## 6.5.4 Pool Boiling Crisis

In this section the approach taken by Zuber, Tribius and Westwater (1961) will be followed. They demonstrated that the phenomenon of boiling crisis can be visualized as a flooding phenomenon (see, for example, Brennen 2005). Consider first the nucleate boiling process depicted in figure 1. As liquid is turned to vapor

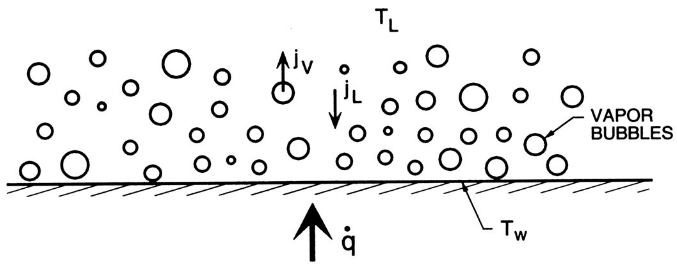


Figure 1: Nucleate boiling.

at or near the solid surface, this results in an upward flux of vapor in the form or bubbles and, necessarily, an equal downward mass flux of liquid. As the heat transfer rate increases these two mass fluxes increase proportionately and the interaction force between the two streams increases. This force inhibits the mass flow rate and there exists a maximum for which this flow pattern cannot sustain any further increase in heat or mass flux. This is known as the flooding point for this flow pattern and the maximum or critical heat flux, $\dot{q}_{c1}$, can be estimated (see, for example, Brennen 2005) to be

$$\dot{q}_{c1} = C_1 \rho_V \mathcal{L} \left\{ \frac{\mathcal{S} g(\rho_L - \rho_V)}{\rho_L^2} \right\}^{\frac{1}{4}} \tag{1}$$

where $\mathcal{L}$ is the latent heat, $\mathcal{S}$ is the surface tension, $\rho_L$ and $\rho_V$ are the liquid and vapor densities, and the typical bubble radius, $R$, is estimated to be given by

$$R = \left\{ \frac{3\mathcal{S}}{2g(\rho_L - \rho_V)} \right\}^{\frac{1}{2}} \tag{2}$$

Now consider the alternative flow pattern sketched in figure 2 in which there is a layer of vapor next to the wall. The flow within that vapor film consists of water droplets falling downward through an upward vapor flow. Analysis of the Rayleigh-Taylor instability of the upper surface of that film leads to the conclusion that the size of the droplets is given by a similar expression as equation 2 except that the factor of proportionality is different. Further analysis of the interaction of downward mass flux of droplets flowing through the upward flux of vapor leads to the conclusion that in this flow pattern there exists a flooding condition with a maximum possible heat flux and mass flow rate. This maximum heat flux, $\dot{q}_{c2}$, can be estimated (Brennen 2005) to be

$$\dot{q}_{c2} = C_2 \rho_V \mathcal{L} \left\{ \frac{\mathcal{S} g(\rho_L - \rho_V)}{\rho_V^2} \right\}^{\frac{1}{4}} \tag{3}$$

where $C_2$ is some other constant of order unity.

The two model calculations presented above (and leading, respectively, to critical heat fluxes given by equations 1 and 3) allow the following interpretation of the pool boiling crisis. The first model shows that the bubbly flow associated with nucleate boiling will reach a critical state at a heat flux given by $\dot{q}_{c1}$ at which the flow will tend to form a vapor film. However, this film is unstable and vapor droplets will continue to be detached and fall through the film to wet and cool the surface. As the heat flux is further increased a second critical heat flux given by $\dot{q}_{c2} = (\rho_L/\rho_V)^{\frac{1}{2}} \dot{q}_{c1}$ occurs beyond which it is no longer possible for the water droplets to reach the surface. Thus, this second value, $\dot{q}_{c2}$, will more closely predict the true boiling crisis limit. Then, the analysis leads to a dimensionless critical heat flux, $(\dot{q}_c)_{nd}$, from equation 3 given by

$$(\dot{q}_c)_{nd} = \frac{\dot{q}_c}{\rho_V \mathcal{L}} \left\{ \frac{\mathcal{S} g(\rho_L - \rho_V)}{\rho_V^2} \right\}^{-\frac{1}{4}} = C_2 \tag{4}$$

Kutateladze (1948) had earlier developed a similar expression using dimensional analysis and experimental data; Zuber *et al.* (1961) placed it on a firm analytical foundation.

