Vertical Film Boiling

The first analysis of film boiling on a vertical surface was due to Bromley (1950) and proceeds as follows. Consider a small element of the vapor layer of length dy and thickness, $\delta(y)$, as shown in figure 1. The temperature difference between the wall and the vapor/liquid interface is ΔT. Therefore the mass rate of conduction of heat from the wall and through the vapor to the vapor/liquid interface per unit surface area of the wall will be given approximately by $k_V \Delta T/\delta$ where k_V is the thermal conductivity of the vapor. In general some of this heat flux will be used to evaporate liquid at the interface and some will be used to heat the liquid outside the layer from its bulk temperature, T_b to the saturated vapor/liquid temperature of the interface, T_e. If the subcooling is small, the latter heat sink is small compared with the former and, for simplicity in this analysis, it will be assumed that this is the case. Then the mass rate of evaporation at the interface (per unit area of that interface) is $k_V \Delta T/\delta \mathcal{L}$. Denoting the mean velocity of the vapor in the layer by $u(y)$, continuity of vapor mass within the layer requires that

$$\frac{d(\rho_V u \delta)}{dy} = \frac{k_V \Delta T}{\delta \mathcal{L}} \tag{Nig1}$$

Assuming that we use mean values for ρ_V, k_V and $\mathcal{L}$ this is a differential relation between $u(y)$ and $\delta(y)$. A second relation between these two quantities can be obtained by considering the equation of motion for the vapor in the element dy. That vapor mass will experience a pressure denoted by $p(y)$ that must be equal to the pressure in the liquid if surface tension is neglected. Moreover, if the liquid motions are neglected so that the pressure variation in the liquid is hydrostatic, it follows that the net force acting on the vapor

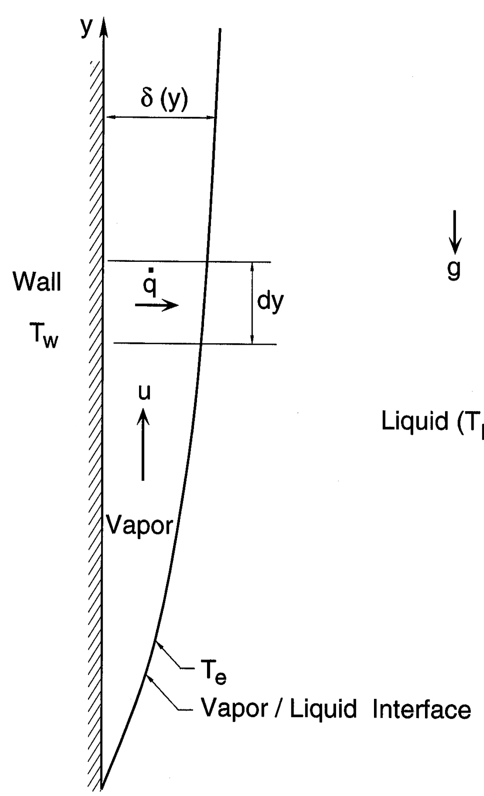

Figure 1: Sketch for the film boiling analysis.

element as a result of these pressure variations will be $\rho_L g \delta dy$ per unit depth normal to the sketch. Other forces per unit depth acting on the vapor element will be its weight $\rho_V g \delta dy$ and the shear stress at the wall that we will estimate to be given roughly by $\mu_V u/\delta$. Then if the vapor momentum fluxes are neglected the balance of forces on the vapor element yields

$$u = \frac{(\rho_L - \rho_V) g \delta^2}{\mu_V} \tag{Nig2}$$

Substituting this expression for u into equation (Nig1) and solving for $\delta(y)$ assuming that the origin of y is chosen to be the origin or virtual origin of the vapor layer where $\delta = 0$ we obtain the following expression for $\delta(y)$

$$\delta(y) = \left[\frac{4 k_V \Delta T \mu_V}{3 \rho_V (\rho_L - \rho_V) g \mathcal{L}} \right]^{\frac{1}{4}} \; y^{\frac{1}{4}} \tag{Nig3}$$

This defines the geometry of the film.

We can then evaluate the heat flux $\dot{q}(y)$ per unit surface area of the plate; the local heat transfer coefficient, $\dot{q}/\Delta T$ becomes

$$\frac{\dot{q}(y)}{\Delta T} = \left[\frac{3 \rho_V (\rho_L - \rho_V) g \mathcal{L} k_V^3}{4 \Delta T \mu_V} \right]^{\frac{1}{4}} \; y^{-\frac{1}{4}} \tag{Nig4}$$

Note that this is singular at $y = 0$. It also follows by integration that the overall heat transfer coefficient for a plate extending from $y = 0$ to $y = \ell$ is

$$\left(\frac{4}{3} \right)^{\frac{3}{4}} \left[\frac{\rho_V (\rho_L - \rho_V) g \mathcal{L} k_V^3}{\Delta T \mu_V \ell} \right]^{\frac{1}{4}} \tag{Nig5}$$

This characterizes the film boiling heat transfer coefficients in the upper right of the figure in section (Nib). Though many features of the flow have been neglected this relation gives good agreement with the experimental observations (Westwater 1958). Other geometrical arrangements such as heated circular pipes on which film boiling is occurring will have a similar functional dependence on the properties of the vapor and liquid (Collier and Thome 1994, Whalley 1987).