

# Collapse and dynamics of a bubble near a rigid boundary enveloped by a vapor film

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**Abstract.** One of the possible consequences of a severe accident at a nuclear power plant with a pressurized water reactor is a steam explosion that occurs as a result of the interaction of a high-temperature melt of core materials with water and can lead to the failure of the containment. The paper considers the initial stage of the steam explosion (premixing of the melt with water) under the stratified geometry. The key phenomenon leading to premixing is the dynamic effect of a collapsing vapor bubble in a liquid on the melt surface. The influence of a vapor film located near a melt surface on the dynamics of a vapor bubble is considered. The Kelvin impulse is used as the main criterion characterizing the dynamic effect of a collapsing bubble on the liquid-vapor interface and on the melt surface. The influence of all the main parameters on the Kelvin impulse was numerically studied. Based on the calculations carried out on the plane of the parameters "film thickness - vapor density", the region of the dynamic impact of the collapsing bubble on the surface is determined. The greatest impacts are observed for thin films of vapor having a high density.

## 1 Introduction

During a severe accident at a nuclear power plant (NPP) with a pressurized water reactor, a high-temperature melt of core materials can interact with water. This interaction is accompanied by a rapid increase in pressure and the appearance of shock waves (steam explosion), which can lead to equipment and containment failure [1-2]. The geometrical configuration of the contact of the melt with water is essential for the dynamic characteristics of a steam explosion. Until recently, it was generally accepted that the most dangerous is the pouring-mode contact, when a jet of melt is poured into a deep pool of water. However, experiments [3-4] have shown that strong steam explosions can also occur in another configuration, namely, in a stratified geometry, i.e., the water layer is located above the melt layer. Such a stratified configuration occurs in the so-called core catchers at NPPs, where the molten core material spreads over the floor of the initially dry room, after which it is cooled from above with water. A necessary condition for the occurrence of a steam explosion is the premixing of the melt with the coolant, leading to the formation of a

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potentially explosive mixture. Experimental observations made it possible to establish the physical mechanism of premixing of water with the melt under conditions of stratified geometry. In experiments using video, it was found that as a result of the collapse of bubbles and the formation of high-speed water jets acting on the surface of the melt, a zone of mixing of the melt with water is formed, in which a spontaneous steam explosion occurs. It was theoretically shown in [5-8] that the impulse resulting from the collapse of a bubble near a surface of the melt is sufficient to knock out melt droplets and throw them to a sufficiently high height, which allows the formation of an explosive mixture of melt and water. However, these studies did not take into account that there is a film of steam between the water and the melt. Since the surface temperature of the melt is much higher than the saturation temperature of water, there can be no direct contact between water and the melt at the initial moment (before the explosion), a steam film forms on the surface of the melt. In this paper, the influence of vapor film parameters on the dynamic effect of a bubble collapsing in a liquid on the melt surface is studied. The Kelvin impulse is considered as the main parameter characterizing this dynamic effect. This concept was introduced by Benjamin and Ellis in 1966 [9], they noted that the Kelvin impulse "...associated with a moving bubble presents much the same intuitive physical picture as the momentum of a rigid projectile in free space, and hence the feasibility of impact effects in the process of cavitation damage is immediately appreciated". In [10], the Kelvin impulse concept was used to analyze cavitation bubble dynamics.

The Kelvin impulse of a collapsing bubble  $I$  according to [10] is expressed as follows:

$$I = \int_0^t F_e(t) dt \tag{1}$$

Where  $F_e(t)$  is the rate of change of the Kelvin impulse (or force)

$$F_e(t) = \rho \int_{\Sigma_b} \left\{ \frac{1}{2} |\nabla\Phi|^2 \mathbf{n} - \frac{\partial\Phi}{\partial n} \nabla\Phi \right\} dS \tag{2}$$

Here  $t$  – time,  $\rho$  – liquid density,  $\Phi$  – velocity potential,  $\mathbf{n}$  – outward normal to the liquid,  $S$  – surface,  $\Sigma_b$  – surface of the boundary.

The sign of the Kelvin impulse determines the direction of migration of a bubble during the latter stages of collapse. The magnitude of the Kelvin impulse determines the violence of the resulting liquid jet.

