Research of pressure pulsations during gas outlet to closed pipe area with liquid and installed disc barrier

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Abstract. A numerical simulation of the gas outflow to a closed region filled with liquid with a barrier disk was performed. The calculations were carried out using the VOF method, supplemented by the k-e turbulence model. Calculations were performed for three cases of 100, 200, and 300 mm distances of the disk from the injector with a gas outflow into water and liquid lead. The pulsations of axial pressure on a disk obstacle were investigated. It was found that the maximum pressure during pulsations of the upper gas volume in lead can be greater than the pressure in the gas receiver.

1. Introduction

In various technological processes of metallurgy, chemical and food industries, there are situations when a gas jet is injected into a volume with a liquid. An accidental release of a gas jet into the water can occur during oil and gas production on the shelf: during drilling, pipeline rupture, accidents of underwater equipment, and gas leakage from the ocean floor. In the energy sector this phenomenon is related to the safety of power equipment with liquid metal coolant. Gas jets in water are implemented in different flow regimes from a bubble flame to a stable jet and depend on the ratio of inertia and buoyancy forces. At low flow rates, a bubbling regime is observed, during which bubbles are formed near the hole. Rayleigh was one of the first how studied their behavior [1]. In [2], it was found that when bubbles are formed, a sound field is generated, which can be used to determine the size of the bubbles. Under certain conditions, a gas jet in a liquid can be stable at high flow rates. The formation of bubbles in this mode occurs far from the place of the outflow. In [3], the outflow of nitrogen into mercury was experimentally investigated for the first time. The distance at which the jet disintegrates into bubbles is investigated. Experimental works [4] and [5] are devoted to the structure of the flow of a submerged high-speed gas jet. The unsteady flow of air into water at a flow rate of 58 to 108 m/s was numerically studied in [6]. Numerical simulation was carried out using the VOF method with the RANS turbulence model. A correlation between the flow structure and the acoustic field was found. In [7], both experimental and numerical studies of gas jets flowing into water under a pressure of 1-3 MPa were carried out.

The problem of numerical simulation of unsteady gas outflow from a high-pressure vessel into a closed tube region filled with liquid with a gas volume in the upper part was previously solved in an axisymmetric, two-dimensional [8] and three-dimensional formulation [9]. It was found that the gas outflow process differs significantly for water and liquid lead. The formulation of the problem in the
form of a gas outflow into a closed tube region with a liquid is an approximation that is implemented in real technical applications. Inside the closed volume, in the real geometry of the working section of technical devices, in addition to the liquid, there are also structural elements (pipes, spacer grids, bushings, racks). The presence of these structural elements significantly changes the process of gas outflow into liquid. The problem of studying the force action on structural elements arises.

The aim of this work is numerical simulation of the injection of gas into a liquid (water, lead) into a closed tube region with a disc barrier inside it, to study the dynamics of axial pressure on the barrier during pulsation of the gas cavity.

2. Methods
To simulate the outflow of air into a tube filled with liquid (liquid lead, water), the compressibleInterFoam solver of the OpenFOAM package is used, which is based on solving the Navier-Stokes equations for a compressible medium supplemented by the k-ε turbulence model, and the interface is tracked using the VOF method (Figure 1). The computational domain is built on an axisymmetric geometry: the inner diameter of the pipe region is 0.2 m, and the length is 0.5 m. The liquid level is set at a height of 0.4 m. The remaining space is filled with air. The initial pressure in the working area is 20 \(10^5\) Pa. Gas outflow into the working area occurs through a nozzle with a diameter of 0.02 m. The initial air pressure in the cavity from which air is supplied is 180 \(10^5\) Pa. The initial temperature of air and liquid lead is 650 K, and the temperature of water is 300 K. The simulation is carried out for three different cases, in which a disk barrier with a diameter of 0.1 m and a thickness of 0.01 m is installed at different distances from the hole: 100, 200, and 300 mm. A detailed description of the calculation methodology is presented in previous works [8, 9].

Figure 1. Computational domain: 1 – receiver with high pressure air, 2 – injector, 3 – working volume, \(W\) – wall type condition, \(P_i\) – the condition of inflow-outflow at constant pressure, \(ax\) – axis symmetry condition, \(h\) – the liquid level, \(H\) – height of the working volume, \(r\) – radius of the gas volume, \(L\) – length of the gas volume, \(r_i\) – radius of the injector, \(L_i\) – length of injector, \(r_d\) – radius of disk, \(L_d\) – width of disk, \(h_d\) – installation level of disk, top figure: red – liquid, blue – gas, bottom figure: red – high pressure, blue – low pressure.

3. Results
Figures 2, 3 and 4 show the field of the volumetric liquid content and axial pressure when air flows into water with a disk at a distance of 100 mm, 200 mm and 300 mm, respectively. The axial pressure in front of the disc is determined by line 1, behind the disc, it is determined by line 2, and in the upper volume, it is determined by line 3. The presence of a disc barrier significantly changes the process of gas outflow into water. The disc barrier blocks the upward propagation of the gas jet and its mixing with the upper volume. The pulsation of the upper gas volume occurs when the pressure rises due to the outflow of the gas jet. Pressure pulsations in the gas volume occur with a period of about 7.5 ms (Figures 2.b, 3.b, 4.b, line 3). Damping of pulsations occurs faster at the greatest distance of the disk from the injector. The explanation for this phenomenon can be associated with the volume of the gas jet. When the disk is located at a great distance, the gas jet is formed with a large volume and a higher degree of dispersion (Figures 2.a, 3.a, 4.a). The axial pressure behind the disc (Figures 2.b, 3.b, 4.b, line 2) changes in antiphase relative to the pressure in the gas volume (line 3). The pressure in front of
the disk at first increases sharply during the formation of the gas jet. After the formation of the jet between the injector and the disc, the pressure begins to pulsate. The frequency of pressure pulsations in front of the disk is higher than behind it. This is due to the pulsations of the gas jet velocity. When the disc is at a distance of 100 mm, the pressure in front of it is higher than behind the disc. For a distance of 200 mm, the axial pressure drop across the disc is reduced. The axial pressure drop across the disc can be negative at a distance of 300 mm. This phenomenon occurs at the time when the compression phase of the upper gas volume occurs.

