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# Impact effects due to hot vapour bubble collapse in subcooled liquid

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Abstract. Collapse of a hot vapour bubble captured by subcooled water can produce a cumulative jet similar to that appearing in cavitating flows. In the context of stratified steam explosions following spreading of hot melt under a water layer, impact of the water jets can be a reason for melt splashes promoting the mixing of cold and hot liquids necessary for energetic interaction. In this work, the characteristics of the directional water flow caused by collapse of a bubble near a wall are obtained, and a correlation is given which relates the ultimate height of melt rise to the bubble parameters and droplet size. Estimates relevant to melt splashes caused by the cumulative water jet impact are presented which agree with the experimental observations available in the literature.

#### 1. Introduction

Ex-vessel steam explosion is one of the major nuclear energy hazards related to severe accidents with the reactor core degradation and release of the high-temperature melt (corium) from the reactor pressure vessel. In particular, this phenomenon is relevant to the molten core catchers being developed now, where a layer of water intended for corium cooling can exist either prior, or after the melt spreading over the bottom of the catcher. Explosive boil-up of water upon interaction with the high-temperature melt can cause significant shock loadings on the structural elements, endangering the reactor and containment integrity.

The most studied case so far is the "classical" steam explosion caused by the interaction of a melt jet with deep enough pool of coolant, where the pool depth is sufficient for complete (or significant) fragmentation of the jet. In this case, the melt jet is fragmented into dispersed melt droplets which are mixed with large quantity of water to form the premixed zone where steam explosion can occur [1]. In the case of shallow pool, or large melt jet diameter, however, the interaction length is too short for significant fragmentation to occur, and the jet reaches the pool bottom, spreading along it to form a stratified configuration with the hot melt layer on the bottom and liquid coolant above it, separated by a vapor film.

For a long time it was believed that in the stratified configuration no significant premixing of the phases can occur [2], therefore stratified steam explosions were considered as having low conversion ratio of thermal energy into mechanical work, being a hazard of secondary importance. However, recent large-scale experiments carried out in KTH (Sweden) [3] renewed the interest to the problem of stratified steam explosions. In the experiments [3] performed on PULiMS and SES facilities,

interaction of binary bismuth and tungsten oxide melts (up to 78 kg mass) with a 20 cm deep water pool was studied. Spontaneous steam explosions (absent for the same materials in deeper pools) were observed, with the peak loadings reaching 710 kN, corresponding to the peak pressure of 5.65 MPa; the duration of the active phase was 3-5 ms, and the impulse per unit area was as high as 24 kPa·s. The explosive loadings caused residual deformation of 10 mm-thick steel bottom of the pool by 35 mm. In a number of tests, the primary explosions were followed by the less powerful secondary ones. Thus, the experimental evidence [3] overturned the existing point of view on possible hazards of stratified steam explosions, bringing about theoretical works explaining different aspects of the problem [4, 5].

The key process determining the amount of material capable of participating in the steam explosion is the formation of the premixed zone. In the experiments [3] it was clearly demonstrated that on the surface of melt spreading under water significant perturbations occur in the form of sporadic melt splashes rising the hot liquid to the height of few centimeters. Therefore, the assumption that mixing of melt and coolant can only occur behind the propagating explosion wave (on which the reasoning of low energetics of stratified steam explosions was based) is found to be incorrect. The premixing mechanism suggested in [3] includes periodic formation of vapor bubbles in subcooled water, their collapse and formation of water jets hitting the melt surface and causing respective melt splashes. To prove the feasibility of this mechanism, detailed fluid dynamics and thermal hydraulics of the processes involved must be studied.

This paper continues our earlier research on the premixing mechanism, related to collapse of hot vapor bubbles in cold liquid, formation of cumulative water jets and their interaction with the liquid melt [6]. In particular, it was found that shrinking of a hot vapor bubble is attributed to gas cooling causing rapid drop in the internal bubble pressure; for high initial vapor superheats the dynamics of bubble is similar to that of cavitation bubble collapse. In this work we consider the hot vapor bubble collapse by the approaches used in cavitation studies, as well as present some estimates relevant to melt splashes caused by the cumulative water jet impact.

#### 2. Problem formulation and numerical method

Shrinking and collapse of a vapor bubble near a solid wall is studied in the geometry sketched in figure 1.





Under the assumption that the liquid surrounding the bubble is inviscid and incompressible, and its flow is potential, the continuity and momentum equations are expressed as the Laplace equation for the velocity potential  $\Phi$  and the Bernoulli equation:

$$\Delta \Phi = 0 \tag{1}$$

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$$\frac{\partial \Phi}{\partial t} + \frac{1}{2} \left( \nabla \Phi \right)^2 + \frac{p - p_{\infty}}{\rho_f} = 0$$
<sup>(2)</sup>

Here, t is the time, p is the pressure in fluid,  $p_{\infty}$  is the pressure at infinity,  $\rho_f$  is the fluid density, respectively.

