On the Growth of Large Sodium Vapor Bubbles in a Liquid Sodium Pool

F. Casadei
Commission of the European Communities, J.R.C. Ispra Establishment, Applied Mechanics Division, I-21020 Ispra (Varese), Italy

M. Dalle Donne
Kernforschungszentrum Karlsruhe GmbH, Postfach 3640, D-7500 Karlsruhe, Germany

ABSTRACT

The study of the dynamics of the expansion of large bubbles of hot sodium vapour in a pool of liquid sodium plays an important role in understanding the effects of a hypothetical core disruptive accident. A model of the growth of the bubble in the pool is described. The equations of the motion of the liquid and of the non-steady heat diffusion problem are solved together with the continuity and energy equations for the vapour phase. A first set of parametric calculations has been performed with constant evaporation and condensation coefficients. In a second set, however, due account has been taken of the effect on condensation of non-condensable fission gases and vapour convection. Due to the very high calculated vapour velocities, non-condensable gases have little effect on the condensation rate, and the percentage amount of condensed sodium is considerably higher than previously calculated by other authors.
1. Introduction

The study of the dynamics of the expansion of large bubbles of hot sodium vapour in a pool of relatively cold liquid sodium plays an important role in understanding the effects of a hypothetical core disruptive accident (HCDA) in liquid-metal fast breeder reactors. This is relevant both to the mechanical effects on the reactor tank and to the retention mechanism of the fission products in the liquid sodium.

As a result of fuel-coolant interaction in an HCDA, a large bubble would be formed by the discharge of a mixture of hot sodium vapour, liquid sodium, highly dispersed fuel and fission products from the core region into the relatively cold liquid sodium pool placed above the core. An isentropic expansion of the bubble down to the equilibrium pressure, taking into account the compression of the cover gas volume, would be a rather simple, but too conservative estimate of the work performed by the bubble. The work potential of the accident is mitigated if heat transfer to the cold liquid pool, mainly due to condensation of hot sodium vapour at the bubble surface, is taken into account. This mitigation effect could be reduced in principle by the presence of the non-condensable fission gases, which tend to accumulate near the condensation surfaces, inhibiting the heat transfer, and enhanced by the convection of the vapour in the bubble.

The objective of this work is to investigate the growth of a large sodium vapour bubble in liquid sodium taking due account of non-equilibrium, i.e. temperature differences between vapour and liquid sodium at the bubble interface, of the non-condensable gas fission products represented here by xenon, and of the vapour circulation in the bubble. Other mechanisms, such as cold liquid sodium entrainment in the bubble, the presence of relatively cold structures in the pool, etc., can generally influence the bubble expansion as well in the sense of mitigating the work potential. They have not been considered in this approach.

2. Previous work

The literature on bubble dynamics that we have examined can be roughly divided into two major classes: the first deals with boiling and the growth of small bubbles in superheated liquids, the second with expansion and collapse of large bubbles surrounded by relatively cold liquid, mainly for HCDA simulation. To the first class belong classical papers like those of Plesset and Zwick [1,2] and of Theocharous et al. [3].

To the second class belongs the paper of Reynolds et al. [4], who examined the condensation of a large sodium vapour bubble while it rises in the liquid sodium pool, assuming a constant condensation heat transfer coefficient (HTC). The condensation process was found to be governed by transient conduction in the liquid, and it was concluded that a significant fraction of the sodium vapour condenses before the bubble reaches the pool surface.

A subsequent paper of Theocharous and Fauske [5] analysed once more the condensation of a rising bubble, taking into account the effect of non-condensables and solving the problem of transient mass diffusion and convection in the liquid phase. The presence of non-condensables was found to delay seriously the condensation process.

The paper by Özişik and Kress [6] treats the problem of condensation in a flat plate geometry. This can be applied to a rising bubble of large dimensions, and it is done in a way similar to Ref. [5], i.e. including the effect of fission gases. However, a turbulent boundary layer is assumed, rather than transfer by molecular diffusion in the vapour phase. The reason for this modification is that a diffusion model may underestimate the condensation rates if strong internal convection motions are present.

