Simulation of the outflow of steam from a high-pressure volume into a closed external region

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Abstract. A numerical simulation of the process of unsteady outflow of steam (steam-water mixture) from a volume under high pressure into a closed region with rigid boundaries is carried out. The calculations used a thermodynamically equilibrium homogeneous model of a vapor-liquid medium. At small and large (up to 0.15 s) times, spatial distributions of pressure, mass vapor content, density and temperature were obtained and analyzed.

1. Introduction

Modeling of dynamic and, in particular, wave processes that occur during depressurization of vessels or pipelines with hot liquid has been studied for quite a long time. There are many that have already become classical works (see, for example, [1, 2, 3]), where emergency depressurization of vessels with a heated water coolant is studied in the framework of evaluative and approximate models. To calculate water boiling during depressurization of pressure vessels, both thermodynamically equilibrium and nonequilibrium models were used [4, 5, 6, 7].

Earlier, on the basis of the relaxation model of the “liquid-vapour” phase transition [6] using the LPCFCT computing complex [8], the authors developed a program code for solving a wide class of problems of depressurization of vessels or pipelines with a water coolant [9, 10, 11]. The code is based on solving unsteady Euler equations [12] by averaging over a unit cell and a time interval using the method of conservative flows. This approach is equivalent to modeling the dynamics of large-scale turbulent vortices with some subgrid turbulence model. The program code was verified on the experimental problem of expiration of superheated water vapour [13]. A comparison of experiment and calculation showed satisfactory agreement [14].

The outflow of saturated steam (steam-water mixture) occurs, in particular, during some design emergencies in water nuclear reactors. Earlier, when simulating the outflow of boiling water into a closed region, the authors obtained the effect of non-stationary condensation [15, 16]. This effect was due to the formation of a complex structure of side pressure jumps, Mach disk, and hanging jumps depending on the distance to the wall, where the calculated pressure was higher than the local saturation pressure. These gas-dynamic calculated structures were obtained already at the initial times of the outflow into the closed region. It was found [15, 16] that an increase in the distance between the wall and the pipe channel leads to a decrease in pressure near the wall and a decrease in the condensation process.

The purpose of this work is a numerical simulation of the process of unsteady flow of steam from a volume filled with water and steam at high pressure into a closed heat-insulated region with rigid boundaries. In this confined area, atmospheric pressure is initially maintained.
Figure 1. Computational domain: 1 – saturated water at high pressure, 2 – saturated steam at high pressure, 3 – steam-water mixture at atmospheric pressure, W – rigid wall type condition, $P_0$ – the condition of free inflow-outflow at atmospheric pressure, $r$ – Tank radius, $r_0$ – outer radius of the ring, R – computational domain radius, h – Tank height, $h_1$ – injector height, $r_1$ – injector radius, H – computational domain height.

2. Methods
Figure 1 shows an axisymmetric computational domain with a height of $H = 10$ m and a radius of $R = 4$ m. At the outer boundary of the region, a boundary condition of the “rigid wall” type was adopted. There was a tank inside the region, at the boundaries of which a “rigid wall” type condition was also accepted - W. Tank height was $h = 5$ m, radius was $r = 2$ m. In the upper part of the tank, there was an injector with height $h_1 = 0.1$ m and radius $r_1 = 0.1$ m. At the lower boundary of the computational domain, there was an annular surface on which the boundary condition of “free inflow-outflow” was established at constant pressure $P_0 = 101$ kPa.

The inner radius of the ring was taken to be $r = 2$ m, and the outer radius of the ring was $r_0 = 2.2$ m. The tank was half full with water (region 1) and steam (region 2). Inside the tank the pressure was 16 MPa and temperature was 347°C (620 K). Water and steam in the tank were on the saturation line. Outside the tank, in the external computational domain, there was an equilibrium steam-water mixture (region 3). The initial pressure of the steam-water mixture was 101 kPa at a temperature of 100°C (373 K) and a mass vapour content of 0.5. A steam-water mixture with such parameters simulates the air atmosphere in terms of density and speed of sound.

The calculation was made in a homogeneous approximation. The solution of the system of Euler equations and continuity was obtained using the software package [4], which uses the finite volume method and the FCT flow correction method. The phase transition process was described by the equilibrium approximation. The calculation method was described in detail, for example, in [14]. In the same work, verification of the program was presented on the experimental problem of the expiration of superheated steam.
3. Results of the study

As it was noted in the Introduction in earlier papers [15, 16], the initial stage of the outflow of superheated (for external atmospheric pressure) liquid into the closed region was simulated. In this case, both the size of the region and the distance from the nozzle to the wall were varied.

