Measurements of pitch-off diameter of gas bubbles in liquid metal

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Abstract. To determine the separation diameter of bubbles in a liquid metal melt, an original technique based on the conductivity method is proposed. A thin electrode is installed in the center of the outflow channel, and the separation of bubbles is determined by closing and opening the electrical circuit. In this way, the separation frequency of the bubbles and their volume can be determined. Additional studies are carried out on a transparent liquid (water). It is shown that the presence of an electrode has little effect on the process of bubble detachment. The processing data of high-speed video filming and the proposed method in a transparent liquid coincide with high accuracy. Measurements of the frequency of bubble detachment in melts of the Rose and lead alloy are carried out. The results obtained are used to tune two-phase flow models when simulating fast neutron reactors with heavy liquid metal coolants.

1. Introduction
The study of the formation of gas bubbles in a liquid metal melt is of great interest both for the metallurgical industry [1] and to produce high-quality steel; argon bubbles are bubbled through the melt. In a nuclear reactor unit, the formation of steam-gas bubbles in the coolant can occur during inter-circuit interaction in a case of a leak in the steam generator.

The separation diameter of a gas bubble in a liquid has been studied in many works and the main regularities in determining the separation diameter of a bubble have been established. For metal melts, such data are significantly limited, first, by the difficulty of measurement due to the optical opacity of the metal melt. In addition, studies in molten lead and its alloys are difficult because of the high temperature and low permeability of lead to X-ray radiation. This imposes several restrictions on possible research methods. Basically, experiments in a lead or lead-bismuth melt environment are carried out using resistive sensors [2]. In a recent work [3], an original non-contact method was proposed for measuring the rate of ascent of bubbles in liquid metal, however, the method of conducting experimental studies is rather laborious.

In this paper, we propose and test a method for measuring the separation radius of a bubble in a liquid metal, based on a change in the electrical contact at the mouth of a gas outflow into a liquid upon bubble separation.

2. Experimental setup
The experiments were carried out in the working section, being a vertical cylinder with a diameter of 68 mm and a height of 800 mm, which was in a thermostatically controlled box that maintained the required temperature of the liquid metal contained inside. The height of the liquid metal in the cylinder
was 600 mm. Gas outflow occurred through a nozzle with an inner diameter of 3 mm, located at the bottom end of the cylinder. The separation diameter of a gas bubble was measured in a liquid Rose alloy at a temperature of 135° C and, partially, in liquid lead at a temperature of 420° C. After filling the test section with melt and holding for about 5 minutes, necessary to stabilize the thermophysical parameters, the experiments began. The melt temperature was measured using thermocouple (Type K). In addition, with the help of several thermocouples, measurements and control of the temperature of the key elements of the unit were carried out. Argon was used as the gas phase, as a medium that does not lead to the oxidation of lead-containing alloys. The gas flow rate during the experiments was varied within 10–1000 ml/min.

Measurement of the pitch-off diameter of a gas bubble in liquid metal was based on a change in the electrical contact at the mouth of the gas outflow into the liquid upon bubble separation (see figure 1). For this, an electrode with a diameter of 0.125 mm was inserted in the center of the nozzle. In this case, it was possible to change the position of the end of the electrode relative to the end of the outflow tube. The second electrode was a metal melt. A weak voltage (5 V) was applied to the electrodes. During the formation of the gas bubble, the electrical circuit was opened. When the bubble separated, the electrode again found itself in the metal melt and the electrical circuit was closed. This process was repeated during the formation and detachment of the following gas bubbles. The volume of pitch-off bubbles can be estimated using the following formulae:

$$V_B = \frac{Q_G}{F}$$

(1),

where $V_B$ is the bubble volume, $Q_G$ is the gas flow rate, and $F$ is the frequency of detachment. Bubble pitch-off diameter can be estimated using the volume of bubble.

To adjust the measuring technique, the process of formation of bubbles in water was visualized while maintaining a geometrically similar system of generation of bubbles. An example of bubble formation is shown in figure 1. Experiments in a transparent liquid were carried out with and without a measuring electrode. The bubble rate was determined using computerized image processing. It was shown that the presence of an electrode does not affect the separation diameter in the range of gas flow rates considered in this study.

![Figure 1. The scheme of measurements and photographs of pitch-off process.](a) Q$_G$ = 300 ml/min.