Finally, Reynolds and Berthaud [7] have theoretically and experimentally analysed the expansion and collapse of large two-phase (water vapour and liquid water) bubbles in a pool of cold liquid water. The effect of non-condensables has not been included. An early instability of the bubble surface is observed. During this phase, conduction-limited heat transfer is shown to be too slow to account for the experimental results, while it describes well the bubble expansion and collapse as soon as the bubble surface becomes stable. The heat and mass transfer, in the absence of non-condensable gases, significantly mitigates the mechanical work.

3. Present model and assumptions

The present model describes the expansion and collapse of a large sodium vapour bubble in a finite pool of relatively cold liquid sodium. During its growth, the bubble is supplied with hot sodium vapour coming from the core region, which is modelled with a superheated vapour source at constant pressure and temperature, connected with the bubble through an orifice. The discharge of hot sodium vapour through the orifice is governed by the pressure difference between core region and bubble. The geometry of the problem is spherical (see Fig. 1).

Temperature and pressure of the vapour in the bubble are considered to be uniform. The presence of the cover volume is also modelled by means of an external spherical gas shell, which may be compressed by the motion of the liquid. The reactor tank is modelled by an external rigid boundary.

The interphase heat transfer problem is solved with the heat conduction in the liquid and the liquid motion problems.
Non-equilibrium between the sodium vapour in the bubble and the liquid at the interface is described by the model, since the temperature of the vapour is generally different from the temperature of the liquid at the wall. The magnitude of this temperature difference is affected by the condensation and evaporation coefficients. Data from the literature for these coefficients for water and liquid metals vary between $2 \times 10^2$ and 1 [3]. Two distinct sets of calculations were performed, the difference being only in the condensation and evaporation coefficients $C_{CO}$ and $C_{CE}$. The first series of calculations has been performed using constant values of $C_{CO}$ and $C_{CE}$. Three different values were used ($1 \times 10^1$ and $10^2$), where $C_{CO}$ and $C_{CE}$ were always assumed to be equal.

The calculations of Theofanous and Fauske [5] show, however, that the presence of non-condensable gas fission products could cause a further considerable decrease of the effective $C_{CO}$ to still lower values. It is a fairly well-known fact that non-condensables tend to assemble near the cold surface and slow down the condensation process. The work of Özügik and Kress [6] shows that the convection motion of the vapour in the bubble has a strong effect on the condensation process as well. It has therefore been decided to perform a second series of calculations, where instead of postulating a value for $C_{CO}$ and $C_{CE}$ and taking it constant through the calculation, we calculate a variable $C_{CO}$ from the results of [6]. From these results, the heat transfer condensation coefficient is taken as a function of the vapour velocity in the bubble and of the gas fission product concentration. Xenon is taken as representative of the gas fission products. The presence of liquid sodium, of fuel and steel particles and fuel vapour in the bubble, the entrainment of liquid drops from the pool, the presence of cold structures, and the instability of the bubble surface are neglected at the present stage of the model. Rising of the bubble in the pool is also neglected, since the expansion characteristic times are much smaller than the time required to rise in the pool.

The mathematical description of the problem is based on a set of differential equations: a) equation of the motion of the liquid; b) energy equation for the liquid; c) continuity equation for the vapour phase; d) energy equation for the vapour phase. The approximated analytical solution of Plesset and Zwick [1] to the problem of heat diffusion across a spherical boundary with radial motion (see point b), is used. The mass transfer at the phase interface is described by relationships similar to those used in previous literature [3,7,8] and based on so-called condensation and evaporation coefficients (to be experimentally determined), representing the ratio of the actual mass transfer to the value derived from the kinetic theory. Full derivation of the governing equations is given in [9].

