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Determination of Parameters of Gas Phase Moving in Liquid Metal-Gas Flow in Magnetic Field of Permanent Magnets by Ultrasonic Pulse Echo Method

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Abstract—The article presents measurements and calculations of selected gas phase parameters in a liquid metal-gas flow in a magnetic field. The gas phase were argon bubbles, while the liquid metal was the GaInSn eutectic. The flow velocities of the gas bubbles, their equivalent diameter, and drag coefficient values were calculated for different argon inlet nozzles. The boundaries between the rise of individual bubbles and the chain flow were also indicated. The ultrasonic pulse echo method was chosen as the measurement method.

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1. INTRODUCTION

Two-phase liquid metal-gas flows are found in many technological processes. Examples are metallurgical processes in secondary steel refining. The processes of degassing, purification, or refining of liquid metal are directly associated with its purge with argon. The refining efficiency depends, among others, on the dimensions and velocity of the rising bubbles, their area of rise, and the stream flow of bubbles. These quantities are related to the Reynolds, Eötvös, and Weber numbers or the bubble drag coefficient, the knowledge of which can allow modelling liquid metal-gas flows. Therefore, it is very important to study the parameters of a gas phase moving in a liquid metal. Such measurements are very difficult to realize in industrial conditions, and therefore they are carried out at laboratory stands, via pumping of argon bubbles into a liquid metal, e.g., GaInSn. The work is also carried out in the presence of a magnetic field, which affects the values of the gas bubble sizes. The article presents the results of measurements and calculations of selected parameters of argon bubbles moving in a liquid metal GaInSn and a magnetic field with an average induction B = 300 mT. The research was carried out in the area of single bubble rising and in a chain flow. The article also indicates the boundaries between the rising of individual bubbles in the magnetic field, i.e., the area where there is no influence of one bubble on another, and in a chain flow. The ultrasonic pulse echo method was chosen as the measurement method.

2. MEASUREMENT METHOD

Of the methods of testing two-phase liquid metal-gas flows, non-invasive techniques have become the most important because they do not interfere with the flow and do not disturb the velocity profile or the distribution of the positions and diameters of the rising bubbles. They allow real-time determination of the basic values of these flows. The research uses the ultrasonic Doppler methods (UDV) [1–5], CT X-ray techniques [6–10], and methods involving vortex flows and electromagnetic sensors [11, 12]. The ultrasonic pulse echo method is becoming increasingly important in analysis of two-phase flows, including liquid metal-gas ones. The echo method has found the widest application in non-destructive testing of materials (ultrasonic flaw detection). It is the basic way of detecting discontinuities of materials, also providing information about their location, dimensions, or spatial orientation. If the gas phase is considered as flow discontinuity, the pulse echo method can be used to determine the quantities characteristic for two-phase liquid metal-gas flows. This method was described in detail by the author

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in articles [13–17] and is presented in Fig. 1. Transmitted pulses from the ultrasonic head pass through the coupling layer and the front wall of the container and are reflected from gas bubbles moving in the liquid metal and found in the ultrasonic field. The reflected ultrasonic pulses return as echo back to the head, which works as the transceiver. Some of them reach the back wall of the container and bounce back from it to the transmitter.

The trajectory of the pulses can be represented in the form of echo amplitudes on the screen of the ultrasonic flaw detector the head is connected to. This is called Z-type imaging and is shown in the top of Fig. 1.

The ultrasonic flaw detector is constructed in such a way that it only registers signals with amplitude exceeding the height of the gate shown in the lower part of Fig. 1. With this gate set, the calculations

