Simulation of an unstationary process of gas outflow into an open pipe area with a ring assembly filled with a liquid

M V Alekseev and S I Lezhnin
Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, 630090, 1 Ac. Lavrentyev Ave., Russia
E-mail: almaxcom@mail.ru

Abstract. Gas outflow into a cavity with different annular assembly filled with liquid by the VOF method, supplemented by the k-ε turbulence model, is numerically simulated. Calculations are performed for three types of ring assembly. Principal scenarios of bubble growth outside the assembly and annular jets inside it are obtained. The characteristic expiration times are investigated.

1. Introduction
The process of gas injection into liquid is found in many technical fields such as energy, metallurgy, chemical and food industries. Also, these processes are found in marine transport systems and in the process of exploration and production of gas and oil. There is also a utilitarian application of this phenomenon for the nuclear industry related to the safety of power equipment with a liquid metal coolant.

In the case of a gas jet outflow into water, the behavior of the interface is characterized by the ratio of inertia and buoyancy forces passing from a bubble “torch” to a stable gas jet. Bubble mode prevails at low gas flow rates when bubbles form near the orifice. Rayleigh was the first to study this phenomenon [1]. It turned out that the generation of the sound spectrum during the outflow of bubbles into water is determined by the size of the bubble [2].

The gas jet is generated at higher gas flow rates and can remain stable under certain conditions. Bubbling occurs in the jet away from the orifice. In the experimental work of Mori et al [3], during the outflow of nitrogen into mercury, for the first time, the point of disintegration of the jet into bubbles was recorded and described. Recent experimental studies of high-velocity gas jets into liquids by Weiland [4] and Harby et al. [5] have revealed a complex interface and flow structure.

Numerical modeling of high-speed gas jets in water was carried out for flow velocities from 58 to 108 m/s using the VOF method, supplemented by the RANS turbulence model [6]. Data were obtained on the relationship between the structure of the flow and the acoustic field.

Experimental and numerical simulation of a gas jet in water under a pressure of 1–3 MPa has shown that the interface of the jet continuously oscillates causing strong mixing in the conical regions [7]. The destruction of the interface leads to the formation of a large number of small gas bubbles, which intensify mixing.

Previously, the authors investigated the processes of gas injection into an open pipe region filled with liquid (water, liquid lead) [8, 9]. The studies were carried out both in an axisymmetric two-dimensional setting [8] and in a three-dimensional setting [9]. Naturally, the presence of structural
elements in the working areas of technical devices such as: branch pipes, spacer bushings, racks, and gratings can significantly affect the development of the process of gas outflow into liquid. In particular, the authors obtained the results of numerical calculations in the presence of a disc-type obstacle inside an open tube working area [10]. The barrier was a localized narrowing of the working space. However, the injection process can develop quite differently if the geometry of the obstacle has an extended and channel structure. In technical applications, this geometry is similar to the geometry of tube bundles in heat exchangers in the fuel elements of the reactor zone.

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, $P_o$ – 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, $h_i$ – installation level of ring assembly, $R_{r0}$ – radius of central rod , $R_{r1}$ – external radius of first ring, $r_{r1}$ - inside radius of first ring, $R_{r2}$ – external radius of second ring, $r_{r2}$ – inside radius of second ring, $A$–$A$ – section of first type assembly, $B$–$B$ – section of second type assembly, $C$–$C$ – section of third type assembly.

The aim of this work is to study in detail the injection of gas into a liquid with significantly different densities (water, liquid lead) into an open pipe region in the presence of an obstacle such as an annular assembly inside it.