4. Case with variable condensation coefficient

Özügik and Kress [6] have obtained the HTC by condensation as a function of vapour velocity and of the molar concentration of xenon in the vapour by solving the transient heat and mass transfer problem in turbulent flow for a flat plate geometry. They performed sample calculations for the condensation of UO$_2$ and of sodium vapour containing non-condensable fission gas. One useful result of this investigation is that the HTCs for the condensation of UO$_2$ and of the sodium vapour, for the same vapour velocity and non-condensable concentration, differ little (the HTC for sodium vapour is ~ 50% higher than in the case of UO$_2$ vapour) considering the very different physical properties of these two vapours. Thus it appears legitimate to extrapolate the data of Özügik and Kress obtained for sodium vapour at 12.6 atm and 1513 K to other sodium pressures and temperatures. The data of Figs. 5 and 7 of Ref. [6] for sodium may be correlated by the empirical formula

$$h_C = (8000 + 1420 \frac{U_{V_{vap}}}{U_{vap}})^{0.8} \cdot \exp\left[-(3.01 + 2.898 \times e^{0.457})^{0.564}\right]$$  \hspace{1cm} (1)

where $U_{vap}$ is the average vapour velocity in the bubble in m/s, $X_{vap}$ is the average molar concentration of non-condensable gas in the bubble and $h_C$ is the condensation heat transfer coefficient in W/m$^2$K. This formula can only be applied in case of net condensation. In Eq.(1) the velocity-independent term is due to the diffusion of the non-condensable gas in the boundary layer near the bubble wall, while the velocity term is due to the turbulent convection of the vapour in the bubble. As expected, $h_C$ decreases if the non-condensable gas concentration in the bubble increases. The HTC decreases slowly with time. The knowledge of $h_C$ allows one to calculate the condensation rate of sodium vapour and hence $C_{CO}$ which now is not constant. This is the main difference of the second formulation of the problem with respect to the first one, which uses constant $C_{CO}$ and $C_{CE}$.

The term $X_{vap}$ appearing in Eq.(1) is calculated by a balance of the mass of non-condensable gas introduced in the bubble through the orifice, which is supposed to be known [9].

To estimate the vapour velocity in the bubble $U_{vap}$ of Eq.(1) the equation of conservation of momentum for the vapour in the bubble is added to the set of equations [9]. In writing this equation, the friction losses and the mass of non-condensable gas are neglected and the vapour inlet velocity is calculated according to gas laws.

5. Results

Bubble growth calculations have been performed starting from a bubble of 0.1 m initial radius, containing saturated vapour (temperature: 1154 K), at atmospheric pressure. The surrounding liquid (volume: 110 m$^3$) has an
initial uniform temperature of 800 K. Orifice parameters are chosen so that maximum mass rates from the core to the bubble of 5 and 100 kg/s of hot sodium vapour (at 1700 K and 5 bar) respectively are reached.

Figures 2 to 4 show the results in the first 270 ms for the case of constant $C_{CO}$ and $C_{CO}$ coefficients (three cases: 1, 0.1 and 0.01) and for a maximum injection rate $M_{in} = 100$ kg/s.

A decrease in the value of the coefficients $C_{CO}$ as it would be in the presence of non-condensable gases that tend to accumulate near the bubble wall, causes a slight increase of the growth velocity and a much greater increase of the vapour temperature, as expected. The liquid interface temperature, on the other hand, is much decreased. Oscillations are due to the presence of the cover gas volume.

Results for the same case but with variable $C_{CO}$ are shown in Figs. 5 and 6 for the first 170 ms.

Four different cases are presented for non-condensable gas concentrations in the injected vapour, $X_{go} = 5 \times 10^{-2}$, $10^{-2}$, $10^{-3}$, and $10^{-10}$, respectively. Fig. 5 shows that $h_{e}$ is practically unaffected by $X_{go}$ below $X_{go} = 10^{-3}$. The vapour velocity in the bubble is not affected by $X_{go}$.

The non-condensable gas concentration in the bubble increases slowly with time due to the vapour condensation in the bubble. The resulting effect on $C_{CO}$ is a slight increase in time up to values of $\sim 10^{-2}$. Here also, $X_{go}$ has only a small effect. Bubble radius (Fig. 6), vapour temperature and pressure are not affected by $X_{go}$. Only the liquid temperature at the interface decreases slightly with increasing $X_{go}$. The results are about the same as those obtained with a constant condensation coefficient of 0.01.