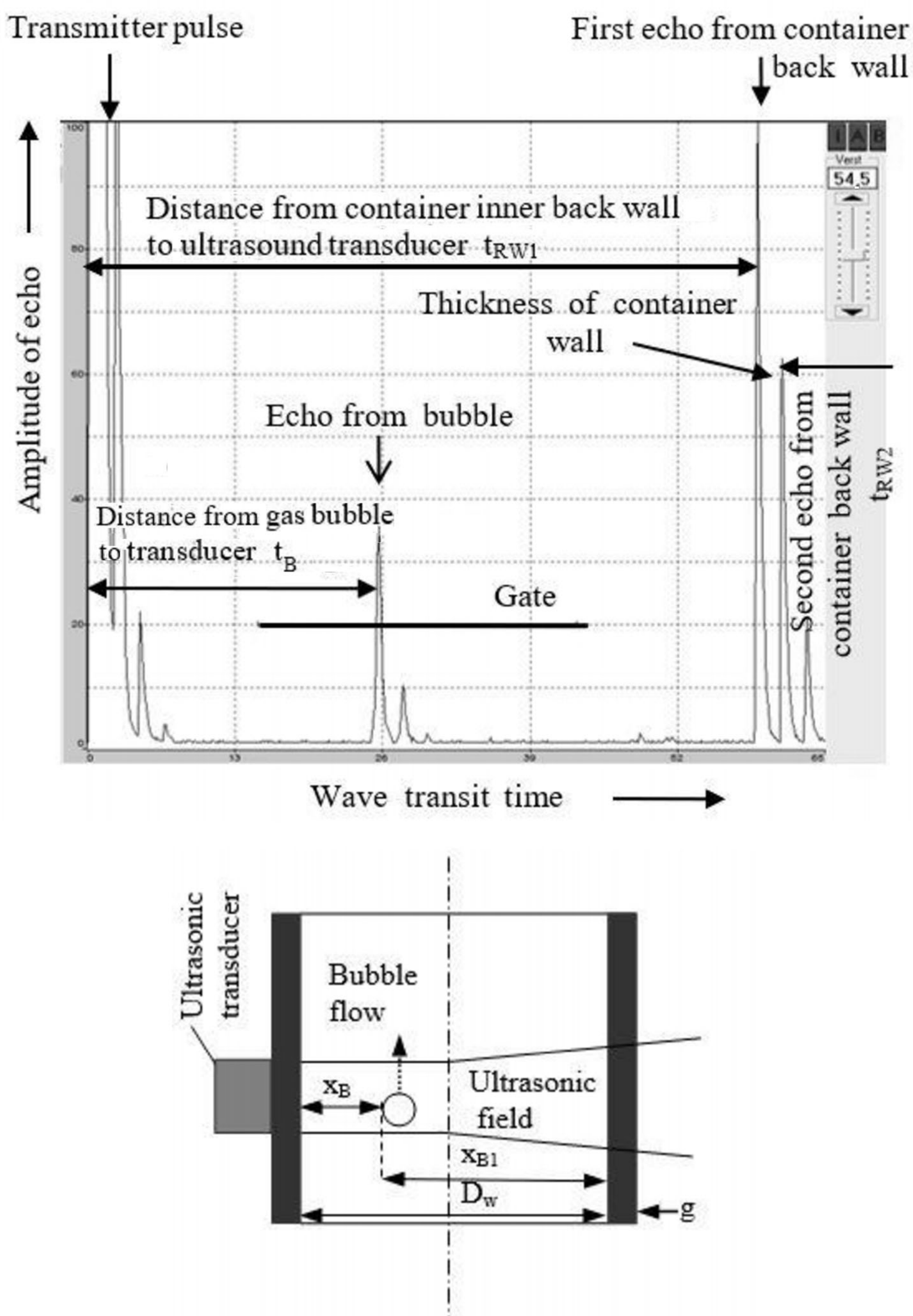


Fig. 1. Ultrasonic pulse echo measurement method [13].

give the time of transit from the transmitter to the reflector and back. Knowing the value of the wave velocity in the container wall and in the tested medium, one can calculate the distance from the reflector. The equation below gives the distance x_{B1} from the bubble to the back wall of the tank, its determination requiring only knowledge of the ultrasonic wave velocity in the liquid metal:

$$x_{B1} = \frac{(t_{RW1} - t_B) \cdot c}{2}. \tag{1}$$

Knowing this distance and the value of the inside diameter of the container, it is easy to determine the distance x_B. At the same time, by changing the length of the gate or its position, the place inside the container in which signals (echoes) from bubbles are recorded is determined. The frequency of repetition of transmitting ultrasonic pulses (IFF) is selected such that the echo reflected from the back wall returns faster than the next pulse is sent.

3. METHOD OF RESEARCH

The measurements were carried out on the stand presented in Fig. 2.

