Influence of a non-condensable gas on mixing of a melt with water in a stratified configuration

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Abstract. The influence of bubbles of hot non-condensable gas formed at the interface between the melt and water on the formation of a mixture of melt with water capable of producing steam explosions is considered. The dynamics of such a bubble in subcooled water is analyzed numerically in a one-dimensional spherically symmetric approximation. It is shown that with significant initial superheat of the bubble relative to the water, a rapid drop in pressure in the bubble occurs due to strong heat removal into the water. This leads to the collapse of the bubble and the appearance of an accompanying flow of water. The results obtained made it possible to approximately describe the stage of collapse of the bubble as the polytropic process and to determine its index. The axisymmetric problem of the impact of the water jet on the surface of a melt during collapse of a gas bubble near the interface between the melt and water is numerically investigated. In this case, the obtained polytropic process equation is used to determine the pressure in the bubble. It is found that the resulting impact on the melt is capable of knocking out melt droplets into the water to a height of several centimeters, which leads to the formation of a layer of water mixed with the melt droplets, which is capable of producing strong steam explosions.

1. Introduction

Severe accidents at nuclear power plants with reactor core melting can be accompanied by steam explosions when the molten materials of the core come into direct contact with water [1]. Sometimes such a contact can be realized with a stratified configuration of the melt (bottom layer) and water (top layer). For a long time, it was assumed (based on experimental studies with low-temperature simulators of melt and water) that such explosions have a low conversion ratio and do not pose a threat to the integrity of the reactor containment [2]. However, recent experiments in Sweden [3] have demonstrated that the interaction of a high-temperature melt with a temperature of up to 1400 °C with water in a stratified configuration results in strong spontaneous steam explosions with a pressure of up to 40 bar. Such explosions can take place only in the case of preliminary mixing of a significant amount of the melt with water.

In [3], a hypothesis was put forward, according to which such mixing in an initially stratified system can occur as follows. At the interface of the high-temperature melt with water, vapor bubbles are formed. These bubbles, floating upward, are surrounded by cold water, as a result of which vapor condensation begins, and the bubbles collapse. During the collapse, a high-speed cumulative jet of
water is formed above the collapsing bubble, directed downward towards the melt. When a jet enters the melt, splashes of the melt are emitted from it into the water. As a result of the superposition of such events in the near-surface layer of water above the melt, there are many drops (splashes) of the melt, which is essentially a mixture of the melt with water capable of producing strong steam explosions.

In [4-6], this hypothesis was quantitatively justified on the basis of a consistent consideration of the collapse of the bubble and the interaction of the resulting water jet with the melt. It was shown that the arising water impulse acting on the melt surface is sufficient to knock out the melt droplets into the water layer to a height of several centimeters.

The present work is a continuation of [4-6] and is related to the study of the collapse of a bubble in water in the presence of non-condensable gas in it. The limiting case of a bubble consisting only of non-condensable gas will be considered. Similarly to [4], in this work, first, in a one-dimensional formulation, the dynamics of an superheated (with respect to the surrounding water) gas bubble at the initial stage of the first compression of the bubble is analyzed. The revealed regularities made it possible to select the polytropic process equation for the bubble collapse process, which describes the relationship between the bubble pressure and its volume. This equation was used to analyze the effect of water on the melt when a hot gas bubble is compressed by cold water near the surface of the melt. The analysis was carried out in the framework of a two-dimensional axisymmetric formulation by the boundary element method [7].

2. Dynamics of a bubble of a hot non-condensable gas in cold water

Let at the initial moment a spherical bubble of non-condensable gas with a radius $a_0$ and a temperature $T_{go}$ be in water with a temperature $T_{io}$, which is lower than the bubble temperature. The initial gas pressure in the bubble is equal to the water pressure, which we denote by $p_0$.

The hot bubble will transfer heat to the water and cool down. Because of this, the pressure in it will drop, and the surrounding water, under the influence of its pressure, will squeeze the bubble, reducing its volume. If the initial bubble temperature is significantly higher than the water temperature, then the pressure drop in the bubble due to its cooling will be significant, and it can decrease its volume by an order of magnitude or more. Let us make an assessment of this process in a spherically symmetric formulation, considering the bubble as a zero-dimensional object and calculating the heat transfer to water using the non-stationary heat conduction equation.

Bubble dynamics equations:
The equations for the mass and energy of the bubble are:

$$a \frac{dp_g}{dt} + 3 \rho_g \frac{da}{dt} = 0, \tag{1}$$

$$\rho_g c_{gv} a \frac{dT_g}{dt} + 3 p_g \frac{da}{dt} = q \tag{2}$$

Here $\rho_g$, $T_g$, $p_g$, $c_{gv}$ – density, temperature, pressure, heat capacity at constant gas pressure, $a$ – radius of bubble, $q$ – heat flux from liquid to bubble surface, $t$ – time.