For a number of relatively simple cases, it is possible to analytically obtain an expression for the Kelvin impulse [10], provided that the bubble is considered as a point source of strength  $m(t)$ . For example, if the bubble is located near a rigid boundary at a distance  $h$ , then the Kelvin impulse in the  $z$  direction perpendicular to the boundary has the following form:

$$I_z(t) = -\frac{\rho}{16\pi h^2} \int_0^t m^2(t) dt < 0 \tag{3}$$

A negative sign of the Kelvin impulse indicates that the bubble is moving towards a rigid boundary, therefore, the high-speed liquid jet formed during collapse will dynamically affect the surface.

For the case when the bubble is located at a distance  $h$  from the interface of two liquids having densities  $\rho_1$  and  $\rho_2$ , respectively, the Kelvin impulse is expressed as:

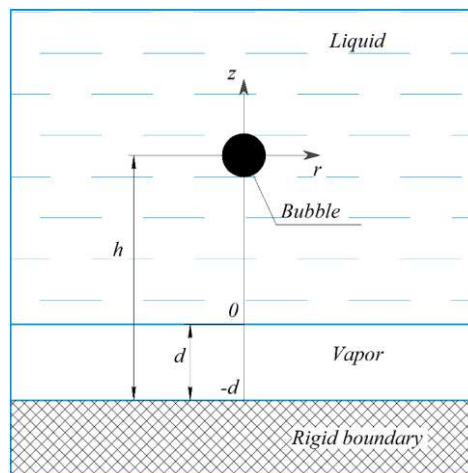
$$I_z(t) = \frac{\rho_1}{16\pi h^2} \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2} \int_0^t m^2(t) dt \tag{4}$$

The bubble is located in liquid with density  $\rho_1$ . The sign of the Kelvin impulse depends on the ratio of the densities of liquids. At  $\rho_1 > \rho_2$ , the sign is positive, therefore, the bubble moves away from the interface. At  $\rho_1 < \rho_2$ , the sign is negative, therefore, the bubble moves towards the interface. Thus, the bubble in this case moves always towards a denser liquid.

For the case when a vapor film is present above a rigid boundary, it is impossible to obtain an analytical expression for the Kelvin impulse, therefore, numerical methods are used in this paper to study the effect of the vapor film on the Kelvin impulse values.

## 2 Materials and methods

Since the density of the melt significantly exceeds the density of the liquid located above it, it is possible to neglect the movement of the melt surface and consider it as a rigid boundary. Therefore, we will consider the following system: rigid boundary – vapor film– liquid, Figure 1. A point source with strength  $m(t)$  is located in the liquid at a distance  $h$  from the rigid boundary, the film thickness is  $d$ .



**Fig. 1.** The schematic of the problem

Liquid and vapor are considered as ideal incompressible media, to describe the motion of which potentials  $\Phi_1$  and  $\Phi_2$ , respectively, are introduced. Since there is a source in the liquid, the Poisson equation is valid for  $\Phi_1$ , which takes into account the presence of a source:

$$\Delta\Phi_1 = m/\rho_1 \tag{5}$$

In the region of vapor, the Laplace equation is written:

$$\Delta\Phi_2 = 0 \tag{6}$$

The boundary conditions have the following form:

1) On the rigid boundary, the normal velocity is zero (no flux condition):

$$z = -d: \quad d\Phi_2/dz = 0 \tag{7}$$

2) A dynamic condition arising from the linearized Bernoulli equation is fulfilled on the interfacial surface:

$$z = 0: \quad \rho_1\Phi_1 = \rho_2\Phi_2 \tag{8}$$

- 3) On the interfacial surface, the equality of the normal velocities of liquid and vapor must also be fulfilled:

$$z = 0: \quad d\Phi_1/dz = d\Phi_2/dz \quad (9)$$

The problem is considered in an axisymmetric formulation using radial  $r$  and axial  $z$  coordinates,