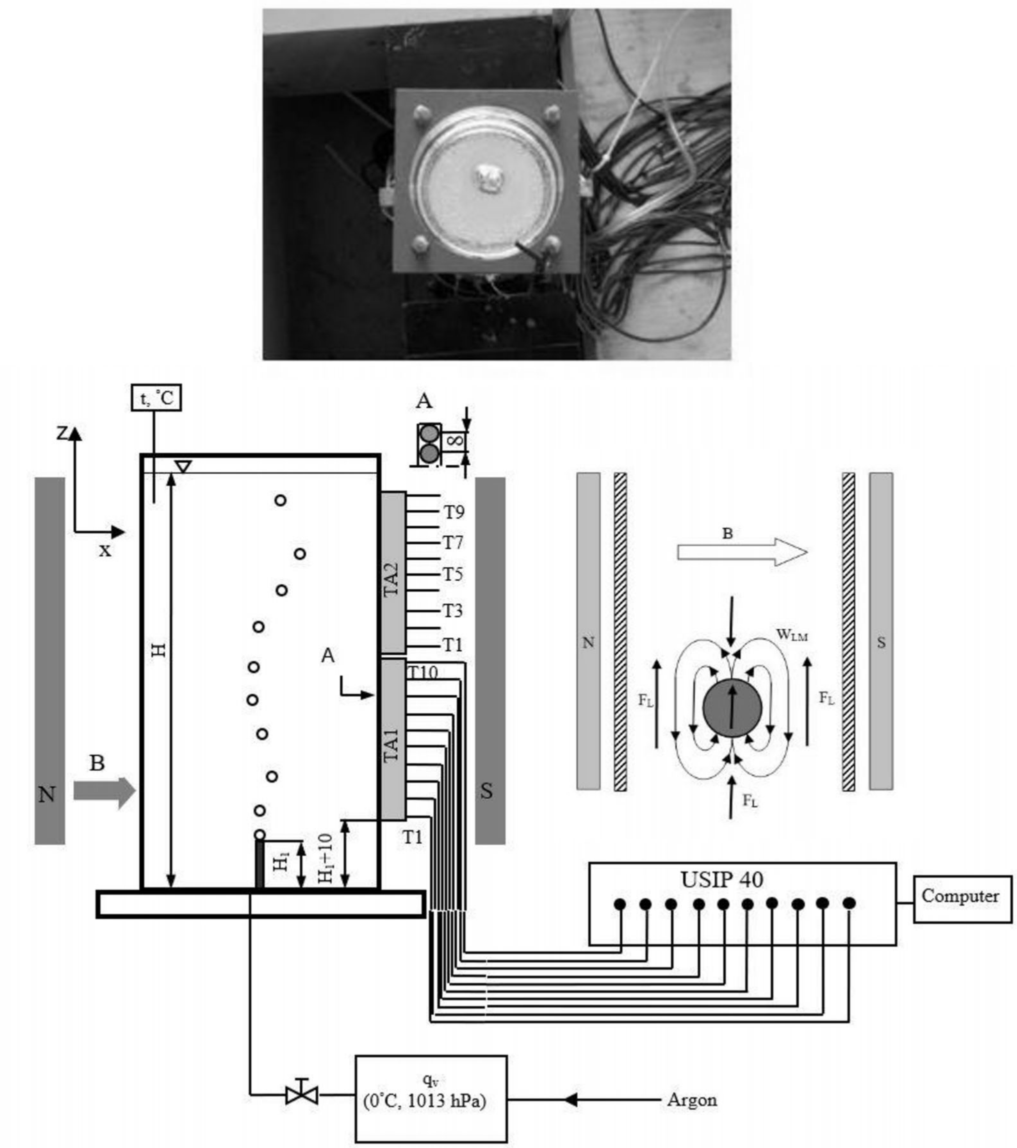


Fig. 2. Measurement stand [17].

Argon in the form of gas bubbles was injected through nozzles into a container with an internal diameter D = 80 mm, filled with liquid metal GaInSn to a height H = 210 mm. In the measurements, the internal diameter of the nozzles was $\varphi = 0.5$ mm, $\varphi = 0.9$ mm, and $\varphi = 1.2$ mm and, their height was H1 = 20 mm. The argon volume flow q_v was measured by a class 1 flowmeter with a thermal sensor (Mass-Flo, MKS Instruments); the flow varied from a single-bubble flow to a chain flow. The first ultrasonic head (TA1) was mounted 10 mm above the argon inlet nozzle. It consisted of 10 sensors of 5 mm in diameter, each having a frequency of 15 MHz, with a spacing of 8 mm; the total distance covered by the sensors was 72 mm. The recording of signals from flowing bubbles was carried out with heads, installed one above the other (TA1 and TA2) so that it was possible to calculate their parameters on a track of approximately 160 mm. The ultrasonic heads were alternately connected to a 10-channel USIP 40 Box ultrasonic flaw detector controlled from a computer using the UltraPROOF program (Krautkramer company). The method of measuring the time of echo transit from bubbles enabled precise determination of the area of flowing bubbles with an echo transit time resolution of 2.5 ns, corresponding to a change in the bubble position in the liquid metal of approximately 0.004 mm. For the pulse repetition frequency, the maximum value of 14286 Hz was set for the 10 ultrasonic sensors, and the signal amplification was chosen such that the signal amplitude exceeded 20%, i.e., the height of the beam in Fig. 1. The signal sampling period was 0.7 ms, and the signal recording time was set equal to 360 s. The permanent magnets were placed at a distance of 115 mm from each other; their dimensions were 160 × 100 × 50. The average induction value determined with the teslameter model 5180 was B = 300 mT. The Lorentz force present in a magnetic field with an induction B is described as shown below [18], and the return of this force is shown in Fig. 2:

$$\vec{F}_L = \vec{j} \times \vec{B} = \sigma_{el}(\vec{w}_{LM} \times \vec{B}) \times \vec{B}, \tag{2}$$

where j is the current density, w_{LM} is the liquid metal velocity, σ_{el} is the electric conductivity, and B is the magnetic induction.

