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Influence Of Non-Condensable Gas On Melt-Water Premixing In A Stratified Steam Explosion

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ABSTRACT

The dynamics of a bubble of hot non-condensable gas formed at the interface between the high temperature melt and subcooled water is analyzed numerically in a one-dimensional spherically symmetric approximation. It is shown that for 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 water flow. The results obtained made it possible to approximately describe the stage of collapse of the bubble as the polytropic process and to determine its power. 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 hydrodynamic impact on the melt is capable to produce melt splashing into the water to a height of several centimetres. If the frequency of formation of such bubbles is high enough, then, as a result of their collapses, the melt-water interface will be transformed into a premixed layer, which is capable to produce 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 due to the generation and collapse of bubbles at the melt-water interface. They wrote [3]: "*Periodic process of growth, expansion and collapse of relatively large steam bubbles has been visually observed in PULiMS and SES tests with subcooled water. During bubble collapse, water at the bubble interface accelerates towards the melt surface. Water impact at the melt interface can be sufficient to produce a splash. At certain frequency of bubble growth/collapse events, sufficient momentum flux can be transferred to the melt in order to sustain existence of the premixing layer. Currently, this mechanism is considered as a working hypothesis as it doesn't contradict to the experimental evidence gathered this far.*" During the collapse, the upper surface of the bubble is transformed into a downward cone, and the water in this cone as a high-speed jet moves down to the surface of the melt. Similar water cumulative jets are formed when cavitation bubbles collapse near a solid wall [4]. A theoretical study of this process in [4] showed that the forming water jets at an external pressure of 1 bar have velocities of about 170 m/s which can explain cavitation damage.

In order for hypothesis [3] to be proved, it is necessary to show that 1) when single bubble collapses, rather high melt splashes occur and 2) many such bubbles must form, that is, the frequency of their formation must be high. In [5], a numerical study of the collapse of a superheated steam bubble in subcooled water was carried out. It was shown that at high steam superheats, which were in experiments [3], the collapse of such a bubble occurs in the same way as the collapse of a cavitation bubble. The forming cumulative water jets have such large velocities that they can produce the melt splashes a few centimeters high.

Thus, the calculations in [5] confirmed hypothesis [3] regarding the possibility of high splashes of the melt after bubble collapse. However, the question of the influence of the non-condensable gas (NCG), which can be in the bubble together with the steam, on the bubble collapse, remained unclear. This gas (air, for example) can be captured by the melt jet during its movement in the gas atmosphere until the jet enters the melt. A recent experimental study [6] confirmed the possibility of this event. NCG decreases the steam condensation rate, which can lead to a decrease in the velocity of the formed cumulative water jet and reduce its action on the melt.

The present work is a continuation of [5]. The influence of NCG on the bubble collapse in cold water has been studied. It is rather difficult to estimate the amount of gas that was captured by the melt jet. Therefore, to evaluate the NCG effect on the bubble collapse, an extreme case was considered, when the bubble consists only of NCG. Similarly to [5], in this work, first, in a one-dimensional formulation, the dynamics of a superheated (with respect to the surrounding water) gas bubble at the initial stage of the first compression of the bubble is analyzed. The revealed features 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 (BEM) [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_{g0} be in water with a temperature T_{l0}, which is lower than the bubble temperature. The initial gas pressure in the bubble is equal to the water pressure level, 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:

$$\frac{d\left(\rho_g V_g\right)}{dt} = 0 \tag{1}$$

$$\frac{dU_g}{dt} + p_g \frac{dV_g}{dt} = Q \tag{2}$$

Here ρ_g, V_g, p_g, U_g – density, volume, pressure, internal energy of a bubble, Q –heat flux from a water to a bubble surface, t – time.

The liquid motion is described by the Rayleigh-Plesset equation

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

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

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

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

where R is a gas constant, T_g is a gas temperature.

It is possible to transform equations (1), (2) and (4) to

$$\frac{dp_g}{dt} = 3\frac{(\gamma - 1)q - \gamma p_g w_a}{a}, \tag{5}$$

$$\frac{dT_g}{dt} = 3\frac{q - p_g w_a}{\rho_g c_{gv} a} \tag{6}$$

where $\gamma -$ heat capacity ratio, q – specific heat flux from a liquid to a bubble surface, c_{gv} – gas heat capacity at constant gas pressure.

