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Development of Tracer Particles for Thermal Hydraulic Experiment by Neutron Imaging

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Abstract. To observe flow velocity distributions by Neutron Imaging, suitable tracers are necessary. Their performance is highly dependent on their density, visibility, and wettability (if applied to liquid metal). Gold cadmium tracers have been developed for the Pb-Bi two-phase flow, however the visibility have not been verified depending on the particle size and the measurement system. As the candidates of tracer particles, Ag, Cd, Au-Cd, and Ag-Cd have been tested by varying its compositions and their diameters. Results show enough visibility if the particles size is larger than 1mm. In addition, Cd tracer particles were applied to the fluidized bed, where the bed materials are metallic particle made of stainless steel, with 1mm diameter. The diameter of Cd trace is about 1.5 mm. From the neutron imaging, the visibility of the tracers is enough to measure the velocity distributions in the fluidized bed.

1. Introduction

During the last decade, the technique of particle image velocimetry (PIV) or of particle tracking velocimetry (PTV) has seen rapidly increasing application for non-intrusive diagnostic investigations of complex flow fields, both on its own and as a complement to laser Doppler anemometry (LDA). However, such optical methods cannot be applied, to non-transparent fluid system, such as liquid-metal flow or fluidized bed. Saito et al. has applied neutron imaging to liquid-metal two-phase flow by using gold cadmium tracer particle, which has similar density to the molten lead bismuth. The PIV or PTV methods rely on the tracer particles suspended in the flow to provide the velocity information for the continuous medium. The accuracy of the velocity field is ultimately limited by the ability of the tracer particles to follow the instantaneous motion of the continuous phase. A compromise between reducing the particle size to improve flow tracking and increasing the particle size to improve light scattering is, therefore, necessary [1]. Proper flow seeding is particularly critical with PIV.

Takenaka et al. [2] have applied $AuCd_3$ tracer particles to the measurement of the lead-bismuth single phase flow by using neutron imaging. Saito et al. [3,4] have also applied $AuCd_3$ tracer particles to the lead-bismuth two-phase flow, where spherical $AuCd_3$ tracer particles were used to improve the mechanical strength of the tracer particles.

In relation to the severe accident of nuclear power plants, the relocation of debris bed has been extensively investigated by using optical visualization [5]. Such relocation of debris bed may be driven by boiling bubble due to the decay heat of the fuel debris in the coolant. Therefore, relocation of metallic particles should be measured in water pool for development of the severe accident analysis. However, it would be difficult to apply optical method to such fluidized bed in water pool [6], consisting of three phases such as solid particles, boiling bubbles, and liquid phase. The purpose of this study is to develop measurement techniques which can be applied to the fluidized bed of heavy bed materials by neutron imaging. To realize this, several kinds of tracer particles containing Cd have been made and visualized by using high-speed neutron imaging.

2. Experimental apparatus and procedure

2.1 Preparation of tracer particles

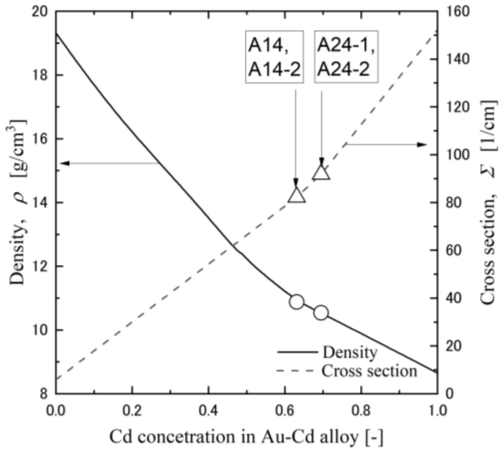
To measure the velocity field in the liquid-metal or the fluidized bed of metallic particles, the density of the tracers should be similar to that of the continuous phase. In addition, the tracer particles should have good wettability to the liquid-metal for the liquid-metal flow application. Among the various candidates, Au-Cd alloy and Ag-Cd ally have been selected for the tracer particles in neutron imaging.