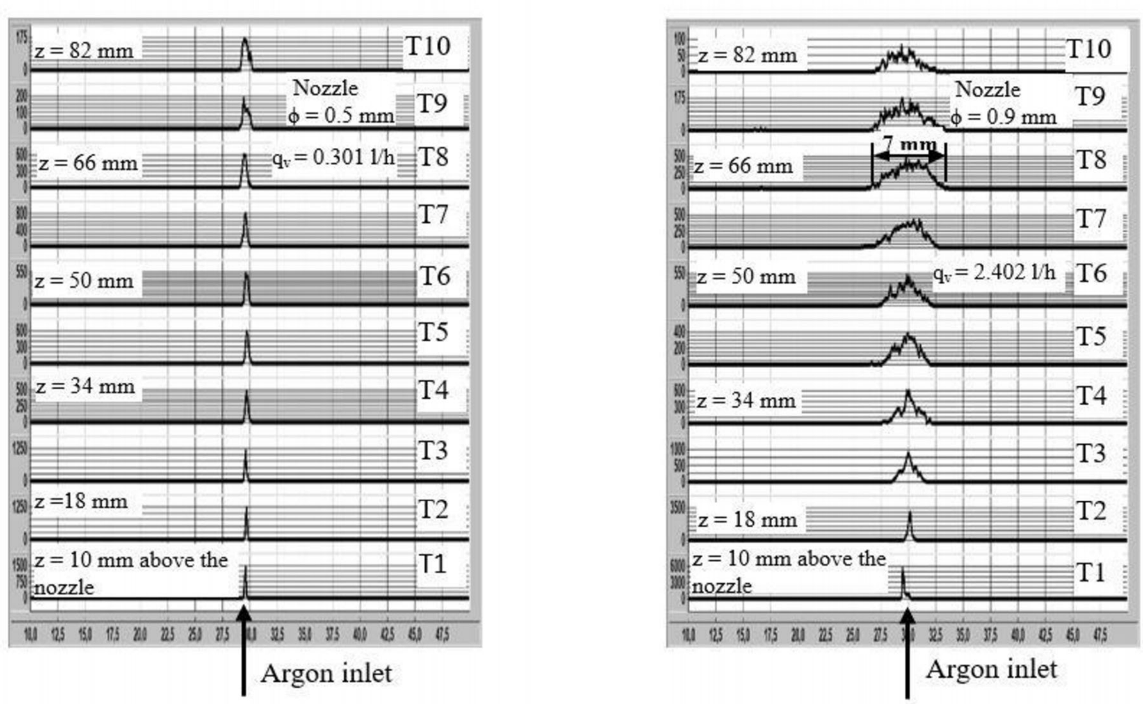


Fig. 3. Distribution of positions of argon bubbles in liquid metal GaInSn for inlet nozzles with $\varphi = 0.5$ mm and $\varphi = 0.9$ mm.