Energy equation for water.

To close the system of equations (3) - (6), it is necessary to determine the specific heat flux from a water to the bubble, q. For this purpose we will use the energy equation for water:

$$\rho_l c_l \left(\frac{\partial T_l}{\partial t} + w_l \frac{\partial T_l}{\partial r}\right) = \frac{1}{r^2}\frac{\partial}{\partial r}(\lambda_l r^2 \frac{\partial T_l}{\partial r}) \tag{7}$$

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

We assume that all the physical properties of a water (ρ_l, c_l, λ_l) are constant. Then the equation of water energy will take the form:

$$\frac{\partial T_l}{\partial t} + w_l \frac{\partial T_l}{\partial r} = \frac{\varkappa_l}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial T_l}{\partial r}\right) \tag{8}$$

where $\varkappa_l = \frac{\lambda_l}{\rho_l c_l}$.

The specific heat flux q on the bubble surface is equal to

$$q = \lambda_l \frac{\partial T_l}{\partial r}\bigg|_{r=a} \tag{9}$$

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 [5], 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 superheating 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] (photo on Fig. 16) is about 1 cm, thus $a_0 = 1$ 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 [5]. 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 [5], 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 superheating of the bubble on the dynamics of the process, a series of calculations were performed, in which this value varied as follows: 350 K, 500 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 superheating, the minimum radius of the bubble is 5.5 mm at a time of 1.4 ms.

(a) (b)

Figure 1: Bubble radius (a) and pressure (b) for various initial steam superheat

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 1a shows that the largest 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 2 shows the time dependences of the radius of a cavitation bubble and a gas bubble with an initial temperature superheating 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 case of superheating 650 K (Figure 1). 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 1b. When calculating later moments of time, the pressure in the bubble was found from the ratio:

$$p_g(t) = p_{g,1}\left(\frac{V_{g,1}}{V_g(t)}\right)^{1.0258} \tag{10}$$

here $p_{g,1}$=0.34487 bar and $V_{g,1} = 4{,}044631 \cdot 10^{-6}\, m^3$ is the pressure and volume of the bubble at the time of 0.2078 ms.

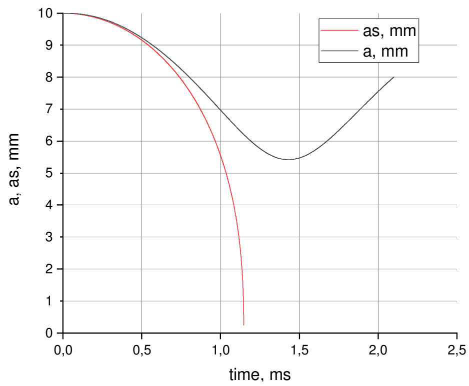


Figure 2: Radius histories of a cavitation bubble $a_s(t)$ and of a gas bubble $a(t)$ with an initial temperature superheating of 650 K

4 EVALUATION OF THE HYDRODYNAMIC EFFECT ON THE MELT DURING COLLAPSE OF A GAS BUBBLE

We will 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. Since the melt density is an order of magnitude higher than the water density, we will approximate the surface of the melt with a rigid wall. The problem is investigated under an axisymmetric formulation, the z axis is directed upwards from the melt surface and passes through the center of the bubble. The radial axis r is located on the melt surface.

The water is assumed to be incompressible; its potential flow is described by the Laplace and Bernoulli equations:

$$\Delta\Phi = 0 \tag{11}$$

$$\frac{\partial\Phi}{\partial t} + \frac{1}{2}\boldsymbol{w}_l^2 + \frac{p_l - p_0}{\rho_l} = 0 \tag{12}$$

where Φ is the velocity potential, p_l is the local pressure in the water. At large distances from the bubble (at infinity), the pressure takes the value p_0, the water velocity vanishes, and the velocity potential tends to an arbitrary constant, taken to be zero.

