Three-dimensional modeling of gas injection into a closed liquid-filled tube region

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Abstract. Three-dimensional modeling of air injection into a closed pipe region filled with liquid (water, liquid lead) is carried out at high pressure drops. It is shown that in the three-dimensional calculation, the instability of the interphase surface in the form of ring waves of deformation on the upper surface of the projectile is significantly manifested. When air is injected into water, the difference in the configuration of the interphase surface obtained in axisymmetric (two-dimensional) and three-dimensional calculations is insignificant. When injected into a liquid with a substantially higher density (liquid lead), this difference is especially pronounced in the compression phase of the gas projectile.

1. Introduction

The study of non-stationary processes of injection of a gas (steam) at high pressure into a volume with a liquid is associated with numerous applications in technology. Earlier the authors performed numerical modeling of gas injection problems in liquids of different densities (water, liquid lead) at large pressure drops in a two-dimensional (axisymmetric) formulation [1, 2]. In particular, the modeling in [1] was carried out as part of a two-speed model of a two-phase medium [3] using the author’s modification of the LCPFCT software package [4]. In addition, a cross-verification of a two-speed model [3] and a single-speed approximation of a two-phase compressible medium by volume fraction transfer (VOF) [5] using the OpenFoam package [6] was carried out in [2]. The OpenFoam thermal-hydraulic code was successfully verified earlier on experimental problems of gas injection into different liquids [7].

This work is a logical continuation of [8], in which three-dimensional modeling of air injection into a liquid (water, liquid lead) was carried out at large pressure drops in the open pipe region. In [8], it was revealed that when a gas is injected into water, a jet outflow of gas occurs, and for outflow into liquid lead, a gas shell forms at the bottom of the channel. In addition, in the calculations, changes in the interfacial region in 2D and 3D models were compared. In three-dimensional calculations, the instability of configuration of the interphase surface in the form of ring waves was significantly manifested. Numerical simulation of gas outflow into a closed pipe region filled with liquids with substantially different densities was previously carried out only in an axisymmetric formulation [9].

The purpose of this work is to study the differences in the numerical simulation results in the axisymmetric (two-dimensional) and three-dimensional approximation of the gaseous coolant outflow from a high-pressure chamber into a closed pipe region filled with liquid.
2. Methods

The model problem of gas outflow through pipe 2 from volume 1 to pipe 3 is solved (Fig. 1). The pipe 3 is filled with liquid (liquid lead or water). In the calculations, the following geometric parameters are chosen: the inner diameter of the pipe $D = 0.2$ m, the length of the pipe $H = 0.5$ m, the liquid level $h = 0.4$ m. The rest of the pipe is filled with air. At the bottom of the pipe with a diameter $d_i = 0.02$ m air was supplied from volume 1. Diameter $1 - d = 0.1$ m.

The thermodynamic design parameters of the problem are: air pressure in the volume of $1 \times 10^5$ Pa, pressure in the pipe of $20 \times 10^5$ Pa, the initial temperature of air and liquid lead [10] of $650$ K, and the initial water temperature of $373$ K.

The problem is solved on the “compressibleInterFoam” solver in the OpenFOAM package in a three-dimensional computational domain (Fig. 1). The left side of Figure 1 shows a three-dimensional region in cross section along the axis of symmetry. A uniform distribution of the initial pressure is adopted: red is the high-pressure region and blue is the low-pressure region (the upper left part of Figure 1). The bottom left of Figure 1 shows the initial distribution of the volumetric liquid content: red is the region filled with pure liquid, and blue is the region filled only with gas. On the lateral boundaries of volume 1, pipe 2 and pipe 3, a wall-type condition $W$ is established. At the lower boundary of volume 1, the condition of “inflow-outflow” is established at a fixed pressure of $180 \times 10^5$ Pa - $P_i$. On the upper boundary of pipe 3, a condition of the wall type $W$ was established. A general view of the computational domain is presented on the right side of the figure (Fig. 1). The grid is uniform, the number of cells for the tube region 3 is $2240000$. The split in the radial direction $N_r = 100$, in the longitudinal direction $N_x = 700$, and in the angle $N_\theta = 32$. Previously, the problem with the same parameters was solved in a two-dimensional (axisymmetric) formulation. The method of two-dimensional calculation is described in detail in previous works [8, 9].