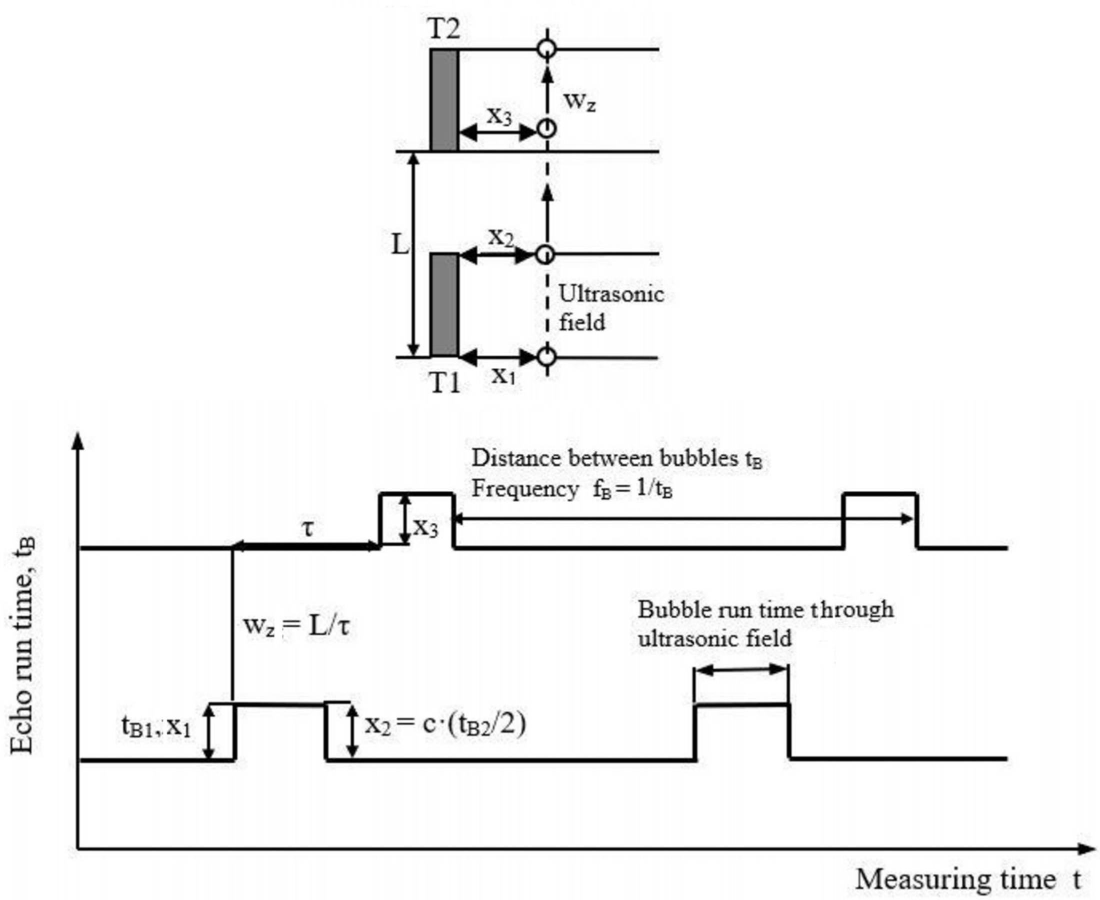


Fig. 4. Interpretation of signals from moving argon bubbles in liquid metal GaInSn.

4. INTERPRETATION OF MEASURED SIGNALS AND METHOD OF DETERMINATION OF CHARACTERISTICS

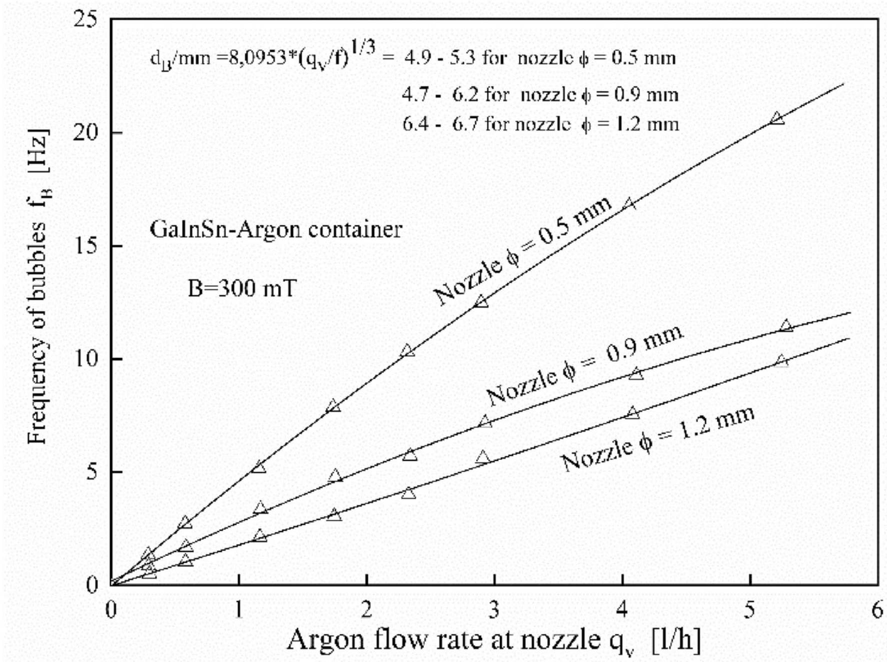
Figure 3 shows distribution of gas bubbles moving in a magnetic field. Analysis of all the measurements carried out clearly shows that for small flows, the argon bubbles move practically rectilinear, while for larger flows, the distribution width does not exceed 10 mm.

Figure 4 shows interpretation of recorded measurement signals from moving bubbles. It presents the bubble velocity w_B, the distance from a bubble to the sensor, e.g., x_2, and a possible way of determining the bubble frequency f_B. It should be noted that the bubble frequencies can also be determined using the Fast Fourier Transform function of the recorded measurement signals. Since the trajectory of the bubbles in the magnetic field is practically a straight line.

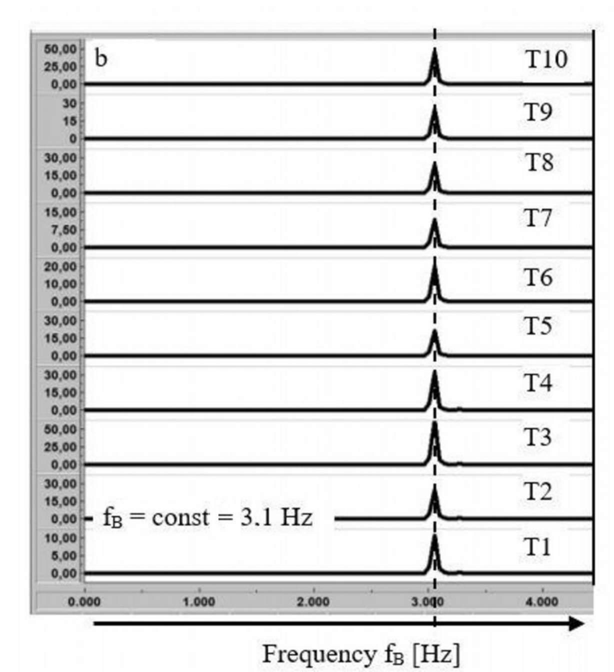
5. RESULTS

Figure 5a shows the dependence of the frequency of bubble formation on the argon volume flow. The frequency of the bubbles was calculated using the Fast Fourier Transform function of the measurement signals. Figure 5b depicts the bubble frequency values at the height of each ultrasonic sensor (T1 ÷ T10). It clearly shows that this frequency is constant, independent of the height of the sensor above the argon inlet nozzle. Knowing the frequency value, one can calculate the equivalent diameters of moving bubbles as follows:

$$d_B = \left(\frac{6q_v}{\pi f_B}\right)^{1/3}. \tag{3}$$



(a)



(b)

Fig. 5. Bubble formation frequency vs. gas flow at inlet nozzle and calculated bubble frequency values for each ultrasonic sensor.