On the bubble surface, the pressure is given by $p_l = p_g$ and the position vector $\boldsymbol{r}$ of the fluid particle and the velocity vector, $\boldsymbol{w}_l = \nabla\Phi$, are related by kinematic formula

$$\mathrm{d}\boldsymbol{r}/\mathrm{d}t = \boldsymbol{w}_l \tag{13}$$

Taking into account that $(\boldsymbol{w}_l\nabla)\Phi = \boldsymbol{w}_l^2$, we can obtain the following equation for the evolution of the velocity potential at the bubble boundary using equation (12):

$$\frac{\mathrm{d}\Phi}{\mathrm{d}t} \equiv \frac{\partial\Phi}{\partial t} + (\boldsymbol{w}_l\nabla)\Phi = \frac{p_0 - p_g}{\rho_l} + \frac{1}{2}\boldsymbol{w}_l^2 = 0 \tag{14}$$

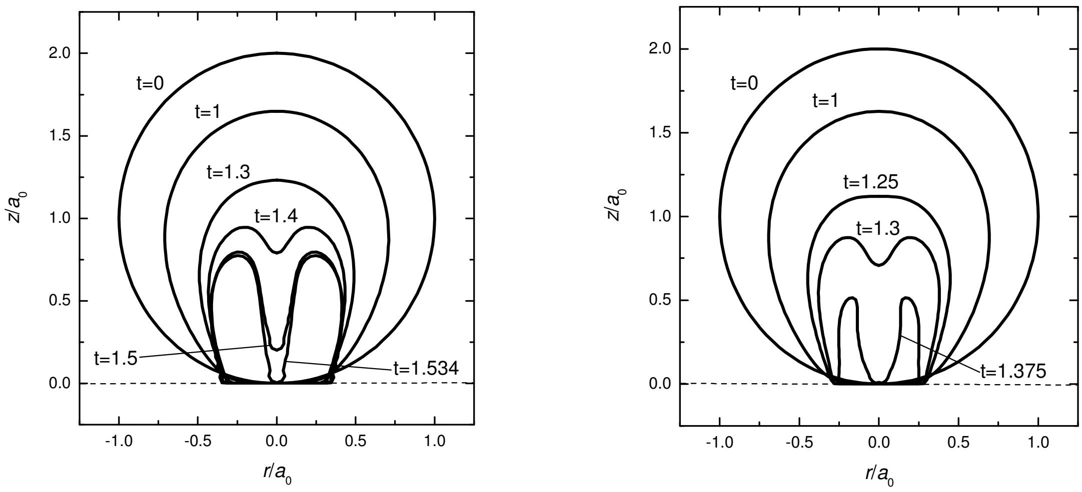
Equations (11)–(14) are solved numerically. Advancement in time of the bubble boundary coordinates according to Eq. (13) and of the velocity potential at those points from Eq. (14) is performed by the first-order Euler scheme. The velocity potential Φ is updated by the boundary element method [7], which enables the water velocity on the bubble boundary to be updated on each time step. The bubble pressure p_g is calculated from Eq. (10).

The collapse of a gas bubble with an initial radius of 10 mm was analysed. 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 [5], with this arrangement of the bubble, the maximum hydrodynamic effect on the melt surface is achieved. The external water pressure p_0 was 1 bar, the water density ρ_l was 974.94 kg/m^{-3}. The bubble pressure during the calculation was calculated in accordance with Eq. (10).

Figure 3a shows the evolution of a collapsing gas bubble. It can be seen that the initially spherical shape of the bubble is transformed into a toroidal one. A high-speed water jet enters the hole of the torus, the jet is directed to the surface of the melt. The last point in time in this figure is 1.534 ms. For comparison, Figure 3b shows the evolution of a cavitation bubble with the same initial parameters. The bubble pressure was kept constant at 0.38 bar, which corresponds to a saturation pressure at an ambient water temperature of 348 K. In the case of a cavitation bubble, hydrodynamic processes develop a little faster (last time moment is 1.375 ms), but in general, both bubbles evolve in a similar way.