2. Methods
Simulation was carried out in an axisymmetric approximation using the OpenFOAM package [11]. The outflow of gas (air) occurred in a pipe with an annular assembly filled with liquid (figure 1). The “compressibleInterFoam” solver was used. It 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. The calculated geometric parameters were: an inner radius of the working section of 0.1 m, the length of 0.5 m, and the liquid level of 0.4 m. An air cushion was located in the upper part of the pipe. At the upper end, in the calculations, the granular condition of free inflow-outflow of the flow was assumed. The initial pressure in the working area was $20 \cdot 10^5$ Pa. At the bottom of the
working section, there was a branch pipe of 0.02 m in diameter and 0.1 m long, from which air was supplied with a pressure of $180 \cdot 10^5$ Pa. Air was supplied from a 0.1 m long volume with a radius of 0.05 m. The initial temperature of the air and liquid lead was 650 K, and the water temperature was 300 K. The first type of assembly was a rod with a diameter of 0.02 m. The second one was a rod and a ring with an inner radius of 0.03 and an outer radius of 0.05 m. The third one was a rod, a small ring and a ring with an inner radius of 0.07 and an outer radius of 0.09 m. The end view of these assemblies is shown in Figure 1, and sections AA, BB, CC correspond to the first, second, and third type of assembly, respectively. A detailed description of the calculation methodology was presented in previous works [8, 9].

3. Results
Calculations of the distribution fields of the liquid volume fraction and the velocity modulus at the outflow of air into lead with assembly of the first, second and third types are presented in figures 2, 3 and 4, respectively. The insert of the rod type (figure 2) leads to the deceleration of the gas jet on the axis during the initial growth of the bubble. When the bubble reaches the assembly, a gas-dynamic structure is formed between the assembly and the outflow channel. Next, an annular jet is formed along the assembly with the appearance of a large, annular bubble around the assembly. Installation of an additional ring around the rod (assembly of the second type, figure 3) does not significantly change the shape of the bubble and the flow rate of the jet until the time instant of 5 ms.

![Figure 2. Fields of liquid volumetric content (a) and velocity modulus (b) at different times for air outflow into lead with the presence of an assembly of the first type.](image)

![Figure 3. Fields of liquid volumetric content (a) and velocity modulus (b) at different times for air outflow into lead with the presence of an assembly of the second type.](image)
Figure 4. Fields of liquid volumetric content (a) and velocity modulus (b) at different times for air outflow into lead with the presence of an assembly of the third type.

At times over 5 ms, a gas annular jet is formed between the rod and the ring and liquid lead is displaced from the gap. The main gas flow propagates in the annular gap of the assembly and then forms an annular gas jet behind the assembly. Part of the gas flow forms an annular gas bubble around the assembly. Installing an additional ring in the assembly (figure 4) does not significantly change the bubble growth rate and the jet outflow rate relative to the second type of insert until the moment of time 10 ms. The gas flow spreads in the annular gaps of the insert and then forms two annular gas jets behind it.

Figure 5. Fields of liquid volumetric content (a) and velocity modulus (b) at different times for air outflow into water with the presence of an assembly of the first type.

Figure 6. Fields of liquid volumetric content (a) and velocity modulus (b) at different times for air outflow into water with the presence of an assembly of the second type.
Figure 7. Fields of liquid volumetric content (a) and velocity modulus (b) at different times for air outflow into water with the presence of an assembly of the third type.

Calculations of the distribution fields of the volume fraction of the liquid and the velocity modulus at the outflow of air into water with an assembly of the first, second and third types are presented in figures 5, 6 and 7, respectively. When gas flows out into water with the presence of an assembly of the first type (figure 5), an annular bubble is formed around the assembly. This bubble completely occupies the entire section and displaces water from the working volume. For the case of an assembly of the second type (figure 6), an annular jet flow is formed through the annular channel of the assembly and behind it. Outside the assembly, an annular bubble first appears, which then collapses due to the flowing fluid flow. In the case of an assembly of the third type (figure 7), two annular gas jets are formed in and behind the assembly.

Conclusions
The outflow of an air jet in a liquid with different densities (water, lead) has been studied numerically for various types of annular assembly. For the assembly of the first type, the formation of an annular bubble is observed around the rod. In the case of an outflow into water, the annular bubble completely displaces the liquid from the working volume. For the case with an assembly of the second type, an annular jet is formed inside and behind it. An annular gas bubble is formed outside the assembly. In the case of water, this bubble is unstable. For the third type, two annular gas jets are formed in and behind the assembly.

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