Simulation of gas injection from a long tube into a liquid-filled pipe

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Abstract. The data on the evolution of the interface at the sudden injection of gas from a long tube into a liquid column was obtained. High speed video of experiments and calculations in OpenFoam software package were used as research methods. Investigations were performed for different initial pressures. Typical configurations of the interface for different time periods were shown both experimentally and numerically.

1. Introduction
Steam Generator Tube Rupture (SGTR) in heavy liquid metal (HLM) cooled reactors is one of the most dangerous accidents. It can be observed in the result the following phenomena:

- Pulse ejection of pressure in lead coolant flow with an amplitude much higher than coolant static pressure.
- Generation of steam cavity near the breakdown point with its following deformation and splitting into separate bubbles.
- Change of lead level in the steam generator body resulting in changing pressure in upper gas blanket.
- The presence of steam bubbles in the main pump and in the core. The uncontrolled growth of the reactivity.

Thereby, investigations of small leakages of steam or gas in HLM and the large ones are very important for nuclear reactors safety. The problem of the small leakage was considered in [1–7]. The information about the process of bubble generation, void fraction distribution and some motion characteristics of two-phase flow was obtained. Investigations of the most dangerous problem (SGTR) were performed in the large-scale experimental facility [8, 9]. When performing the experimental tests for verification of thermal-hydraulic codes in nuclear power engineering, it is necessary to consider a number of significant limitations on the methodology for conducting experiments. The main limitation of the benchmark is the creation of boundary conditions in the experiment, which can be uniquely defined in thermal-hydraulic codes. On the other hand, the experiment should reflect the thermal-hydraulic processes that may occur in real nuclear power plants. Earlier, the authors carried out numerical and experimental studies of pulsed gas injection into a vertical pipe filled with liquid (water or HLM) with a diameter of 25 mm from a cylinder under pressure through a short tube [10–12]. The verification of the
thermal-hydraulic code HYDRA/IBRAE/LM was performed using the experimental data as a boundary conditions (the volume of the injected gas, the initial front velocity, the change of the liquid column level etc.) [12]. But at real emergency in a steam generator when a tube breaks, continuous injection is more adequate. The purpose of this work is to perform experimental investigation of gas injection from the straight overpressure pipe into the liquid column and further using of the obtained data to perform the verification of the code, based on the OpenFoam. The air/water interaction was studied in this work.

2. Methods

Pressure waves inside a long thin tube can change the outflow mode due to the small volume of tubes. In the present work (as opposed to [10, 11]) the gas was injected from a thin tube 1 m long. The volume of this tube was filled with air overpressured of 100 – 500 kPa. A rubber tube was used as a valve between the tube and the working area. Sealing was carried out with the help of a clamp, the weakening of which made it possible to quickly open the channel. High-speed video showed that the ”valve” opening time is 5–10 ms. The scheme of the experimental setup is shown in the Figure 1.a. It consists of a tube with high-pressure air – 1, a rubber tube (valve) –2, an inlet injector – 3, a working channel pipe – 4. In the lower part of tube 1 there was an inlet valve – V which was connected to the high–pressure line $P_0$. The internal diameter of the tube with a high pressure was $d_1 = 6$ mm, the length of the tube was $h_1 = 1020$ mm. The length of the rubber tube (valve) was $h_r = 60$ mm, the inner diameter was $d_r = 8$ mm. The length of the injector was $h_i = 40$ mm, the internal diameter of the injector was $d_i = 6$ mm. The height of the test section was $h_c = 1200$ mm, internal diameter was $d_c = 25$ mm. The high–speed camera (frame rate 400 fps), was utilized to obtain the information about the dynamics of the process. Figure 1.b – 1.d shows the axisymmetric computational domain. Numerical simulations were performed in OpenFOAM. The area is made in the form of a sector (Fig. 1.b – frontal projection, Fig. 1.c – lateral projection, Fig. 1.d — axonometric projection). The geometrical parameters of the computational domain coincided with

![Figure 1](image_url)