![Figure 2](image-url)

**Figure 2.** The field of the volumetric liquid content (red - liquid, blue - gas) at different times (a) and axial pressure (b) during air injection into water: 1-pressure in front of the disk, 2-pressure behind the disk, 3-pressure in the gas volume, the disk is at a distance of 100 mm.

Figures 5, 6 and 7 show the field of the volumetric liquid content and axial pressure during the outflow of air into liquid lead with a disc barrier at a distance of 100 mm, 200 mm and 300 mm, respectively. The process of gas outflow into liquid lead occurs with the formation of a gas slug at the bottom wall of the tube due to the high density of the liquid. The presence of the disc barrier additionally blocks the upward gas propagation. When a gas slug is formed, the upper gas volume pulsates with an increase in pressure due to the outflow of a gas jet.

Pressure pulsations in the gas volume occur with a period of about 12.5 ms (Figures 5.b, 6.b, 7.b, line 3). In contrast to the process of outflow into water for lead, attenuation of pulsations in the gas volume is not observed. The maximum pressure during pulsations of the upper gas volume may be greater than the pressure in the gas receiver. The maximum pressure during the pulsation of the upper gas volume was 23-25 MPa. The explanation for this phenomenon can be associated with the large inertia of the liquid, which causes an increase in hydrohammer effects.

![Figure 3](image-url)

**Figure 3.** The field of the volumetric liquid content (red - liquid, blue – gas) at different times (a) and axial pressure (b) during air injection into water: 1-pressure in front of the disk, 2-pressure behind the disk, 3-pressure in the gas volume, the disk is at a distance of 200 mm.
The pulsations of the axial pressure behind the disc (Figures 5.b, 6.b, 7.b, line 2) vary depending on the location of the disc barrier (line 3). At a distance of 100 mm, the pressure pulsations behind the disc are out of phase with the pressure in the upper gas volume (Figures 5.b, lines 2, 3). The frequency of pressure pulsations behind the disc is greater than the frequency of pressure pulsations in the upper gas volume at a distance of 200 mm (Figures 6.b, lines 2, 3).

At a distance of 300 mm, the pressure pulsations behind the disc are in phase with the pressure in the upper gas volume (Figures 7.b, lines 2, 3). The pressure in front of the disk is determined by the formation and pulsation of the gas slug below. When the disc is at a distance of 100 mm, the pressure in front of it is higher than behind the disc. For a distance of 200 mm, the axial pressure drop across the disc can be either positive or negative. The axial pressure drop at a distance of 300 mm on the disk is determined by the phase of the pulsations of the upper gas volume. In the unloading phase, the pressure drop across the disc is positive, in the compression phase it is negative.

Figure 4. The field of the volumetric liquid content (red - liquid, blue – gas) at different times (a) and axial pressure (b) during air injection into water: 1-pressure in front of the disk, 2- pressure behind the disk, 3- pressure in the gas volume, the disk is at a distance of 300 mm.

Figure 5. The field of the volumetric liquid content (red - liquid, blue – gas) at different times (a) and axial pressure (b) during air injection into lead: 1-pressure in front of the disk, 2- pressure behind the disk, 3- pressure in the gas volume, the disk is at a distance of 100 mm.
4. Conclusion

The outflow of an air jet in a liquid with different densities (water, lead) into a closed tube region for different distances from the disk barrier to the injector is studied numerically. It is shown that the presence of a disk barrier significantly changes the process of gas outflow into water. There is a blockage of the upward propagation of the gas jet and its mixing with the upper volume. The period of pressure pulsation in the upper gas volume is revealed. It is shown that the attenuation of the pulsations of the upper gas volume in water depends on the location of the disc barrier from the injector. It is shown that, in contrast to the process of gas outflow into water for lead, the attenuation of pulsations in the gas volume is not observed. It is found that the maximum pressure during pulsations of the upper gas volume in lead can be greater than the pressure in the gas receiver. When the disk is installed at a distance of 100 mm, the first pressure peak in the upper gas cavity is 23 MPa, for 200 mm the first pressure peak is 20.5 MPa, and for 300 mm the first pressure peak is 21.5 MPa with the initial pressure in the receiver of 18 MPa.

**Figure 6.** The field of the volumetric liquid content (red - liquid, blue – gas) at different times (a) and axial pressure (b) during air injection into lead: 1-pressure in front of the disk, 2- pressure behind the disk, 3- pressure in the gas volume, the disk is at a distance of 200 mm.

**Figure 7.** The field of the volumetric liquid content (red - liquid, blue – gas) at different times (a) and axial pressure (b) during air injection into lead: 1-pressure in front of the disk, 2- pressure behind the disk, 3- pressure in the gas volume, the disk is at a distance of 300 mm.
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