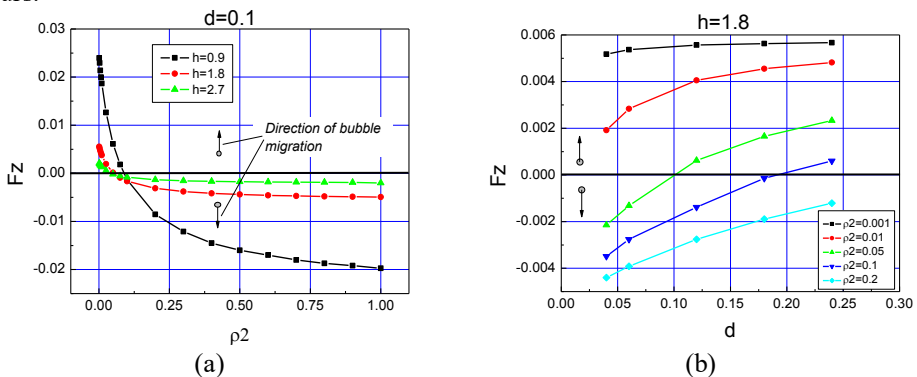
It is convenient to consider the problem in non-dimensional variables. The characteristic scales of the system are initial maximum radius of the bubble  $R_m$ , density  $\rho_1$ , time  $R_m (\Delta p / \rho_1)^{-0.5}$  ( $\Delta p = p_\infty - p_b$  - the initial pressure difference between the pressure at infinity  $p_\infty$  and vapor pressure of the bubble  $p_b$ ) and the potential  $R_m (\Delta p / \rho_1)^{0.5}$ . Further, all the results are presented in dimensionless variables, which for brevity are denoted by the same notation as the dimensional variables.

To solve the system of equations described above, the numerical integration method SIMPLE [11-13] is used.

### 3 Results

A large number of calculations were performed, in which the following main parameters varied: 1) the density of the vapor film, 2) the thickness of the vapor film, 3) the distance of the bubble from the interface surface, 4) the strength of the source. Let's consider the main trends obtained in the calculations.

The influence of vapor density on the magnitude of the Kelvin impulse is illustrated in Figure 2a (non-dimensional film thickness is 0.1). At low vapor densities, the force  $F_z$  has a positive sign, which means that the bubble moves upwards away from the interface surface. With increasing density, the force  $F_z$  decreases and at a certain density value becomes a negative value, i.e. the bubble in this case moves towards the interface surface. The closer the bubble is to the interfacial surface, i.e., the smaller  $h$ , the higher the density value when the transition from positively directed bubble motion to negatively directed occurs.

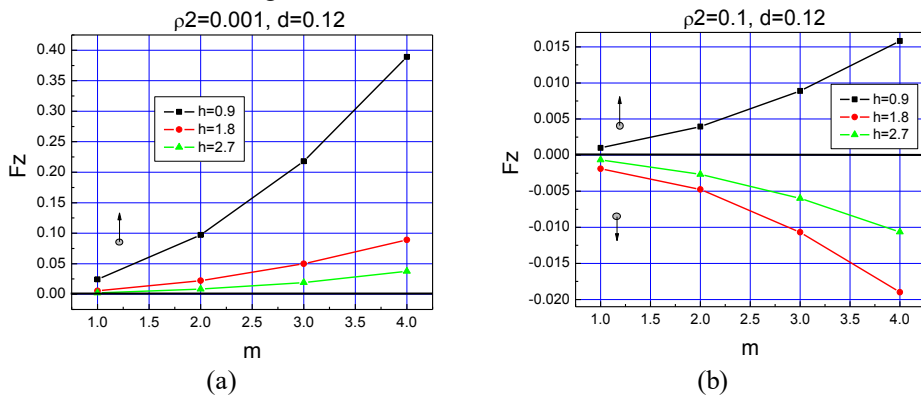


**Fig. 2.** Influence of film parameters on the force  $F_z$  : (a) vapor density, (b) film thickness.

The effect of the thickness of the vapor film on the magnitude of the Kelvin pulse is illustrated in Figure 2b (non-dimensional bubble height is  $h = 1.8$ ). An increase in the thickness of the vapor film leads to an increase in force  $F_z$ . At the same time, for low vapor densities of  $\rho_2 \leq 0.01$ , the force  $F_z$  for all values of the film thickness has a positive value, i.e. the migration of the bubble is directed away from the interfacial surface. For vapor

densities of  $\rho_2 \geq 0.05$  with small thicknesses of the vapor film, the value has a negative value, i.e. the bubble moves to the interfacial surface. As the film thickness increases, the force  $F_z$  sign changes to a positive value, i.e. the bubble in this case moves away from the interfacial surface. If the vapor density is significant ( $\rho_2 = 0.2$ ), then at any values of the film thickness, the force  $F_z$  retains a negative value and the bubble moves towards the interfacial boundary.