On the bubble surface  $\Gamma$ , a constant pressure  $p_c$  equal to the saturated vapor pressure at the temperature of liquid is assumed:

$$p\big|_{\Gamma} = p_c \tag{3}$$

Also, on the bubble surface a kinematic relationship is satisfied,

$$\frac{\mathrm{d}\boldsymbol{x}}{\mathrm{d}t} = \boldsymbol{v} \tag{4}$$

where x is the position vector of a surface point,  $v = \nabla \Phi$  is its velocity.

The impermeability boundary condition is posed on the rigid surface z = 0

$$v_{z}\big|_{z=0} = \frac{\partial \Phi}{\partial z}\Big|_{z=0} = 0$$
(5)

whereas at infinity  $r^2 + z^2 \rightarrow \infty$  the velocity potential  $\Phi$  tends to a constant value (taken equal to zero).

The numerical procedure includes the advancement in time the coordinates of points on the bubble boundary (see equation (4)) and of velocity potential at those points (described by equation (2) recast in the form of substantial derivative of  $\Phi$ ). Integration of these equations is performed by a first-order Euler scheme. The fluid velocity on the bubble boundary is then found from the updated potential calculated by the boundary element method (BEM) [7].

#### 3. Simulation results

Calculations were performed for variable initial position of the bubble with respect to the wall,  $\gamma = h/a_0 = 1-4$ , where *h* is the distance from the bubble centre to the wall. The variation of collapsing bubble shape at different  $\gamma$  are presented in figure 2. The results obtained agree, both qualitatively and quantitatively, with previous works where collapse of a near-wall bubble was studied [8, 9].

The primary output parameter of the simulations was the Kelvin impulse (having dimensions of  $kg \cdot m/s$  in SI units), defined by

$$I_{z} = -\rho_{f} \boldsymbol{e}_{z} \int_{\Gamma} \boldsymbol{\Phi} \boldsymbol{n} \, \mathrm{d} \boldsymbol{\Gamma}$$
(6)

where  $\Gamma$  is the bubble surface,  $e_z$  is the unit vector in the z coordinate direction, *n* is the unit surface normal vector (pointing into the bubble). The concept of Kelvin impulse is well-known in fluid dynamics; it is very handful in the analysis of unsteady flows near deformable bodies immersed in liquid, in particular near collapsing cavities and cavitating bubbles, see review in [10]. The Kelvin impulse characterizes the directional fluid flow arising due to the collapsing bubble surface deformation near a wall, and the associated wall impact [11]. For a symmetric bubble collapsing in an infinite fluid, the Kelvin impulse is zero, whereas for a near-wall flow considered here, only its vertical component (6) is meaningful.



**Figure 2.** Bubble shape evolution for different initial positions  $\gamma$  above the surface (shown by the dashed line). The non-dimensional time is  $t^* = t / (a_0 \sqrt{\rho_f / (p_\infty - p_c)})$ .

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In figure 3, the time histories of the non-dimensional Kelvin impulse  $I_z^* = I_z \left(a_0^6 \rho_f \left(p_0 - p_c\right)\right)^{-1/2}$ during the bubble collapse are plotted for different initial bubble distances to the wall  $\gamma$ . The Kelvin impulse increases monotonically, reaching its maximum at the instant of bubble collapse. The maximum value of  $I_z$  is growing when the initial distance to the wall is decreasing. Note that for a bubble collapse in an infinite liquid the Kelvin impulse is equal to zero.



Figure 3. Non-dimensional Kelvin impulse for different distances to wall.

In figure 4, the maximum values of the non-dimensional velocity of water jet  $v_j^* = v_j / \sqrt{(p_\infty - p_c) / \rho_f}$  and Kelvin impulse  $I_z^*$  observed at the instant of bubble collapse are plotted as functions of the initial bubble distance to the wall. It is interesting to note that the jet velocity is growing with the distance to the wall, while the Kelvin impulse, as was discussed above, is diminishing.



Figure 4. Maximum non-dimensional jet velocity and Kelvin impulse as functions of the distance to wall.

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Estimate now the effects of water jet generated by a collapsing bubble in the problem of melt-water interaction relevant to the development of a premixing zone in stratified configurations. Experimental observations made in the course of stratified steam explosion tests [3] show that melt spreading over a shallow water pool bottom is featured by the development of a water-melt premixing zone of about 5 cm thickness. The melt-water system is, of course, different from the vapour bubble in water near a rigid wall considered above. Firstly, since the melt temperature by far exceeds the boiling temperature of water, a vapour film separates the hot and cold liquids. Secondly, the melt liquid, and its surface is deformable, not rigid. However, because the vapour film is expected to be rather thin (as is the case in subcooled film boiling), the bubble collapse time is short, and the melt density is an order of magnitude larger than that of water, we neglect these effects when estimating the characteristics of water jet impinging on the melt surface and take the impact parameters from the simulation results presented above.