3. Results of the study

Figures 2 and 3 show the development of the interphase surface (projectile) during the injection of gas (air) into water and liquid lead, respectively, at different times. The figures show the first pulsation period of an emerging gas projectile. It may be noted that when the gas flows into water (Fig. 2), the gas projectile and the first ripple occur in 8 ms. The growth of the gas cavity occurs in vertical direction. The bubble comes off the lower wall already at the 4th ms with the formation of a tourniquet. By the time moment of 8 ms, the projectile is substantially compressed in its middle part. One can notice the manifestation of instability of the interphase surface: first, ring waves appear on the surface by the time instant of 6 ms. At a time of 8 ms, an increase in ring waves occurs in the middle of the
gas projectile with the formation of a ring in the form of a “skirt”. The upper parts of Figures 2 and 3 show oscillations of the liquid level boundary during gas injection into a closed pipe region.

![Figure 2. The development of the interface (slug) with gas injection (air) into water at different points in time.](image)

![Figure 3. The development of the interface (slug) at gas injection (air) into lead at different points in time.](image)

When air flows into a liquid with a significantly higher density (liquid lead), the formation of a gas projectile and its first pulsation occur much later, namely, at about the 24th ms (Fig. 3). Unlike water in liquid lead, the air cavity increases in size, both vertically and radially. At a time of 6 ms, an annular wall region forms in the form of a “skirt” at the bottom of the projectile. This area is separated from the main bubble by a ring wave. By the time moment of 24 ms, the projectile is substantially compressed in its middle part (for water, this happened by the time moment of 8 ms). Similar to water, instability of the interphase surface occurs in the form of ring waves on the surface (by the time of 18 ms). At the time of compression of 24 ms, the shape of the projectile takes the form of a large bubble with a “skirt”.

For clarity, Figures 4 and 5 show the evolution of volumetric gas content for air injection into a closed volume with water and liquid lead, respectively. The upper parts of the figures show the results of a two-dimensional (axisymmetric) calculation, and the lower parts contain a three-dimensional calculation.

It is seen that for the case of injection into water, the difference between the two-dimensional and three-dimensional calculations is insignificant. In the three-dimensional calculation, at time moments of 2-3 ms with the bubble growth, a deflection of the surface of the bubble inward is observed in its upper part. In a two-dimensional calculation, there is no deflection. At a time of 8 ms for three-dimensional calculation, an annular interphase instability is observed in the form of a “skirt” in the middle of the bubble. For a two-dimensional axisymmetric calculation, this instability is not observed.

When gas is injected into lead in three-dimensional calculation at the initial moment of time 3 ms, an inward deflection of the bubble surface is also observed in the upper part of the projectile. In the compression phase, by the time moments of 15-24 ms, there is a significant difference between the results of calculations for the axisymmetric two-dimensional and three-dimensional cases. In the two-dimensional case, an interphase instability forms in the upper part of the bubble, which leads to the separation of small bubbles from the projectile. In three-dimensional calculation, this instability is not observed. As indicated above, compression occurs in the middle of the bubble. Apparently, in the
three-dimensional case, the energy of longitudinal vibrations decreases due to the transition of energy into transverse asymmetric vibrations, and in the two-dimensional case this becomes impossible and leads to the formation of detached bubbles. This can also explain the lower compression of the gas layer in the three-dimensional case, both for water and for lead.

Figure 4. Evolution of gas void fraction for injecting air into the closed volume with water (first period of oscillation).

Figure 5. Evolution of gas void fraction for injecting air into the closed volume with liquid lead (first period of oscillation).

Conclusion
Three-dimensional modeling of air injection in a liquid with significantly different densities (water, liquid lead) has been carried out at large pressure drops in a closed pipe region filled with liquid. It is shown that in the three-dimensional calculation, the instability of the interphase surface in the form of ring waves, the inward deflection of the bubble surface is significantly manifested. When air is
injected into water, the difference in the configuration of the interphase surface obtained with axisymmetric (two-dimensional) and three-dimensional calculations is insignificant. When injected into a liquid with a substantially higher density (liquid lead), this difference is especially pronounced in the compression phase of the gas projectile. In the two-dimensional case, an interphase instability forms in the upper part of the bubble, which leads to the separation of small bubbles from the projectile. In three-dimensional calculation, this instability is not observed.

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