Module 8: Boiling

Lecture 32: Conservativeness of Hsu's Criteria

The Lecture Contains:

Module 8: Boiling

Lecture 32: Conservativeness of Hsu's Criteria

Waiting Period

After inception a bubble grows until it encounters cold liquid such that the condensation rate at the top of the bubble equals the evaporation rate or the bubble departs upon reaching a certain size. During the growth period, the bubble pushes the surrounding liquid outwards causing some mixing of the cold liquid with the warm liquid in the thermal layer. After the bubble departs, colder-liquid will tend to fill the space vacated by the departing bubble. Figure 8.8 shows this process schematically. A new bubble at this location will not grow until the superheated liquid layer is re-established and the inception criteria is satisfied. The time taken by the thermal layer to redevelop prior to the inception is termed as the waiting period. Hsu proposed a model to calculate this period . In his model it was assumed that an ambient liquid layer of thickness δ and extending to infinity in the plane of the heater comes in contact with the wall and is transiently heated. During the heating period the temperature of the wall and the final thickness of the thermal layer remain constant.

The transient heat diffusion equation for an infinite slab of thickness δ with appropriate initial and boundary conditions can be written as

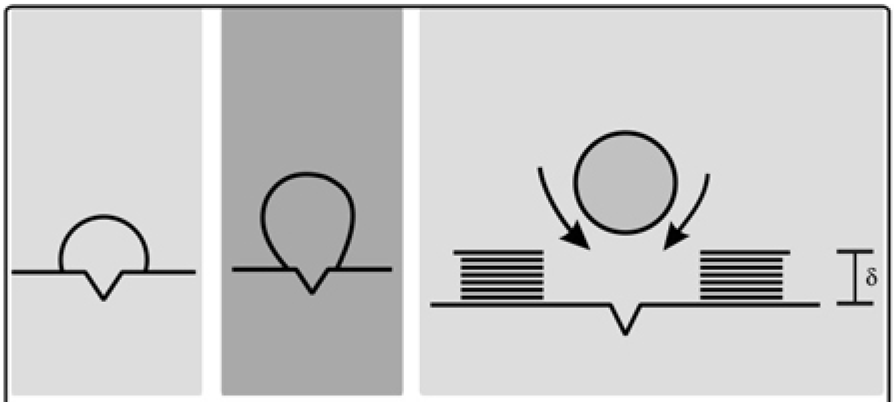

Fig 8.8: Thermal layer development after bubble departure

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$$\frac{\partial^2 T}{\partial y^2} = \frac{1}{\alpha_l}\frac{\partial T}{\partial t} \quad \textbf{(8.32)}$$

The initial and boundary conditions are :

Initial condition

$$T = T_{sat} \; at \; t = 0 \; for \; all \; y \quad \textbf{(8.33)}$$

$$T = T_w \; at \; y = 0 \; \; for \; all \; t \geq 0 \quad \textbf{(8.34)}$$

and

$$T = T_{sat} \; at \; y = \delta \; for \; all \; \; T \geq 0 \quad \textbf{(8.35)}$$

The solution of the problem can easily be written as

$$\frac{T - T_{sat}}{T_w - T_{sat}} = \left(1 - \frac{y}{\delta}\right) + \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^n}{n}\sin\left[n\pi\left(1 - \frac{y}{\delta}\right)\right]e^{-n^2\pi^2\tau} \quad \textbf{(8.36)}$$

Where

$$\tau = \frac{\alpha_l t}{\delta^2}$$

The temperature profiles obtained from equation (8.36) for various times , τ ,are plotted in Fig. 8.9 . In this figure the liquid superheat determined from equation (8.6) is also plotted.The intersection of this curve with the temperature profiles gives the waiting time for a particular size cavity.It is noted that waiting time increases with increase in cavity size.Since with increase in wall superheat the size of the nucleating cavity decreases, the effect of increased wall superheat will be to reduce the waiting time for a particular size cavity.It is noted that waiting time increases with increase in cavity size.Since with increase in wall superheat the size of the nucleating cavity decreases,the effect of increased wall superheat will be to reduce the waiting time.As can be seen from Figure 8.9, for a given wall superheat certain very small and very large cavities may never nucleate.