The quantity which characterizes the directional fluid flow generated by the collapsing bubble, is the Kelvin impulse, namely, its vertical component

$$I_z = -\rho_l\boldsymbol{e}_z\int_S \Phi\,\boldsymbol{n}\mathrm{d}S \tag{15}$$



(a) gas bubble (b) cavitation bubble

Figure 3: The bubble shape evolution. Times are given in ms

In Eq. (15), $\boldsymbol{e}_z$ is the unit vector in the vertical direction, $\boldsymbol{n}$ is the unit surface normal vector pointing into the bubble, S is a bubble surface. The Kelvin impulse is well-known in fluid dynamics, providing a meaningful way to quantify unsteady flows near deformable bodies immersed in liquid, including collapsing cavities and cavitating bubbles; a review of this concept with necessary references can be found in [7]. For the problem in question, the Kelvin impulse characterizes the flow momentum directed towards the melt, and can be used to calculate the melt impact.

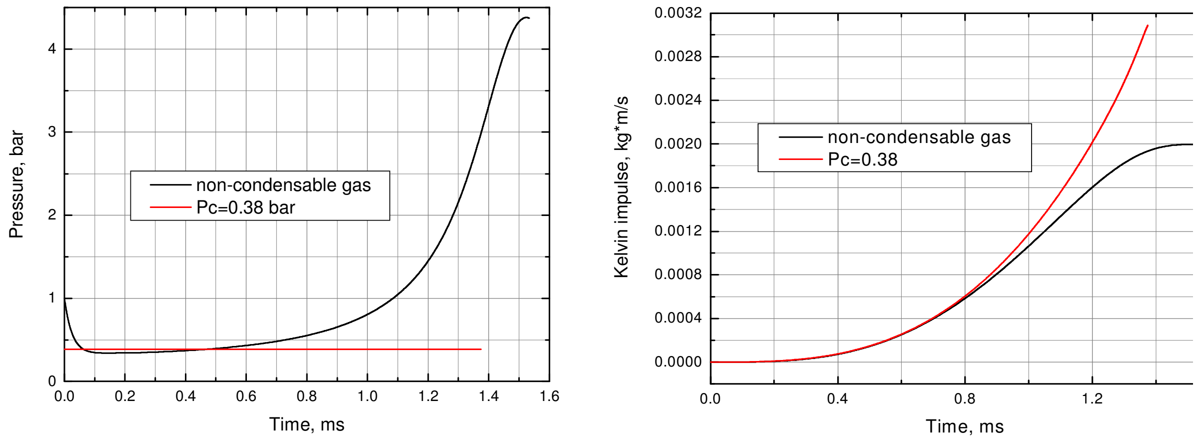
Figures 4a and 4b show the time dependences of the pressure in the gas bubble and the Kelvin impulse. For comparison, these figures show similar dependencies for a cavitation bubble. It is clearly seen how the pressure in the collapsing bubble quickly falls to the saturation pressure and stays at this level for a relatively long time (up to about 0.6 ms). 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 decreasing of the bubble is stopped.

Figure 4b shows the time dependences of the Kelvin impulse for gas and cavitation bubbles. As it was shown in [5], this value determines the height of the release of melt droplets into the water during the collapse of the bubble. It follows from Figure 4b that the Kelvin impulse 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 [5], it was found that the collapse of superheated steam bubbles formed near the melt-subcooled water interface can produce melt splashes into the water to a height of several centimetres. This process can be considered as one of the main physical reasons of a premixed layer formation in stratified systems. Second main reason is a frequency of the bubble growth/collapse events. This item is outside of the frame of the current study.

The influence of NCG on the bubble collapse was studied in the present work because NCG can decrease the condensation rate and reduce the effect of water on the melt. It was investigated an extreme case, when only NCG bubble is collapsed in the cold water. It was found that in this case, a rapid collapse of the bubbles occurs also, which leads to a hydrodynamic action on the melt of the same order as in the case of superheated pure steam bubbles.



(a) (b)

Figure 4: Comparison of dynamics of gas and cavitation bubbles:
(a) pressure, (b) Kelvin impulse

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, the collapse of NCG bubble becomes similar to the collapse of a cavitation bubble with the formation of a cumulative water jet acting on the melt. It is obvious that in the intermediate case of a bubble consisting of a steam-NCG mixture, the process of the bubble collapse will be realized in the same way.

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