

3.3 Liquid PbBi experiment

Figure 4 (c) shows the output of the static gas type level meter in the experiment with liquid PbBi. Green open squares indicate the experimental output of the level meter, and a green solid curve indicates the theoretical output obtained by Eq. (2) and the insertion depth by the conductive type level sensor. The differential pressure measured by the level meter agreed well with the theoretical curve. Figure 4 (f) indicates the insertion depth of the measurement compartment which was obtained by Eq. (2) with the differential pressure measured in the experiment. The solid line indicates the actual insertion depth. The insertion depth measured by the static gas type level meter agreed well with that measured by the conductive type level sensor. The coefficient of determination R^2 of the level meter output indicated that it had excellent linearity and stability. The 95% confidence interval of the level meter output was obtained within ± 4.1 mm.

The insertion depth measured by the level meter was larger than the actual depth at all the conditions. The relative error of the output in the experiment was indicated by green open squares in Fig. 5 (a). The error was larger than the error in the experiments with water and PVA starch.

The surplus gas involved had initially convex shape as shown in Fig. 3 (A-iii-4'). Liquid PbBi had poor wettability since the contact angle of liquid PbBi to 316 L austenitic steel was more than 120 deg at 623 K [10]. The shape of the surplus gas could transform from convex to concave due to the poor wettability as shown in Fig. 3 (A-iii-5'). Large surface tension of liquid PbBi (0.406 N/m at 473 K [8]) could also promoted this shape transformation. The concave shape having a thickness of 2.7 mm could be formed in the compartment. The thickness of the surplus gas initially involved in the insertion procedure of the test with water was approximately 1.5 mm, though the thickness in the test with liquid PbBi was not measured. When the thickness in the test with liquid PbBi was the same with that in the test with water, the volume reduction and the pressure increase of the gas filled in the compartment by the shape transformation could be estimated as 6.7×10^{-7} m^3 and 1.1 kPa, respectively. This pressure increase could output approximately 13 mm deeper than the actual insertion depth. This difference agreed well with that appeared in the test as shown in Fig. 4 (f).

3.4 Performance of measurement compartment with slits

3.4.1 Water experiment

The relative error in the output by the slit type level meter is indicated by black open circles in Fig. 5 (b). The error by the slit type compartment was smaller than that by the normal type one. Fig. 3 (B-ii) shows the slit type compartment inserted into water in the experiment. The red circle in Fig. 3 (B-ii) indicates that the surplus gas involved was less than that in the experiment with the normal type measurement compartment. The surplus gas could escape through the slits.

3.4.2 Liquid PbBi experiment

The relative error of the output in the slit type level meter is indicated by black open squares in Fig. 5 (c). Green and black broken lines are the fitting curves of the relative errors. The relative error was clearly mitigated even when the liquid level was low. The surplus gas could escape through the slits and the effect on the level meter output was suppressed as illustrated in Fig. 3 (B-iii). The relative error of the output in the experiment performed with the slit type compartment at shallow insertion depth seems to have a larger variation than that with the normal type one. The relative error was large only when the surplus gas could not escape through the slits in a few experiments. However, the relative error of the data obtained in the experiments with the slit type compartment was smaller, since the surplus gas could escape in almost all the experiments. The positive relative error of the data was large in the experiment with PbBi even when the experiments were conducted with the slit type compartment. The surface tension and wettability might affect the result.

The required accuracy in fusion reactors is not determined. However, the required accuracy should be determined by the detection sensitivity in the initial stage of leakage and blockage accidents. In these accidents, the change of the liquid level in the tank may be several centimeters. The error between the meter output and the insertion depth of the measurement compartment was approximately 10% when the insertion depth was 150 mm. The error was larger than 20% when the insertion depth was less than 40 mm. Therefore, the calibration procedure of the liquid level meter is necessary to accurately detect the change of liquid level. The relative error of the calibrated level meter is less than 2% when the insertion depth in the fluid is 100 mm. In this condition, the change of the liquid level in the accidents can be accurately detected.

4. Conclusions

Major conclusions are follows:

1. The static gas type level meter with a simpler structure was newly designed. The fundamental performance of the level meter was evaluated in the tests with water, viscous fluid (PVA starch) and liquid metal PbBi. The output of the level meter indicated high linearity, high stability and high reproducibility. There was an error in the measurement, since the meter output was influenced by the surplus gas involved in the measuring procedure.
2. The static gas type level meter which had 8 slits in the measurement compartment was designed. The error of the level meter was improved by the use of the slit type compartment which promoted the release of the surplus gas in the measurement procedure.

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