Au-Cd system and Ag-Cd system have been intensively investigated because the shape memory effect was found in the Au-Cd system by Chang and Read in 1951 [7]. The Cd concentration in such Cd system can be theoretically adjusted from 0 to 100%. However, it should be noted that the Ag-Cd or Au-Cd system have various kinds of intermetallic compounds, depending on the Cd concentration [8]. Therefore, the stable tracer particles should be prepared by taking the phase diagram into account. Table 1 shows the summary of the prepared tracer particles of AuCd and AgCd alloy including pure Ag and Cd particles, where the calculated density and total cross-section of materials are also shown.

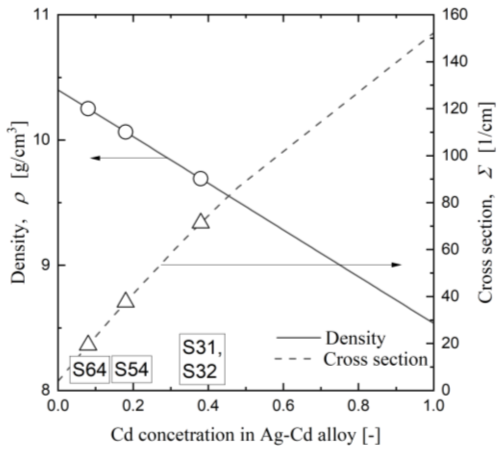
Table 1. Prepared tracer particles.

Tracer Name	Cd Composition [wt%]	Diameter [mm]	Density [g/cm^3]	Total Cross-section [1/cm]
S01	Ag(0)	1.96	10.5	3.95
S31	Ag-Cd(38)	2.19	9.69	71.3
S32	Ag-Cd(38)	2.59	9.69	71.3
S54	Ag-Cd(18)	1.83	10.0	37.6
S64	Ag-Cd(8)	1.79	10.3	19.3
A14-1	AuCd3(63.1)	1.46	10.9	82.2
A14-2	AuCd3(63.1)	1.46	10.9	82.2
A24-1	AuCd4(69.5)	1.46	10.5	91.9
A24-2	AuCd4(69.5)	1.46	10.5	91.9
C01	Cd(100)	1.19	8.65	152

The Au-Cd and Ag-Cd have been made in a vacuum furnace, by adjusting the concentration of Cd before the heating process in the furnace. The synthesized alloy has been cooled down and mechanically broken to adjust the tracer size. Broken tracer particles have some angular shape and are mechanically fragile. Therefore, the tracer particles are heated by an arc melting method under inert Argon gas atmosphere to obtain spherical shape, which has a good mechanical strength in flow field. The obtained particle size is from 1 to 2 mm as shown in Table 1. Figures 1 a) and b) show the density and the macroscopic total cross section for thermal neutrons of each compound.



a) Au-Cd alloy



b) Ag-Cd alloy

Figure1. Effect of Cd concentration on density and cross section of alloys.

The cross section of Au-Cd is ranged from 80 to100 cm^{-1} and that of Ag-Cd is ranged from 20 to 70 cm^{-1}, respectively. The density of $AuCd_4$ (A24-1, A24-2) is almost the same as that of lead bismuth eutectic, and that of Ag-Cd (S31, S32) is almost the same as that of Newton alloy, respectively. $AuCd_4$ has been already applied to lead-bismuth two-phase flows. However, the applicability of the Ag-Cd tracers has not been investigated at present.

2.2 Fluidized bed experiment

As described above, the density of the tracers should be similar to that of the continuous phase. To adjust the density, the authors are trying to develop lead bismuth spherical particles for the fluidized bed experiment, where the Au-Cd or Ag-Cd particles can be used as the tracers. It is still difficult to obtain uniform particles size. Therefore, commercial stainless-steel particles were used for their uniform diameter in this study. Figure 2 shows the schematic diagram of the test section, which consists of a rectangular aluminum duct (80 mm in width, 200 mm in height, and 10 mm in depth), three gas injection nozzles, an gas outlet, a flow meter and an air compressor. One-millimeter stainless-steel particles are filled in the aluminum tank at certain height. Air is supplied from the gas injection nozzles. The flow rate was changed from 0 to 100 l/min at the present experiment. To observe the flow field, Cd particles are added to the stainless-steel particles.