The fluid motion is described using the Rayleigh equation

$$\frac{dw_a}{dt} + \frac{3}{2} \frac{w_a^2}{a} = \frac{p_g - p_0}{\rho_l a}, \tag{3}$$

where $\rho_l$ – the density of water, which we will assume to be constant, $w_a = da/dt$ - the bubble surface velocity, $a$ - the current radius.

For a gas, we take the equation of state for an ideal gas:

$$\rho_g = \frac{p_g}{RT_g}, \tag{4}$$

So, it is possible to transform equations (1) and (2) to
\[ \frac{dp_g}{dt} = \frac{3(\gamma - 1)q - \gamma p_gw_a}{a} \quad (5) \]

\[ \frac{dT_g}{dt} = \frac{3q - p_gw_a}{\rho_g c_{p_g} a} \quad (6) \]

where \( R \) – ideal gas constant, \( \gamma \) – heat capacity ratio.

Equation of thermal conductivity of water:

To close the system of equations (3) - (6), it is necessary to determine the heat flux from water to the bubble \( q \), for which we use the equation of heat conductivity of water:

\[ \rho_l c_l \left( \frac{\partial T_l}{\partial t} + w_l \frac{\partial T_l}{\partial r} \right) = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T_l}{\partial r} \right) \quad (7) \]

where \( T_l = T_l(r, t) \) и \( w_l = w_l(r, t) \) – temperature and velocity of water, \( c_l \) и \( \lambda_l \) – specific heat capacity and thermal conductivity of water, \( r \) – the radial coordinate originating from the center of the bubble.

We assume that all the physical properties of water \( \rho_l, c_l, \lambda_l \) are constant. Then the equation of thermal conductivity of water will take the form

\[ \frac{\partial T_l}{\partial t} + w_l \frac{\partial T_l}{\partial r} = \frac{\kappa_l}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T_l}{\partial r} \right) \quad (8) \]

where \( \kappa_l = \frac{\lambda_l}{\rho_l c_l} \).

The heat flux \( q \) on the bubble surface is equal to

\[ q = \lambda_l \frac{\partial T_l}{\partial r} \bigg|_{r=a} \quad (9) \]

### 3. Numerical study of the dynamics of a hot gas bubble in a cold liquid

For the analysis, the parameters of the experiment E6 [3], which was considered in [4], were used: the initial water temperature \( T_{l0} = 348 K \), the water pressure \( p_0 = 1 \) bar. It was assumed that the non-condensing gas is air, which is captured by the melt jet during its movement. The initial temperature of the bubble is an uncertain value, so its variation was carried out. We were interested in the dynamics of the bubble, first of all, at its high temperatures, when we could expect rapid compression of the bubble and the occurrence of rapid dynamic processes. Therefore, the calculations used high initial temperatures of the bubble up to its initial superheat relative to water 650 K, when its temperature was almost equal to the temperature of the melt. The typical size of the bubbles observed in [3], \( a_0 = 1 \) cm, was set as the initial bubble size.

For the purposes of this study, the most important is the initial stage of reducing the pressure in the bubble and reducing its size. This stage is somewhat analogous to the process of collapse of a steam bubble, studied in [4]. Due to the fact that a bubble of non-condensing gas is now being considered, its collapse is impossible, since with a decrease in the volume of the bubble, its pressure increases and does not allow the bubble to collapse. However, if we consider the dynamics of such a bubble near the melt surface, then, as follows from the results [4], the bubble will deform with the formation of a jet of water directed towards the melt. It can be assumed that although the bubble will not collapse, it will break up into separate fragments in such a way that a jet of water reaches the surface of the melt.

In order to study the effect of the initial superheat of the bubble on the dynamics of the process, a series of calculations were performed, in which this value varied as follows: 100 K, 200 K, 400 K, 650 K. Figure 1a shows the time dependences of the bubble radius under these superheats. It can be seen that the largest decrease in the size of the bubble occurs at its largest initial superheat, the minimum radius of the bubble is 5.5 mm at a time of 1.4 ms.
It follows from Figure 1b that at first there is a rapid drop in the bubble temperature due to heat transfer into the water, and by the time of about 0.1 ms, the bubble temperature in all variants becomes equal to a value that is several degrees higher than the ambient water temperature. The subsequent decrease in the bubble temperature to the water temperature is significantly slower.

Figure 2a shows that the deepest drop in pressure in the bubble occurs at the highest initial temperature of the bubble, it falls about three times compared to the initial value. This happens at a time of 0.12 ms. Due to the compression of the gas in the bubble, its pressure begins to increase, and by the time of 1 ms, the pressure of the bubble is compared with the pressure of the surrounding water, and then begins to exceed it. Because of this, the bubble begins to expand.