For the nozzle with $\varphi = 0.5$ mm, $d_B = (4.9 \div 5.3)$ mm; for the nozzle with $\varphi = 0.9$ mm, $d_B = (5.7 \div 6.2)$ mm; for the nozzle with $\varphi = 1.2$ mm, $d_B = (6.4 \div 6.7)$ mm.

Figure 6 shows examples of the dependence of the bubble velocity on the height above the inlet nozzle for the nozzles with $\varphi = 0.5$ mm and $\varphi = 0.9$ mm.

Bubble velocities at each height were calculated according to Fig. 4. The relative standard deviations of the average velocities were as follows: 3.7% and 4% for the nozzle with $\varphi = 0.5$ mm; 3.4% and 3.8%

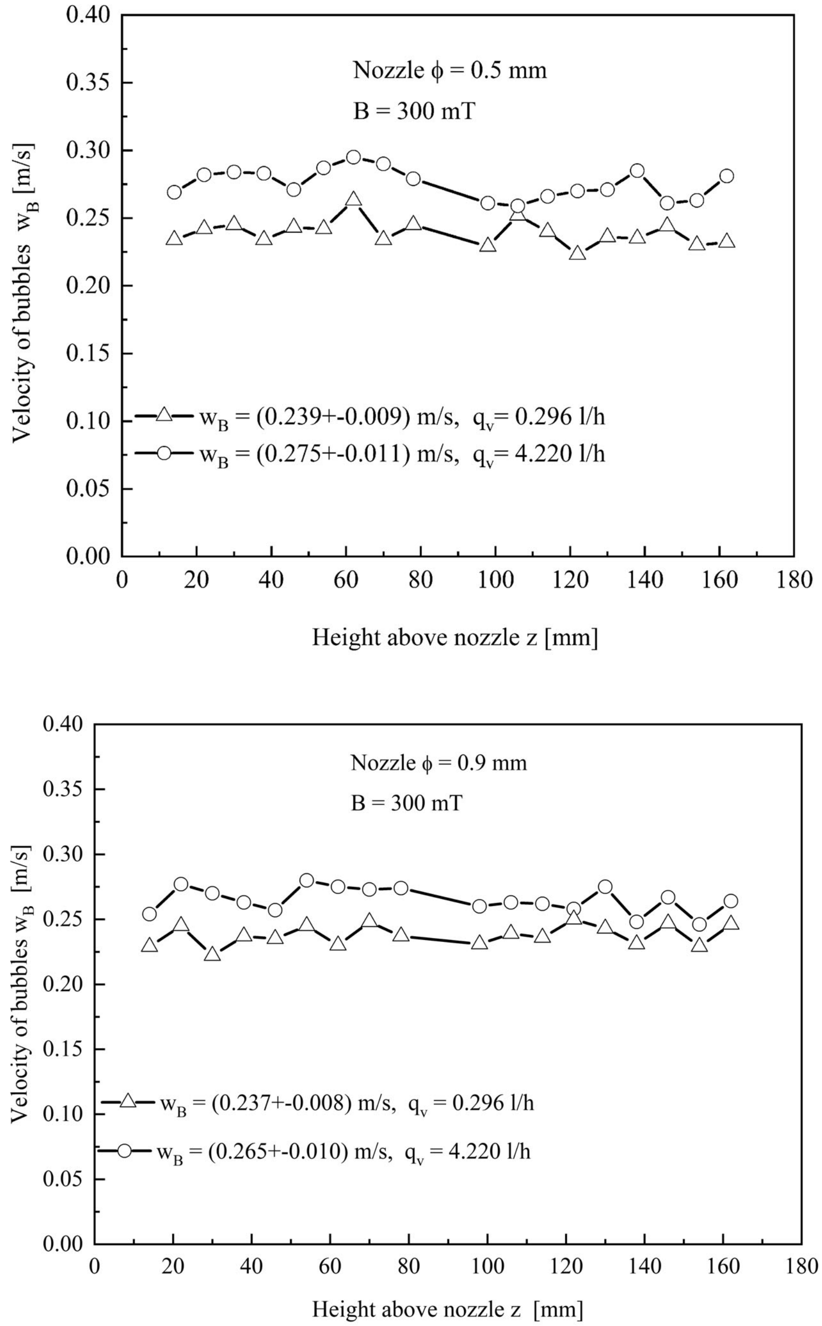


Fig. 6. Example of dependence of bubble velocity on height above gas inlet nozzle.