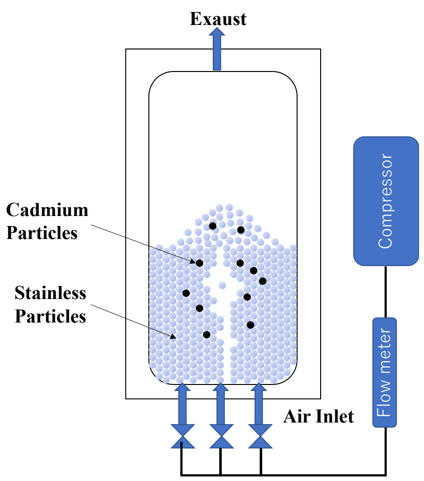


Figure 2. Schematic of fluidized bed.

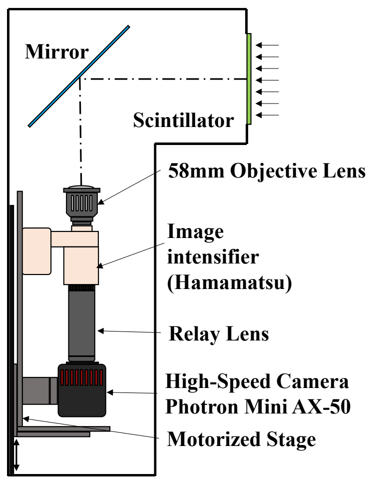


Figure 3. Schematic of Imaging system.

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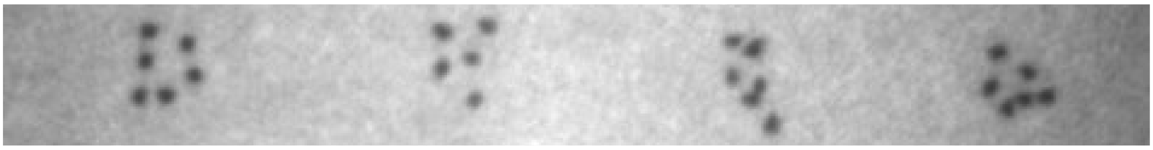
2.3 Neutron imaging

Neutron radiography measurements were performed at the Thermal Neutron Radiography Facility (TNRF) of JRR3 at the Japan Atomic Energy Agency (JAEA). The nominal power of the JRR3 is 20 MW, and the neutron flux at the beam exit of the TNRF port was approximately 1×10^{8} n/cm^{2}. Figure 3 shows a diagram of the imaging system, which consists of the 6-LiFZnS scintillator (Tritec Co. Ltd.), the mirror, the dark box, the objective lens, the optical image intensifier (MCP(GaAsP)+Booster, Hamamatsu Co. Ltd.), the relay lens, and the high-speed camera (Photron Mini AX-50), which enables more than 10,000 fps imaging at the TNRF.

3. Results and Discussion

3.1 Neutron imaging of tracer particles

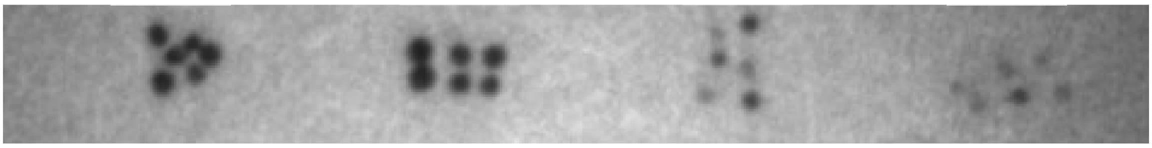
Figure 4 shows the neutron images of the Au-Cd tracer particles. As can be seen, each tracer particle has a good visibility. Since the particle size is not uniform, it was difficult to estimate the visibility quantitatively at the present experimental conditions.



a) $AuCd_3$(A14-1) b) $AuCd_3$(A14-2) c) $AuCd_4$(A24-1) d) $AuCd_4$(A24-2)

Figure 4. Neutron Images of AuCd tracer particles.