It is interesting to compare the dynamics of collapse of a gas bubble with the collapse of a cavitation bubble, that is, a steam bubble in which a constant pressure is maintained equal to the saturation pressure at the ambient water temperature. The dynamics of a cavitation bubble is described only by the Rayleigh-Plesset equation (3), supplemented by a kinematic relationship between the velocity and the radius of the bubble. Figure 2b shows the time dependences of the radius of a cavitation bubble and a gas bubble with an initial temperature superheat of 650 K. The water temperature is 348 K, the water pressure is 1 bar. The curves coincide for about 0.5 ms, then at the moment of 1.15 ms the cavitation bubble collapses, and the radius of the gas bubble reaches a minimum at the moment of 1.4 ms, after which it begins to expand.

To perform a two-dimensional hydrodynamic calculation of the compression of a gas bubble with water near the melt surface by the boundary element method, it is necessary to determine the dependence of the pressure in the bubble on time. For this purpose, we will use the obtained solution of a one-dimensional spherical problem. For the two-dimensional calculation of bubble collapse by the BEM method, the bubble pressure was determined by the following procedure. When calculating the time interval from 0 ms to 0.2078 ms, the tabular dependence $P_g(t)$ was used, which is graphically shown in Figure 2a. When calculating later moments of time, the pressure in the bubble was found from the ratio:

$$P_g(t) = P_{g,1} \left( \frac{V_1}{V(t)} \right)^n$$

(10)

here $P_{g,1} = 0.34487$ bar and $V_1 = 4.04463 \cdot 10^{-6}$ m$^3$ is the pressure and volume of the bubble at the time of 0.2078 ms, $V$ is the current volume of the bubble.
4. Evaluation of the hydrodynamic effect on the melt during collapse of a gas bubble

We study the evolution of a gas bubble in incompressible water, which at the initial moment of time has a radius $a_0$ and is located at a distance $h$ from the melt surface. The problem is investigated in an axisymmetric approximation, the $z$ axis is directed upwards from the melt surface and passes through the center of the bubble. The mathematical formulation of a problem is presented in [4].

The collapse of a gas bubble with an initial radius of 10 mm was calculated using the BEM method. The initial distance of the bubble center from the melt surface was also 10 mm, that is, the bubble touched the melt surface. As it was shown in [4], with this arrangement of the bubble, the maximum hydrodynamic effect on the melt surface is achieved. The water pressure was 1 bar, the water density was $974.94 \text{ kg m}^{-3}$. The bubble pressure during the calculation was calculated in accordance with (10).

Figures 3a and 3b show the time dependences of the pressure in the gas bubble and its volume. For comparison, these figures show similar dependencies for a cavitation bubble. It is clearly seen how the pressure in the contracting bubble quickly falls to the saturation pressure and stays at this level for a relatively long time (up to about 0.6 ms), while the volumes of both bubbles are almost the same. Then the pressure in the gas bubble begins to increase, the elastic properties of the gas begin to affect the pressure more strongly than the heat sink into the water. The pressure increases by about 4 times compared to the initial value, and only at this pressure does the collapse of the bubble stop.

Figure 3c shows the time dependences of the kinetic energy of water for gas and cavitation bubbles. It can be seen that the kinetic energy of water reaches a maximum at about 1.1 ms, and then begins to fall. This is explained by the fact that at this time the potential energy of water begins to grow, associated with an increase in pressure in the water near the bubble due to an increase in the gas pressure in the bubble itself.
Figure 3d shows the time dependences of the Kelvin pulse (the integral impulse of water on the melt surface) for gas and cavitation bubbles. As it was shown in [4], this value determines the height of the release of melt droplets into the water during the collapse of the bubble. It follows from Figure 10 that the Kelvin pulse is maximal at the moment when the water jet reaches the melt surface, while for a gas bubble the value of the maximum Kelvin pulse is approximately 2/3 of the same value for a cavitation bubble.

5. Conclusion
In the study [4], it was found that the collapse of superheated steam bubbles formed near the interface of the melt and subcooled water can have such a hydrodynamic effect on the surface of the melt, in which melt drops will be lifted into the water to a height of several centimeters from the melt. This can lead to the formation of an explosive mixture of melt and water (steam explosion).

In this paper, the effect of hot non-condensing gas bubbles in this system was studied. It was found that in this case, too, a rapid collapse of the bubbles occurs, which leads to a hydrodynamic effect on the melt of the same order as in the case of superheated steam bubbles. The physical reason for the similarity of these processes is a strong heat sink from the bubble in both cases, leading to a rapid drop in the pressure in the bubble. As a result, in both cases, the process becomes similar to the collapse of a cavitation bubble with the formation of a high-speed jet of water acting on the melt. It is obvious that in the intermediate case of a bubble consisting of a mixture of steam and non-condensing gas, the
process of its collapse will proceed in the same way if the necessary condition for a significant initial superheat of the vapor-gas mixture relative to water is met. The latter is provided by direct contact of the vapor-gas mixture with a high-temperature melt.

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