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An analytical expression for the waiting time can be obtained if the cold liquid layer contacting the heated wall is assumed to be semi-infinite. This is exactly the approach which was taken by Han and Griffith (1965). During transient diffusion of heat in a semi-infinite slab, the film thickness can be written as

$$\delta = \sqrt{\pi \alpha_l t}$$

Elimination of liquid temperature between equations 8.21 and 8.6 and upon substituting for bubble height and bubble radius in terms of cavity size we obtain,

$$\frac{C_2 r_c}{C_1 \delta} = \left[1 - \frac{2C_1 \sigma T_{sat}}{(T_w - T_{sat})\rho_v h_{fg} r_c}\right]$$

or

$$\delta^2 = \left[\frac{C_2 r_c}{C_1\left[1 - \frac{2C_1 \sigma T_{sat}}{(T_w - T_{sat})\rho_v h_{fg} r_c}\right]}\right]^2 \qquad \textbf{(8.40)}$$

Substituting for δ^2 from **equation (8.38),** the waiting time is obtained from **equation (8.40)** as

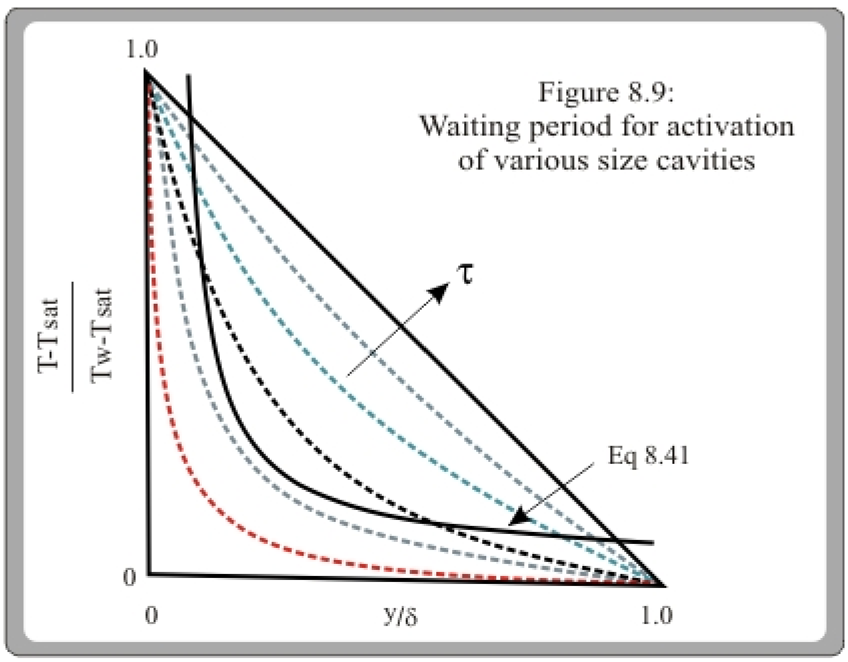

Fig 8.9 Waiting Period For Activation of Various Size Cavities

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$$t_w = \left[\frac{C_2 r_c}{\sqrt{\pi \alpha_l} C_1 \left[1 - \frac{2 C_1 \sigma T_{sat}}{(T_w - T_{sat}) \rho_v h_{fg} r_c} \right]} \right]^2 \qquad \textbf{(8.41)}$$

It can be seen from **equation (8.41)** that the waiting time will first decrease and then increase with cavity size but it will continue to decrease as the wall superheat is increased.

The waiting times obtained from **Fig. 8.9** or **equation (8.41)** are based on the assumption that during heating of the liquid, the heater wall temperature remains constant. This assumption corresponds to a wall heat flux that varies with time. Generally in laboratory experiments it is the heat flux that is held constant. This condition in turn implies that during transient heating, the wall temperature will vary.Also, it is possible that during the bubble growth period the heat flux associated with evaporation of the microlayer, as we will discuss in more detail later, can exceed the wall heat flux and thereby reduce the wall temperature. Thus during transient heating of the liquid adjacent to the wall, the wall temperature may have to be increased as has been pointed out by **Hatton and Hall (1966).** These factors need to be included in the model for a more realistic prediction of the waiting time. However Fig. 8.9 or **equation (8.41)** give trends which are consistent with the experimental data.

Example 4: Calculate and plot the waiting time as a function of cavity size for a surface submerged in a pool of saturated water at one atmosphere pressure. Assume the wall superheat to be 10^0 C and the contact angle to be $\frac{\pi}{2}$.