**Figure 1.** Scheme of the test section (a) and calculation area: frontal projection (b), side projection (c), axonometric projection (d): 1 – tube with high pressure air, 2 – rubber tube, 3 – injector, 4 – test section, 5 – receiver, V – valve, $P_0$ – high pressure line, $h_1$ – tube length, $d_1$ – tube diameter, $h_r$ – rubber tube length, $d_r$ – rubber tube diameter, $h_i$ – injector length, $d_i$ – injector diameter, $h_c$ – channel length, $d_c$ – channel diameter, $h$ – water level, w – wall type condition, $P_a$ – inflow condition at atmospheric pressure, ax – condition type axis of symmetry, b – condition type edge mating – back, f – condition type edge mating – front.
the parameters of the experimental setup. In addition, a receiver was introduced into the computational domain (Fig. 1.b) – 5 for a stable calculation with matching of the boundary inflow and outflow at constant pressure $P_a = 101315$ Pa. The Figure 1.b shows the initial pressure distribution (red is the high pressure area, blue is the low pressure area). The condition of the axis of symmetry type - ax was set at the edge of the sector angle (Fig. 1.b). At the initial moment of time, the pressure $P_a = 201315–601315$ Pa was established in tube 1. The rubber tube was compressed so that the flow area was zero. Full opening of the rubber tube occurred to be 10 ms. The injector – 2 was filled with water, the working volume was filled at the level $h = 500$ mm. The problem was solved on the “compressibleInterFoam” solver in the OpenFOAM package. The calculation method is described in detail in [10, 11, 13, 14].

3. Results
The experimental records of the interface position (up) and results of calculations of the gas void fraction distribution (bottom) at a pressure in the tube $P_a = 201315$ Pa and $P_a = 301315$ Pa, are shown in Figures 2 and 3 respectively. In the experiment, there is a "mushroom" form of the interface. Two areas can be identified: the leading edge is a bubble cluster, followed by a gas cavity. The gas cavity expands and moves the liquid column with the bubble cluster. A similar "mushroom" form of the interfacial surface is observed when calculating the volumetric gas content. The main difference from the experiment is the absence of a bubble cluster. The rate of extrusion of the liquid column by the gas cavity is higher than in the experiment.

In previous studies [10–12], a gas cavity was formed during pulsed gas injection. The gas cavity accelerated the liquid column up. Then an oscillation period of the gas cavity was observed. A similar process can be detected at the continuous injection of gas under pressure from a thin long tube. In this case, the termination of injection into the test section was due to the pressure drop in the tube. Let us consider how the height of the two-phase boundary changes during the first pulsation. Figures 4.a and 4.b show the time dependence of the height of the two-phase region for the pressure in the tube $P_a = 201315$ Pa and $P_a = 301315$ Pa, respectively. Line 1 corresponds to the experimental values. Line
Figure 3. Experimental registration of the interface (up) and calculation of the volumetric gas content (bottom) at a pressure in the tube $P_a = 301315 \text{ Pa}$, red color – water, blue color – air.

Line 2 corresponds to the calculation obtained on a uniform grid in the computation domain of 0.5 * 0.5 mm. Line 3 corresponds to the calculation on the grid of 1.25 * 1.25 mm. So for the pressure in the tube $P_a = 201315 \text{ Pa}$ for the steep grid, the level of two-phase pulsation is lower than the experimental level. For a fine grid, the ripple level is higher than the experimental one (Fig. 4.a). When the pressure in the tube changes to $P_a = 301315 \text{ Pa}$, the level pulsations of the two-phase region coincide for calculation.

Figure 4. The time history of the amplitude of the two–phase area for the injection of gas (air) in water, 1 – experimental data, 2 – two-dimensional calculation (small cells calculation domain), 3 – two-dimensional calculation (large cells calculation domain), a – $P_a = 201315 \text{ Pa}$; b – $P_a = 301315 \text{ Pa}$. 
Figure 5. The time moment of the two phase area for the injection of gas (air) in water, 1 – experimental data, 2 – two-dimensional calculation (small cells calculation domain), 3 – two-dimensional calculation (large cells calculation domain), a – $P_a = 201315$ Pa, b – $P_a = 301315$ Pa, red color – water, blue color – air.

on a large fine grid. The level oscillations of the two-phase region for the calculation are above the experimental level ones (Fig. 4.b). The figures show the most important time periods: the beginning of the injection, the moment of the maximum value of the two-phase area during the first oscillation, the moment of the minimum value of the level of the two-phase area during the first oscillation. Figures 5.a and 5.b show the view of the two-phase region for the pressure in the tube $P_a = 201315$ Pa and $P_a = 301315$ Pa, respectively. Figure marked as 1 corresponds to the experiment, 2 corresponds to the calculation of gas void fraction on a fine grid, 3 corresponds to the calculation of gas void fraction on a large grid.

Summary
Experimental and numerical investigations of the dynamics of the interface at the sudden injection of gas from a long tube into a liquid column were carried out. The high-speed video was used as an experimental method. Numerical research was conducted in the OpenFoam package. As a result, time histories of the interphase boundary dynamics were obtained for different initial pressures. Despite the use of a simplified computational domain, a satisfactory agreement between the experimental and numerical results was obtained.
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