Borishanski (1956), Kutateladze (1952), Zuber *et al.* (1961) and others have examined the experimental data on critical heat flux in order to determine the value of $(\dot{q}_c)_{nd}$ (or $C_2$) that best fits the data. Zuber *et al.* (1961) estimate that value to be in the range $0.12 \rightarrow 0.15$ though Rohsenow and Hartnett (1973) judge that 0.18 agrees well with most data. Figure 3 shows that the values from a wide range of experiments with fluids including water, benzene, ethanol, pentane, heptane and propane all lie within the $0.10 \rightarrow 0.20$. In that figure $(\dot{q}_C)_{nd}$ (or $C_2$) is presented as a function of the Haberman-Morton number, $Hm = g\mu_L^4(1 - \rho_V/\rho_L)/\rho_L \mathcal{S}^3$, since the appropriate type and size of bubble

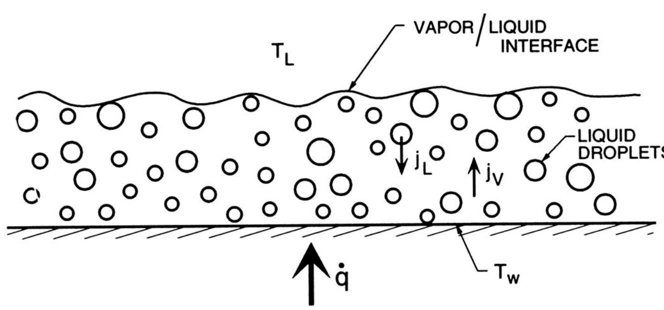


Figure 2: Sketch of the conditions close to film boiling.

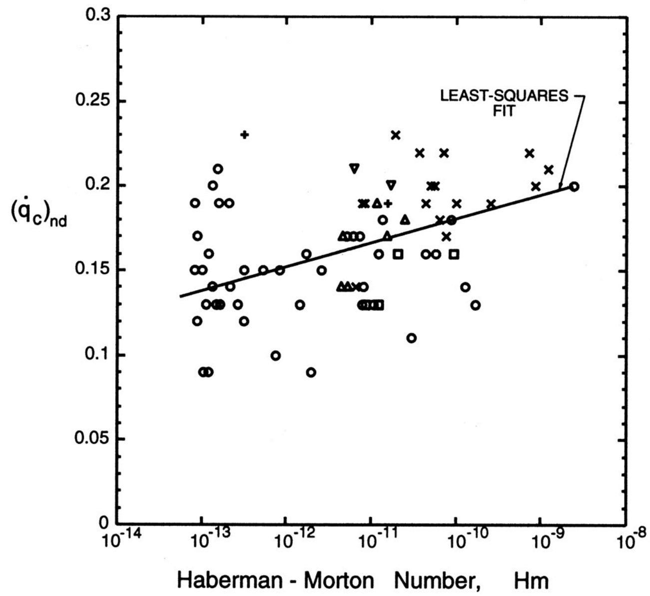


Figure 3: Data on the dimensionless critical heat flux, $(\dot{q}_c)_{nd}$ (or $C_2$), plotted against the Haberman-Morton number, $Hm = g\mu_L^4(1-\rho_V/\rho_L)/\rho_L\mathcal{S}^3$, for water (+), pentane (×), ethanol (⊡), benzene (△), heptane(▽) and propane (∗) at various pressures and temperatures. Adapted from Borishanski (1956) and Zuber *et al.* (1961).

that is likely to form in a given liquid will be governed by $Hm$ (see, for example, Brennen 2005).

Lienhard and Sun (1970) showed that the correlation could be extended from a simple horizontal plate to more complex geometries such as heated horizontal tubes in which the typical dimension (for example, the tube diameter) is denoted by $d$. Explicitly Lienhard and Sun recommend

$$(\dot{q}_c)_{nd} = 0.061/C^{**} \quad \text{where} \quad C^{**} = d/\left\{\frac{\mathcal{S}}{g(\rho_L - \rho_V)}\right\}^{\frac{1}{2}} \tag{5}$$

where the constant, 0.061, was determined from experimental data; the result 5 should be employed when $C^{**} < 2.3$. For very small values of $C^{**}$ (less than 0.24) there is no nucleate boiling regime and film boiling occurs as soon as boiling starts.

For useful reviews of the extensive literature on the critical heat flux in boiling, the reader is referred to Rohsenow and Hartnet (1973), Collier and Thome (1994), Hsu and Graham (1976) and Whalley (1987).