During experiments on the study of the separation diameter of a gas bubble in a metal melt, the duration of bubble formation and the frequency of generation of gas bubbles were measured. The measurement results are a graph of the voltage between the electrodes versus time. Spectral analysis of
this distribution serves to obtain an isolated frequency that corresponds to the frequency of bubble detachment. Typical examples are shown in figure 3, depending on the gas flow rate. From the separation frequency, knowing the gas flow rate, the value of the separation diameter of gas bubbles in the liquid metal was calculated.

At low gas flow rates, a pronounced frequency peak is noticeable, which corresponds to the separation frequency of the bubbles. With an increase in $Q_G$, some blurring of the spectral characteristics of the signal occurs, however, the fundamental frequency corresponding to the period of bubble detachment stands out – figure 3. According to the data shown in figures 2 and 3, the estimated bubble diameter is 6.6 mm, 7.2 mm, 8.6 mm, 9.1 mm for flow rates of 20, 300, 500, 900 ml/s, respectively. Photographs of bubbles at detachment in water for different $Q_G$ are presented in figure 4.

**Figure 2.** The signal from the sensor and its spectrum depending on the gas flow rate: (a) 20 ml/sec, (b) 300 ml/sec. Rose alloy, $T = 135^\circ$C.

**Figure 3.** The signal from the sensor and its spectrum depending on the gas flow rate: (a) 500 ml/sec; (b) 900 ml/sec. Rose alloy, $T = 135^\circ$C.
Figure 4. Photographs of bubbles at detachment in water:
(a) $Q_g = 100$ ml/min; (b) $Q_g = 300$ ml/min; (c) $Q_g = 600$ ml/min; (d) $Q_g = 1000$ ml/min.

The performed measurements allowed determining the separation diameter of the gas bubble in the Rose alloy and its dependence on the gas flow rate. The pitch-off diameter of the bubble formed in the liquid Rose alloy depending on the gas flow rate. As expected, with an increase in the gas flow rate, the separation bubble diameter increased.

Separate single measurements with low gas flow rates of 10–50 ml/min were carried out during the formation of a gas bubble in liquid lead. The diameter of the bubbles corresponded to those in the liquid Rose alloy.

It should be noted that the bubble shape depends on the gas flow rate: the lower the gas flow rate through the outlet hole, the more spherical the bubble shape. The minimum separation bubble diameter corresponds to the minimum gas flow rate and correlates with the diameter of the outflow hole and the capillary constant. It is known that the separation size of the bubble is determined by the capillary constant, with the same diameter of the outflow hole. So, for water the capillary constant is $2.73\text{mm}$ and $T = 20^\circ\text{C}$, for lead the capillary constant is $2.07\text{mm}$ and $T = 450^\circ\text{C}$, and for Rose alloy, the capillary constant is $2.08\text{mm}$ and $T = 135^\circ\text{C}$. As one can see, this value for liquid metal is slightly less than for water. The bubble size is related to the capillary constant as [4]:

$$R_B \approx \frac{3}{\sqrt{g \rho L \sigma}} \cdot \sqrt{\frac{R_{OF} \delta_{CAPIL}}{\rho_L \rho_G}} = \frac{3}{\sqrt{g \rho L \sigma}} \cdot \sqrt{R_{OF} \delta_{CAPIL}}$$

where $R_B$ is the bubble radius, $R$ is the orifice radius, $\sigma$ is the surface tension, $g$ is the gravity acceleration, $\delta_{CAPIL}$ is the capillary constant, and $\rho_L$ and $\rho_G$ are the densities of liquid and gas, respectively. This is observed in measurements corresponding to low gas flow rates, at which an almost spherical bubble is formed. With an increase in the gas flow rate, the shape of the detached bubble is significantly distorted. At high gas flow rates through the outflow hole, the sizes of bubbles in liquid metal and water are practically the same.

Conclusions
Experimental studies of bubble pitch-off process have been carried out in water and heavy liquid metals using the conductivity probe. The influence of gas flow rate on bubble diameter at detachment has been estimated. Despite the successful test measurements in a transparent liquid in the presence and absence of a measuring electrode, its effect on the separation of bubbles, especially at low $Q_g$, is an open question. For the development of the proposed method, it is recommended to use conductive spraying on the wall of the outflow capillary. The results of the work have been used to refine the correlations of the dependence of the bubble diameter and the rate of its generation on the gas flow rate [5].
References
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