The problem studied in this work is characterized in that a saturated vapour cushion is located near the injector in the tank. Saturated steam first flows out of the tank through the injector, and then the steam-water mixture. This statement of the problem greatly simplifies its solution, since it allows one to calculate within the framework of the equilibrium model for large times up to the establishment of a quasi-steady-state expiration regime.

Figure 2 shows the calculated normalized spatial distribution of pressure for time instants $t = 0.005$, $0.05$, and $0.15$ s. The occurrence of a gas-dynamic structure is observed upon supersonic expansion of a steam-water mixture into a closed volume.

The gas-dynamic structure is understood as the structure of pressure surges arising during the outflow of a steam-water mixture and its expansion. The outflow process is unsteady and is associated with a change in pressure fields during the generation and propagation of acoustic waves.

For convenience of analysis, the calculated values were averaged (over time $50 \mu s$). It can be noted that the structure of pressure surges is built in the form of a “torch” with a length of about $1$ m and a radius of $0.5$-$0.7$ m.
Figure 3. Field of mass vapour content at different points in time: a – 0.005 s, b – 0.05 s, c – 0.15 s.

Figure 3 shows the spatial distribution of the mass vapor content at time $t = 0.005$, $0.05$, $0.15$ s. The change in the mass vapor content in the tank shows that the boundary between the liquid and the vapor is “blurred”, that is, an area with a steam-water mixture is formed. The outflow of the steam-water mixture occurs through the tank injector in a gas-dynamic mode, condensation occurs inside the “torch”, vaporization occurs on the lateral and end boundary of the “torch”.

The mass vapor content increases and the steam-water mixture continues to move in the direction of the upper wall of the closed external volume. Let us consider how the distributions of pressure (Fig. 4a), mass vapor content (Fig. 4b), density (Fig. 5a) and temperature (Fig. 5b) along the $Z$ axis change over time.

The pressure in the tank after establishing the steady-state flow regime remains almost unchanged during the estimated time of $0.15$ s. Spatial evaporation of liquid occurs inside the tank; the mass vapor content changes along the axis (Fig. 4b). A similar pattern is observed in Figure 3. The density distribution of the vapour-liquid mixture in the tank changes in a similar way with time, and the boundary between the liquid and the vapour in the tank is blurred (Fig. 5a). The temperature in the tank remains constant and, according to the model, is on the saturation line (Fig. 5b).

During gas-dynamic expansion inside the "torch", the following occurs:
1. a decrease in pressure along the $Z$ axis from $160$ MPa to $0.05$ MPa (Fig. 4 a);
2. condensation (Fig. 4 b);
3. a density drop from $100$ to $0.05$ kg/m$^3$;
4. cooling of the steam-water mixture from $347^\circ$C to $40^\circ$C.

At the boundary of the gas-dynamic “torch”, the pressure rises abruptly to the level of $0.1$ MPa, and the steam-water mixture boils abruptly to a mass vapour content of $X = 0.8-0.95$, and the temperature increases to $100^\circ$C.

Between the "torch" and the boundary of the computational domain, the pressure of the moving steam-water stream fluctuates within $0.1-0.2$ MPa, condensation occurs (mass vapour content drops), temperature and density pulsate after pressure. Due to the inhibition of the steam-water flow, the
pressure on the outer wall of the region increases to 0.2 MPa, the temperature increases to 140°C, and the density of the steam-water mixture increases to 2 kg/m³.

![Figure 4](image1.png)

**Figure 4.** Pressure (a) and mass vapor content (b) distribution along the Z axis at times: 1 – 0.005 s, 2 – 0.05 s, 3 – 0.15 s.

![Figure 5](image2.png)

**Figure 5.** Density (a) and temperature (b) distribution along the Z axis at times: 1 – 0.005 s, 2 – 0.05 s, 3 – 0.15 s.

**Conclusion**
A numerical simulation of the process of unsteady flow of steam from a volume half filled with water and steam at high pressure into a closed region with rigid boundaries, in which atmospheric pressure was initially maintained, was carried out.

It was numerically obtained that, upon the expiration of a steam-water mixture, a gas-dynamic structure of pressure shocks about 1 m long and a radius of 0.5–0.7 m forms near the injector.

It was revealed that under the steam-water mixture expansion inside the gas-dynamic structure, the significant drops in pressure, temperature, density and mass vapor content take place.

An abrupt change in pressure, temperature, density, and mass vapor content occurs at the boundary of the gas-dynamic structure. The process of vaporization (increase in mass vapor content) occurs with increasing density, temperature and pressure of the steam-water mixture.

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