for the nozzle with $\varphi = 0.9$ mm. Calculations for all flow velocities showed that the relative standard deviations of the average velocities did not exceed 4%. It can be assumed that these velocities have constant values along the entire length of the trajectory of the bubbles. Knowing the average velocities w_B and the bubble frequency, one can calculate the distance Δz_B between two moving argon bubbles as follows:

$$\Delta z_B = \frac{w_B}{f_B}. \tag{4}$$

The upper part of Fig. 7 presents the dependence of the bubble velocity on the bubble equivalent diameter; the lower part shows the dependence of the bubble velocity on the equivalent diameter for 3

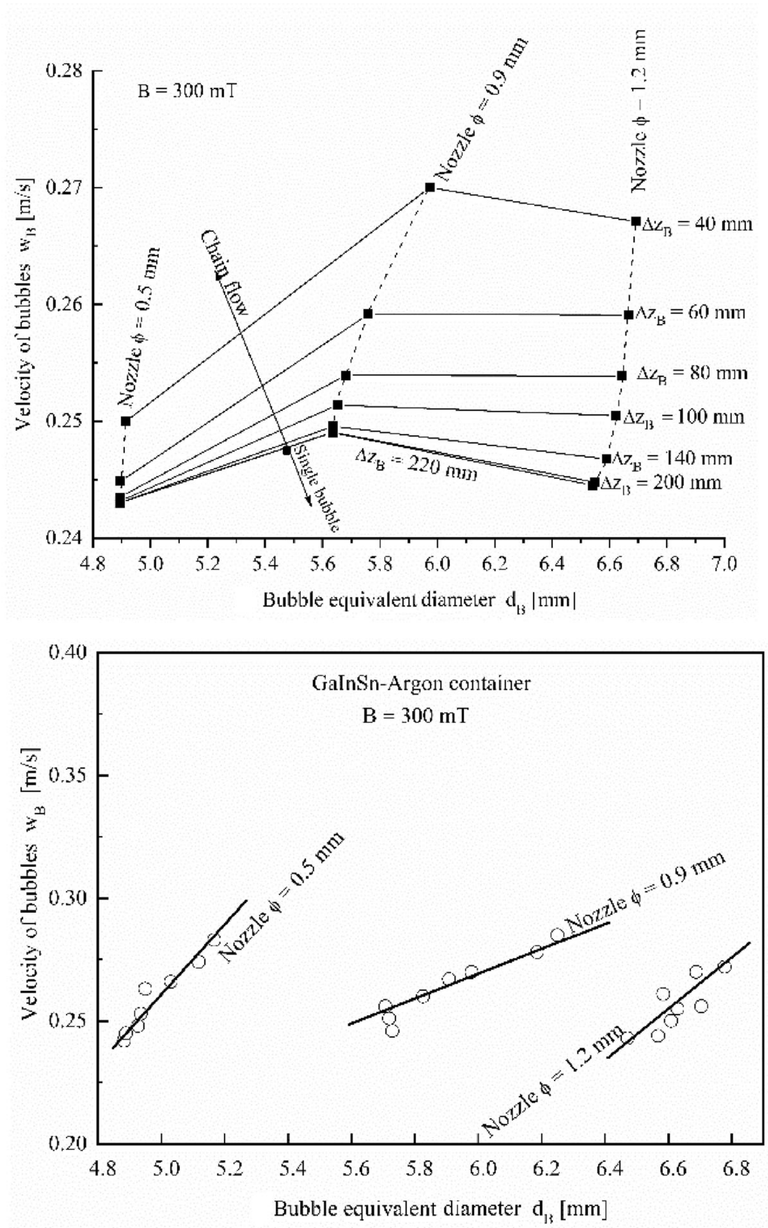


Fig. 7. Velocity of bubbles vs. their equivalent diameter.

different inlet nozzles and the distance between the moving bubbles. Figure 7 clearly shows that for an inter-bubble distance Δz_B of 200 and 220 mm, their velocities practically do not change. It can be concluded that an inter-bubble distance $\Delta z_B \geq 220$ mm corresponds to the rise of a single argon bubble in the liquid metal. For the nozzle with $\varphi = 0.5$ mm, this distance corresponds to argon flows $q_v < 0.25$ l/h; for the nozzle with $\varphi = 0.9$ mm, it corresponds to argon flows $q_v < 0.5$ l/h; for the nozzle with $\varphi = 1.2$ mm, it corresponds to argon flows $q_v < 0.6$ l/h.