The main conclusion of these calculations is that the effect of the non-condensable gases in the bubble is surprisingly small on the bubble growth and even on the vapour condensation rate. This is mainly due to the fact that the vapour in the bubble is highly turbulent: the vapour velocity reaches maximum values of almost 800 m/s and then decreases relatively slowly. It was thought that these high velocities might be given by the choice of the very high maximum injection rate of hot sodium vapour of 100 kg/s. Calculations were thus performed for a maximum injection rate of 5 kg/s for $X_{go} = 5 \times 10^{-2}$ and $10^{-3}$. The effects of $X_{go}$ are now greater, but not because of smaller vapour velocities. In fact, these remain about the same as in the previous case. However, here the condensation is much more effective than in the previous case, due to the higher surface-to-volume ratio of the bubble (smaller bubble radius). Due to this strong condensation ratio, the concentration of non-condensable gas increases rapidly in the bubble in the case $X_{go} = 5 \times 10^{-2}$ and this, of course, reduces the condensation rate. Altogether the effects of non-condensable concentration remain relatively small.

Figure 7 shows the ratio of the condensed sodium to the injected sodium as a function of time for the six calculated cases with variable condensation coefficient. In the smaller bubble ($M_{in} = 5$ kg/s), after 0.6 s, a constant ratio of 0.8 is reached. For the bigger bubble ($M_{in} = 100$ kg/s), the percentage of condensation reaches a value of 70% in $\sim 3$ s. These are considerably higher values than those of Theofanous and Fauske [5], who neglected the effects of vapour convection, and those of Özışık and Kress [6], who assumed vapour velocities of up to 20 m/s for a rising bubble without vapour injection. In our case, however, we have calculated much higher vapour velocities and obtain much higher condensation rates.

6. Concluding remarks

The present calculations show that the condensation and evaporation coefficients, at least in the range between $10^{-2}$ and 1, which covers all the data for liquid metals from the literature, have a relatively small effect on the radius and on the expansion velocity of a large vapour sodium bubble in a liquid sodium pool. Thus mechanical energy is also minimally affected. The choice of those coefficients has, however, a large influence on the vapour and on liquid temperatures at the interface, and on the sodium vapour condensation rates.

If one takes account of the non-condensable fission gases and of the vapour convection effects on the condensation with an empirical equation obtained from the calculations of Özışık and Kress, one obtains, at least for the conditions assumed in the present calculations, a condensation coefficient of $\sim 10^{-2}$. Due to the very high calculated vapour velocities, non-condensable gases have little effect on the vapour condensation rate. Furthermore, the percentage amount of condensed sodium is an order of magnitude higher than calculated neglecting the effect of vapour convection. We calculate percentages between 70 and 80% in times of 3 to 0.6 s according to the size of the bubble ($R \approx 2$ or 0.6 m). This is, of course, an important result in assessing the fission products retention capability of the liquid sodium, before the bubble reaches the surface of the sodium pool.

As stated in the introduction in our analysis we have neglected the effects of sodium entrainment in the bubble, the presence of droplets inside the bubble and of relatively cold structures in the pool. All these factors tend to increase the exchange surface between liquid and vapour and thus increase the condensation (although the experiments of Reynolds and Berthoud [7] show that entrainment plays an important role only at the very beginning of the bubble expansion) to even larger percentages than the values, already quite high, found with the present simplified analysis. Thus, the present results are probably pessimistic. In the real core, the percentage of condensed sodium may be even higher than 70 - 80%.
References


---

Fig. 1 - Schematic representation of the used model.
Fig. 2 - Bubble radius, constant C.

Fig. 3 - Bubble vapor temperature; constant C.

Fig. 4 - Liquid temperature at the interface of the bubble; constant C.

Fig. 5 - Condensation heat transfer coefficient $\dot{M}_{in} = 100$ kg/s.

Fig. 6 - Bubble radius, $\dot{M}_{in} = 100$ kg/s.

Fig. 7 - Ratio $\rho$ of the condensed to the injected sodium mass.