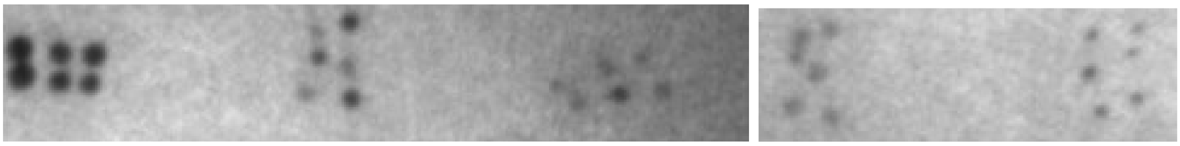
Figure 5 shows the neutron images of the Ag-Cd tracer particles. The Cd concentration was changed from 38wt%(S31) to 8wt%(S64). The visibility of tracers decreases with decreasing Cd concentrations. However, the uniformity in the Cd concentration in Ag-Cd might be not kept, as shown in Fig.5 c), where the difference in the visibility can be seen. Such non-uniformity may be caused by the unperfect mixing during the heating process in the furnace.



a) Ag-Cd(S31) b) Ag-Cd(S32) c) Ag-Cd(S54) d) Ag-Cd(S64)

Figure 5. Neutron Images of AgCd tracer particles.

Figure 6 shows the comparison of Ag-Cd particles with pure Ag and Cd particles. The visibility of the Ag particles seems better than that of the Cd particles as shown in Fig. 6 d) and e), which may attribute to the difference in the particle diameter. Figure 7 shows edge identified images of each particle by applying Laplacian filter. Figure 7 (a), (c) and (d) show highly identified edges due to high cadmium content. Figure 7 (b) shows different edges and contrast for each particle due to inhomogeneous distribution of cadmium contents. This probably is attributed to the particle production method which is required to improve. Figure 7 (e) and (f) show pure silver and cadmium particles. The silver particles in Figure 7 (e) indicate lower intensity of edges were observed compared to the others and the circling shape edges were scarcely observed, which was difficult to recognize. The cadmium particles in Figure 7 (f) show similar edge intensity to the silver particles. However, the circling shape of edges of the cadmium particles were observed although lower edge intensity than the others. Thus, the visibility of the silver particles by human eye was better than the cadmium particles, however, edge recognition of the cadmium particles could be better than the silver particles in the present experiment.



a) Ag-Cd (S32) b) Ag-Cd(S54) c) Ag-Cd(S64) d) Ag e) Cd

Figure 6. Neutron images of Ag-Cd, Ag, and Cd particles.

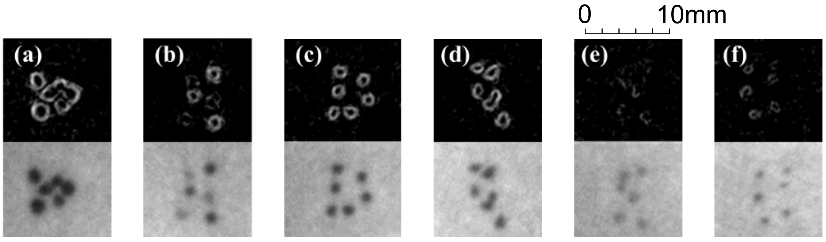


Figure 7. Edge identification of particle images of (a) Ag-Cd(38)(S31), (b) Ag-Cd(18)(S54), (c) $AuCd_3$(63.1)(A14-1), (e) AgCd(18)(S54) and (e) Ag(S01), and (f) Cd(C01)

3.2 Neutron imaging of fluidized bed

Figure 8 shows the successive neutron images of the fluidized bed. The gas flow rate was 100 l/min. White region denotes the gas phase, gray region denotes the stainless-steel bed, and the black points denote the Cd particles. From these images, gas phase, bed materials, and Cd tracer particles can be clearly identified. The gas bubble is rising and the bed materials in the central region beneath the gas bubble are blown up resulting in the separation of gas bubble at t =100 ms. Velocity measurements can be also performed by tracking each Cd tracer suspended in the bed materials as shown in Fig.9, where the local void fraction is also denoted by color. The density of the stainless steel is smaller than that of Cd, which might cause some velocity drift of tracer particles in the bed materials. Therefore, further improvements should be required to adjust the particle size and its density to enhance the traceability.

