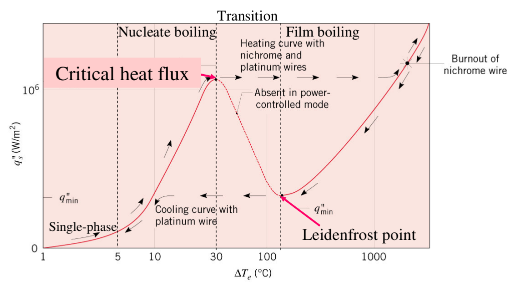
Boiling Heat Transfer-I

- Boiling is associated with transformation of liquid to vapor by heating
- It differs from vaporization in the sense that it is associated with the formation of bubbles
- The formation of bubbles stir the fluid and breaks the boundary layers thereby increasing the heat transfer coefficient
- The bubbles are normally formed on the surface scratches. The bubbles do not appear till the wall is heated in excess of the saturation temperature, called wall superheat.

Boiling Heat Transfer-II

- The excess temperature required for the onset of formation of bubbles decreases with increase in the size of surface scratches
- Models exist for the prediction of this, but will not be discussed in this first level course.
- One of the main interest is the prediction of heat transfer coefficient
- The general features can be understood for the experiment conducted by Nukiyama. The results are summarized in what is known as Boiling Curve

Pool Boiling Heat Transfer-I



Boiling curve at 1 atm

Pool Boiling Heat Transfer-II

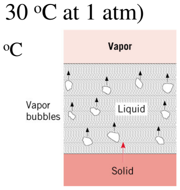
- Free convection region $\Delta T_{Sat} < 5\ ^oC$ (single phase)
- Vapor formed at the free surface
- Onset of nucleation $\Delta T_{sat} \sim 5\ ^oC$
- Bubbles nucleate, grow and detach from the surface
- Increase of wall superheat leads to more vigorous nucleation and rapid increase in heat transfer
- As the superheat is increased, the vapor formation become vigorous, it blankets the surface and the heat transfer decreases. This turn around point is called the Critical Heat Flux or Boiling crisis

Pool Boiling Heat Transfer-III

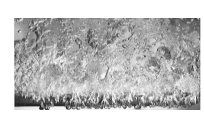
- As the superheat is increased, more blanketing causes the heat transfer to drop, till the entire heated surface is blanketed
- Now the radiation heat transfer also starts playing a role and eventually, the heat transfer starts increasing due to increase convection and radiation heat transfer
- The second turnaround point is called Leidenfrost point or rewetting point.
- The heat transfer beyond this point is called film boiling
- We shall briefly look at some details

Pool Boiling Heat Transfer-IV

- Nucleate Boiling (Wall super heat < 30 ^oC at 1 atm)
  - ➢ Isolated bubbles Region $5 < \Delta T_{Sat} < 10\ ^oC$
    - – Liquid motion is strongly influenced by nucleation of bubbles at the surface.
    - – 'h' rapidly increases with wall superheat
    - – Heat transfer is principally due to contact of liquid with the surface (single-phase convection) and not due to vaporization.

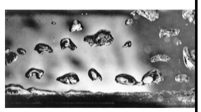


  - ➢ Jets and Columns Region ($10 < \Delta T_{Sat} < 30\ ^oC$ at 1 atm)
    - – Increasing nucleation density causes bubbles to coalesce to form jets and slugs
    - – Liquid wetting impaired
    - – 'h' starts decreasing with increase in superheat



Pool Boiling Heat Transfer-V

- Critical Heat Flux (Wall super heat ~30 °C at 1 atm)
  - Typically 1MW/m^2 at 1 atm and increases with pressure
  - If the wall pumps heat flux, there is a potential for the wall to melt as the heat transfer coefficient is very low here due to vapor blanketing.
- Film Boiling (Wall super heat >120 °C at 1 atm)
  - Heat transfer by conduction and radiation across vapor blanket
  - Usually not a preferred mode of cooling but can occur during the ECCS injection in an uncovered core



Pool Boiling Heat Transfer-VI

- Transition Boiling (30 °C < ΔT_{sat} < 120 °C at 1 atm)
  - Called Unstable film boiling
  - Surface conditions oscillate between nucleate and film boiling.
- Boiling Heat Transfer Correlations
  - Different models exist and there is no single view on this aspect.
  - We shall just list the correlations for application purposes