Assume that impingement of a water jet on the melt surface results in the appearance of a melt droplet moving upwards. Assume also that, in accordance with the principle of momentum conservation, the Kelvin impulse of the water jet is transferred completely to the melt droplet, i.e.,

$$I_{z,\max}(\gamma) = m_m w_m \tag{7}$$

where  $m_m$  and  $w_m$  are the mass and initial vertical velocity of the melt droplet, respectively. Neglecting the drag exerted on the rising melt drop by the surrounding fluid due to the significant difference in densities, we obtain from the conservation of mechanical energy in the gravity field that the ultimate rise height of the melt droplet,  $\Delta h$ , is related to the initial velocity by the familiar relationship

$$\frac{m_m w_m^2}{2} = m_m g \,\Delta h \tag{8}$$

Expressing the initial velocity from equation (7) as  $w_m = I_{z,\max}(\gamma)/m_m$ , substituting it into (8) and introducing the melt droplet radius  $a_m$  (with  $m_m = 4\pi a_m^3 \rho_m$ , where  $\rho_m$  is the melt density), obtain the following relationship:

$$\frac{a_m}{a_0} = \left(0.0285 \frac{p_0 - p_c}{\rho_f g}\right)^{1/6} \left(\frac{\rho_f}{\rho_m}\right)^{1/3} \left(\frac{I_{z,\max}(\gamma)}{a_0^3 \left[\rho_f(p_0 - p_c)\right]^{1/2}}\right)^{1/3} \frac{1}{\Delta h^{1/6}}$$
(9)

Note that the expression in the third parentheses on the right-hand side is, in fact, the non-dimensional maximum Kelvin impulse  $I_{z,\max}^*$  presented in figure 4.

For the estimates, take the parameters of the experiments [3]:  $\rho_f = 974.86 \text{ kg/m}^3$ ,  $p_0 = 10^5 \text{ Pa}$ ,  $p_c = 0.38595 \cdot 10^5 \text{ Pa}$  (water temperature  $T_f = 348 \text{ K}$ ),  $\rho_m = 7811 \text{ kg/m}^3$ . By using the values  $I_{z,\text{max}}^*(\gamma)$  obtained above (see figure 4), the melt-to-bubble radius ratio  $a_m/a_0$  can be obtained as a function of the bubble position  $\gamma = h/a_0$ . In figure 5, these dependencies are plotted for three values of terminal rise height of melt droplet  $\Delta h = 3$ , 5, and 7 cm.

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**Figure 5.** Relative size of melt droplets as a function of bubble distance to wall, obtained for three terminal melt rise heights.

It can be seen that the impact produced by a collapsing bubble on the melt surface can be quite significant. Being near the water-vapor interface ( $\gamma = 1-1.5$ ), the bubble can produce a water microjet capable of knocking out a melt drops of radius  $a_m = (0.34-0.5)a_0$  which can rise to the heights  $\Delta h = 3-7$  cm above the melt surface. It is noted in [3] that bubbles of few centimeters in size were observed in the experiments. Thus, if we take the initial bubble radius to be 1 cm, the characteristic radii of the melt droplets penetrating the mixing layer of 5 cm depth can be about 3.4-5 mm.

#### 4. Conclusions

The presence of high-temperature melt droplets of several millimeters in size in water is a prerequisite for the occurrence of powerful steam explosions. The premixing zone containing so-called coarsely dispersed melt can be formed in the stratified geometry due to splashes of melt spreading over the water pool bottom. The results obtained in this work support the idea that splashing can be caused by impact of water micro-jets from collapsing bubbles on the melt surface. These results provide quantitative estimates of the impact effects of water jets.

The calculation of Kelvin impulse for the cumulative jet flow of water generated by collapse of vapor bubble in subcooled water show that the subsequent impact of water jet on the melt surface can result in the knocking out of melt droplets which can rise to the heights of few centimeters. Penetrating in water above the melt layer, these droplets can contribute to the development of a premixing zone above the melt layer.

The estimates obtained in the paper are based on the assumption that a single melt drop is knocked out by the jet impinging on the melt surface. However, it is quite possible that multiple jet droplets, or even melt splashes can result from such an impact. Since the estimates are based on the integral considerations, they can be also applicable to more complex melt splashing, provided that the effective melt droplet diameter is defined appropriately. These problems will be tackled in the future work where numerical simulations of melt-water jet interactions will be involved. In particular, such characteristics of the premixed zone as the average volume fraction of vapor, water, and melt, as well as the thickness of three-phase zone will be required for the evaluation of steam explosion shock effects upon interaction with reactor vessel and other structures.

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