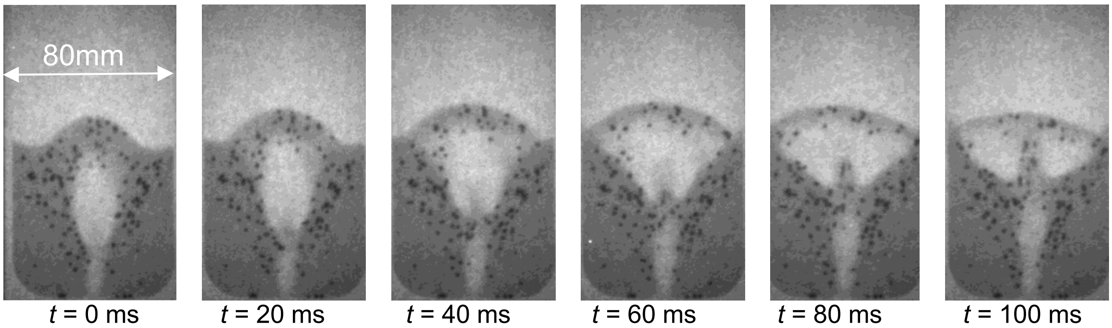


Figure 8. Successive images of flow behavior in fluidized bed.

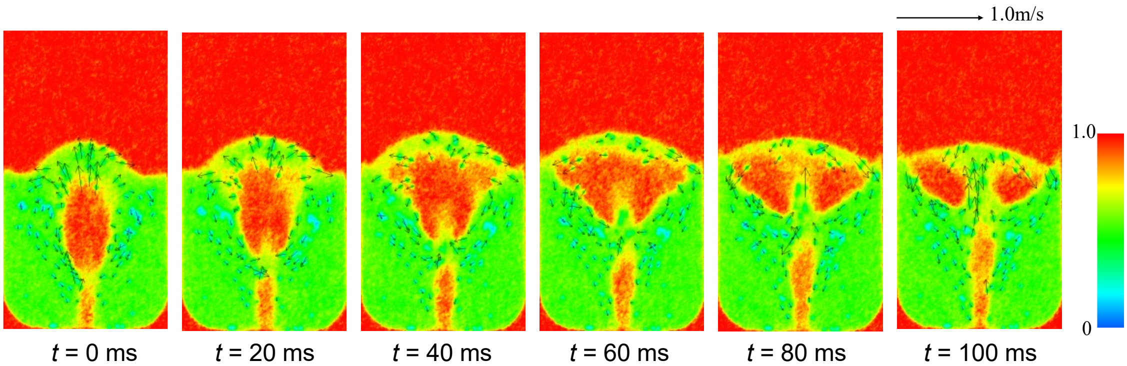


Figure 9. Processed images of flow behavior in fluidized bed.

4. Conclusion

In this study, several tracer particles have been made to investigate the visibility of the tracer particles for neutron imaging, which can be applied to liquid-metal flow or fluidized bed with heavy metal. Experimental results show the AgCd particles are the good candidate for the measurement of Newton alloy liquid-metal or fluidized bed.

As for the preliminary experiments of fluidized bed, pure Cd tracers were applied to the fluidized bed of stainless particles. The gas phase, the bed materials, and the Cd tracer particles can be clearly visualized by the high-speed neutron imaging at 250 fps by using the TNRF of the JAEA.

Acknowledgments

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References

[1] Melling A and Whitelaw J H 1973 *Symposia on Turbulence in Liquids* 107
[2] Takenaka N, Asano H, Fujii T, Motomura Y, Ono A, Matsubayashi M, Tsuruno A 1996 *Nuclear Instruments and Methods A* **377-1** 156
[3] Saito Y, Mishima K, Tobita Y, Suzuki T, Matsubayashi M 2005 *Experimental Thermal and Fluid Science* **29-3** 323
[4] Saito Y, Mishima K, Tobita Y, Suzuki T, Matsubayashi M, Lim I C, Cha J E 2005 *Nuclear Instruments and Methods A* **542** 168
[5] Thakre S, Konovalenko A, Ahlin A, Kudinov P 2022 *Annals of Nuclear Energy* **174**
[6] Werther J 1999 *Powder Technology* **102** 15
[7] Chang L C, Read T A 1951 *Trans. Am. Inst. Min. Metall. Eng.* **189** 47
[8] Guthikonda V S, Elliott R S 2009 *Continuum Mech. Thermodyn.* **21** 269