Knowing the velocity values from the equivalent diameter of bubbles, one can determine the drag coefficient:

$$c_D = \frac{4}{3} \cdot \frac{(\rho_{LM} - \rho_B) \cdot d_B \cdot g}{\rho_{LM} \cdot w_B^2}. \tag{5}$$

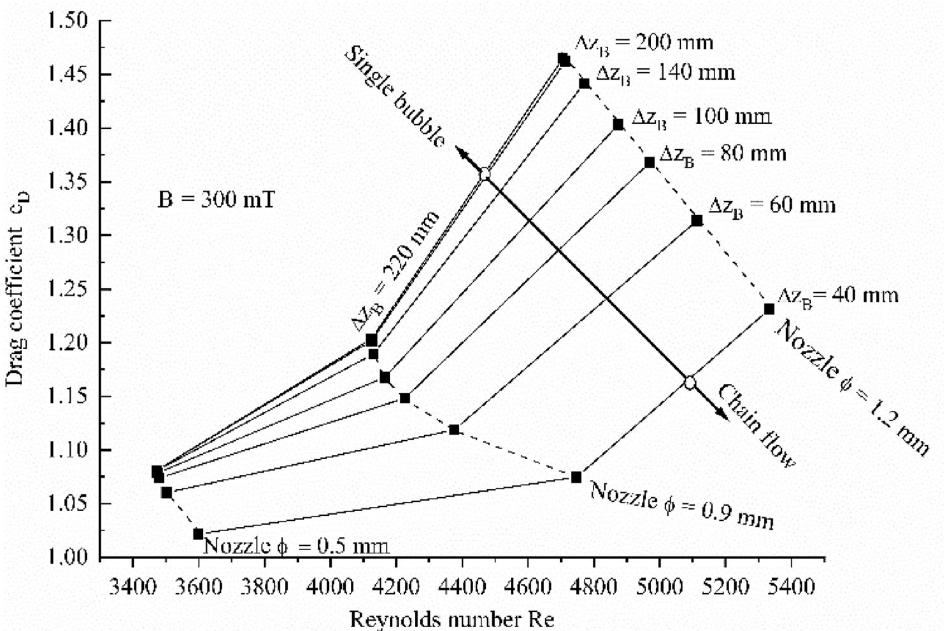


Fig. 8. Drag coefficient vs. Reynolds number.

Figure 8 shows the dependence of the drag coefficient on the Reynolds number for three argon inlet nozzles at constant distances between the moving bubbles. The Reynolds number was calculated as follows:

$$\mathrm{Re} = \frac{w_B \cdot d_B \cdot \rho_{LM}}{\mu_{LM}}. \quad (6)$$

This figure also shows that for a bubble distance of 200 and 220 mm, the drag coefficient values practically do not change for each of the nozzles. It can be assumed that the distance between the bubbles $\Delta z_B = 220$ mm is the one from which the rising of a single bubble begins. The values of the drag coefficients are in the following ranges: $(1.021 \div 1.081)$ for the nozzle with $\varphi = 0.5$ mm, $(1.075 \div 1.203)$ for the nozzle with $\varphi = 0.9$ mm, and $(1.231 \div 1.465)$ for the nozzle with $\varphi = 1.2$ mm.

6. CONCLUSIONS

In the article, selected parameters of argon gas bubbles moving in liquid metal GaInSn in a magnetic field of permanent magnets with the average induction B = 300 mT were determined. The measurements were made for three gas inlet nozzles with internal diameters of 0.5 mm, 0.9 mm, and 1.2 mm for single bubbles rising and for a chain flow. The measurements were made by the ultrasonic pulse echo method. The most important conclusions resulting from the research conducted are as follows:

—due to the arising Lorenz force, the trajectory of gas bubbles in the liquid metal is practically a straight line; for the examined gas flows, the width of the bubble distribution does not exceed 10 mm;

—the velocities of bubbles in the liquid metal are practically constant along the flow trajectory, the relative deviations of average velocities not exceeding 4%;

—the equivalent diameters for the tested flows and for the three argon inlet nozzles were in the range of $d_B = \langle 4.9 \div 6.7 \rangle$ mm;

—the inter-bubble distance $\Delta z_B = 220$ mm was the one from which the rising of a single argon bubble began. For the nozzle with $\varphi = 0.5$ mm, the argon volume flow $q_v < 0.25$ l/h; for the nozzle with $\varphi = 0.9$ mm, the argon volume flow $q_v < 0.5$ l/h; for the nozzle with $\varphi = 1.2$ mm, the argon volume flow $q_v < 0.6$ l/h;

—the drag coefficient values for the three considered nozzles and for the tested gas flows were in the range $c_D = \langle 1.021 \div 1.465 \rangle$.

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NOTATIONS

c—velocity of sound
B—magnetic induction
F_L—Lorentz force
f_B—gas phase formation frequency
w_B—gas phase velocity
d_B—bubble equivalent diameter
q_v—argon volume flow at the inlet nozzle
x_B—distance from the bubble to the container wall
w_{LM}velocity of liquid metal
c_D—drag coefficient
D_w—internal diameter of the container
H—height of filling the container with liquid metal
t_e—echo transit time
t_B—echo transit time from the bubble
t_{RW1} and t_{RW2}—echo transit times from the back wall of the container
z—height above the inlet nozzle
Δz_B—distance between bubbles
ρ_B and ρ_{LM}—density of the bubble and liquid metal
μ_{LM}—dynamic viscosity of liquid metal
φ—inner diameter of the inlet nozzle

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