Solution: For $\beta = \frac{\pi}{2}$ both the constant **C1 and C2** are unity. Evaluating the various physical properties at the mean temperature of 1050 C, the expression for waiting time from **equation (8.41)** is

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$$t_w = \left[\frac{r_c}{\sqrt{\pi(1.68)10^{-7}}\left[1-\frac{2(57.9)10^{-3}(373)}{(10)(0.695)(2.245)10^{6}}\right]}\right]^2$$

$$= \left[\frac{1.38\times10^{+3}(r_c)}{1-\frac{2.77\times10^{-6}}{r_c}}\right]^2$$

$$= -364\times10^{-6}\text{sec} \quad \text{for } r_c = 10\times20^{-6}$$

It can be seen from the above equation that cavities equal to or smaller than **2.77 micron** will never nucleate. From **Fig. 8.10,** it is found that the waiting time is of the order of a millisecond.

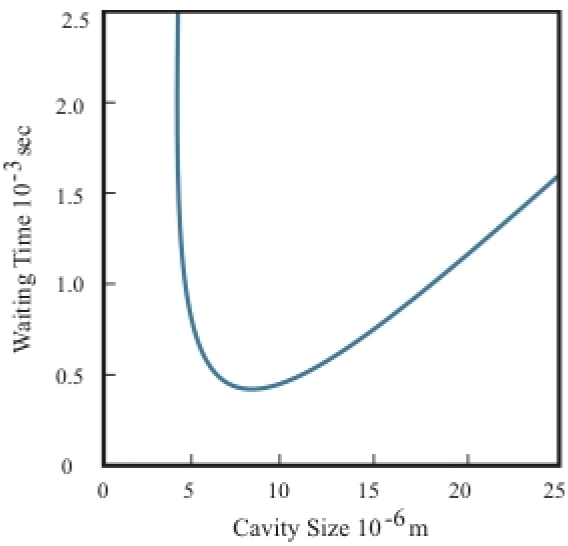

Fig 8.10 Dependence of Waiting Time on Cavity size

The life span of a bubble can be divided into two periods the waiting period during which conditions conductive to bubble growth are created near the heating surface, and the growth period during which the bubble actually grows to a certain size before departure. The growth of a bubble at the wall is influenced by several factors such as the thermal and flow field around the bubble and the volume and thickness of the microlayer underneath the bubble.

The bubble shape itself is influenced by the contact angle, the direction of gravitational acceleration and the flow around the bubble.The description of growth of such a bubble is quite complex . We can hope to address some features of this process only after developing an understanding of the growth of a totally spherical bubble in an infinite medium under gravity free conditions.

Bubble Growth Without Heat or Mass Transfer

The growth of a high pressure gas bubble in an infinite medium was first described by **Lord Rayleigh (1917).** For an inviscid incompressible liquid, the potential function can be written as

$$\Phi = \frac{R^2 \dot{R}}{r} \qquad \textbf{(8.42)}$$

Where R is the instantaneous radius of the bubble, $\dot{R}$ is first time derivative of the radius and r is any radius measured from the center of the bubble. From **equation (8.42),** the radial velocity is obtained as

$$u = -\frac{\partial \Phi}{\partial r} = \frac{R^2 \dot{R}}{r^2} \qquad \textbf{(8.43)}$$

For a uniform pressure in the bubble, the momentum equation describing the radial

Velocity of the liquid can be written as

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$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}=-\frac{1}{\rho_l}\frac{\partial P}{\partial r} \quad \textbf{(8.44)}$$

After substitution for u from **equation (8.43)** and **(8.44)** becomes integration of

$$\frac{R^2\ddot{R}}{r^2}+\frac{2R\dot{R}^2}{r^2}+\frac{1}{2}\frac{\partial}{\partial r}\left(\frac{R^4\dot{R}^2}{r^4}\right)=-\frac{1}{\rho_l}\frac{\partial P}{\partial r} \quad \textbf{(8.45)}$$

Equation (8.45) from far away from the bubble (r = ∞) to the outer surface of the bubble **(r = R)**, yields

$$-\left[\frac{R^2\ddot{R}}{r}+\frac{2R\dot{R}^2}{r^2}\right]_{\infty}^{R}+\left[\frac{R^4\dot{R}^2}{2r^4}\right]_{\infty}^{R}=-\frac{1}{\rho_l}[P]_{\infty}^{R} \quad \textbf{(8.46)}$$

$$R\ddot{R}+\frac{3}{2}\dot{R}^2=\frac{1}{\rho_l}[P_{bo}-P_l] \quad \textbf{(8.47)}$$

where ,

$$P_{bo}=P_b-\frac{2\sigma}{R} \quad \textbf{(8.48)}$$

and P_l is the pressure in the liquid far away from the bubble. **Equation (8.46)** is called **Rayleigh's Equation.**

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