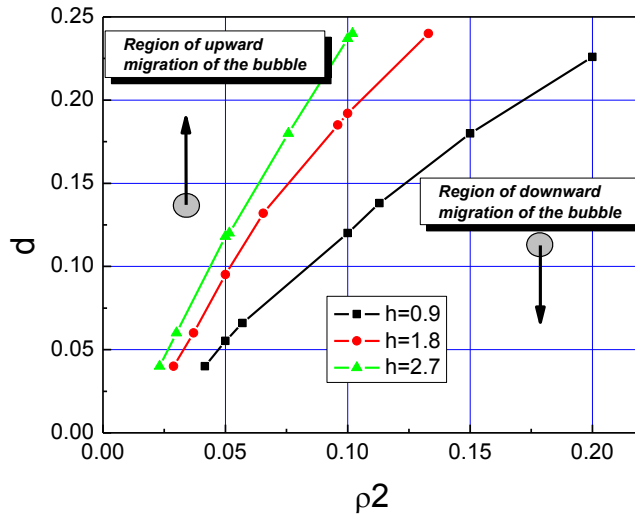
The variation of the strength of a point source  $m$  is illustrated in Figure 3. The thickness of the vapor film  $d = 0.12$ . At a low vapor density ( $\rho_2 = 0.001$ ), an increase in the strength of the point source causes an increase in force  $F_z$ , while the force value at any height is positive, i.e. the bubble moves in the opposite direction from the interfacial boundary, Figure 3a. The higher the bubble height  $h$ , the less force  $F_z$ . At a higher vapor density ( $\rho_2 = 0.1$ ) an increase in the strength of the point source also causes an increase in force  $F_z$  (in absolute magnitude), Figure 3b. At a low bubble height ( $h = 0.9$ ) the force  $F_z$  has a positive sign, i.e. the bubble moves upwards in the direction opposite from the interfacial boundary. At high values of height ( $h = 1.8$  and  $h = 2.7$ ), the force value is negative, i.e. the bubble moves to the interfacial boundary. In absolute magnitude, the force decreases as the bubble height is decreased.



**Fig. 3.** Influence of strength of point source on the force  $F_z$ . Vapor density: (a)  $\rho_2 = 0.001$ , (b)  $\rho_2 = 0.1$ . Film thickness  $d = 0.12$ .

## 4 Discussion

The calculation results were summarized on the  $d - \rho_2$  (film thickness - vapor density, see Figure 4) plane in order to visually display the parameter regions at which the collapsing bubble moves away from the interphase boundary (thereby not having a dynamic effect on the interface and the rigid boundary), and the parameter region at which the bubble moves towards the interphase surface, causing a dynamic effect on the interface and the rigid boundary, i.e. potentially leading to the destruction of the rigid boundary (melt surface). The most dangerous area of parameters for the destruction is the large values of the density of the vapor film ( $\rho_2 \geq 0.01$ ) and the small thickness of the vapor film ( $d \leq 0.1$ ).



**Fig. 4.** The  $d - \rho_2$  parameter space for bubbles near interface. Right side - region of downward migration of the bubble, left side - region of upward migration of the bubble.

## 5 Conclusion

The analysis carried out using the developed model showed that the presence of a vapor film significantly affects the dynamics of a collapsing bubble near a rigid boundary. The presence of even a thin film of vapor having a low density ( $\rho_2 = 0.001$ ) prevents the dynamic effect of a collapsing bubble on a rigid boundary. However, in the case of a sufficiently dense and thin vapor film, the dynamic effect of the collapsing bubble on the surface is still possible. In this paper, based on numerical calculations, a dynamic impact region on the plane "film thickness – vapor density" is obtained. The results obtained indicate the potential danger of steam explosions in core catchers at NPPs at relatively high pressures (15-20 bar), when the vapor density is quite high. To reduce the likelihood of steam explosions, it is necessary to diminish the pressure in the core catchers during severe accidents at NPPs to values of 1-5 bar.

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