Pool Boiling Heat Transfer-VII

- Nucleate Boiling
  - Rohsenow's correlation is most popular

$$q'' = \mu h_{fg}\left(\frac{g(\rho_l - \rho_v)}{\sigma}\right)^{0.5}\left(\frac{c_{p,l}\Delta T_{sat}}{C_{s,f}\, h_{fg}\, Pr_l^{\,n}}\right)^3$$

  - $C_{s,f}$, n depends on Surface/fluid combination (Given in Table 10.1 of your book)
- Critical Heat Flux
  - Lienhard's correlation

$$q'' = 0.149\, h_{fg}\,\rho_v\left(\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right)^{0.25}$$

Pool Boiling Heat Transfer-VIII

- Minimum Heat Flux (Leidenfrost's point)
  - Adapted from Zuber's correlation

$$q'' = 0.09\, h_{fg}\,\rho_v\left(\frac{\sigma g(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2}\right)^{0.25}$$

Not very reliable

- Film Boiling
  - Both Convection and radiation effects are important
  - Bromley's correlation is most quoted

$$\overline{h}_{overall}^{\,4/3} = \overline{h}_{conv}^{\,4/3} + \overline{h}_{rad}\,\overline{h}_{overall}^{\,1/3}$$

Pool Boiling Heat Transfer-IX

$$\overline{Nu}_L = \frac{\overline{h}_{conv} L}{k_v} = 0.943\left(\frac{h'_{fg}\, g(\rho_l - \rho_v)L^3}{\nu_v k_v (T_s - T_{sat})}\right)^{0.25}$$

$$h'_{fg} = h_{fg} + 0.8 c_{p,v}(T_s - T_{sat})$$

$$\overline{h}_{rad} = \frac{\varepsilon\sigma(T_s^4 - T_{sat}^4)}{(T_s - T_{sat})}$$

Vapour properties are evaluated at average film temperature, liquid property at saturated temperature

For other cylinder and sphere, the convective heat transfer coefficient is modified as

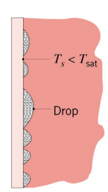
$$\overline{Nu}_D = \frac{\overline{h}_{conv} D}{k_v} = C\left(\frac{h'_{fg}\, g(\rho_l - \rho_v)D^3}{\nu_v k_v (T_s - T_{sat})}\right)^{0.25}$$

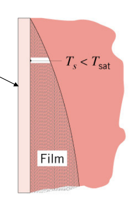
The value of C for Horizontal cylinder = 0.62, for sphere, C = 0.67

As an approximation, when $\overline{h}_{conv} > \overline{h}_{rad}$ $\quad \overline{h}_{overall} = \overline{h}_{conv} + \frac{3}{4}\overline{h}_{rad}$

Condensation Heat Transfer-I

- Condensation implies transformation of vapor back to liquid
- There are basically two mechanisms for condensation
  - Film Condensation
  - Drop Condensation

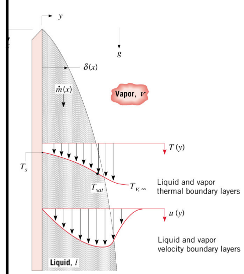




Condensation Heat Transfer-II

- Film Condensation
  - Entire surface is covered by the condensate, which flows continuously from the surface and provides a resistance to heat transfer between the vapor and the surface.
  - Thermal resistance is reduced through use of short vertical surfaces and horizontal cylinders.
- Dropwise Condensation
  - Surface is covered by drops ranging from a few micrometers to agglomerations visible to the naked eye.
  - Thermal resistance is greatly reduced due to absence of a continuous film.
  - Surface coatings may be applied to inhibit *wetting* and stimulate dropwise condensation.

Analysis of Film Condensation-I



Nusselt Analysis for Laminar Flow

Assumptions:

- A pure vapor at T_{sat}
- Creeping boundary layer flow
- Negligible shear stress at liquid/vapor interface.

We shall derive it from the basic equations

Analysis of Film Condensation-II

- Momentum Equation

$$\rho_l\left(u\frac{\partial(u)}{\partial x}+v\frac{\partial(u)}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu_l\left(\frac{\partial^2 u}{\partial y^2}\right)-\rho_l g$$

Negligible $\qquad \rho_v g$

$$\Rightarrow(\rho_f-\rho_v)g=\mu_l\left(\frac{d^2u}{dy^2}\right)\qquad\Rightarrow\left(\frac{d^2u}{dy^2}\right)=\frac{(\rho_f-\rho_v)g}{\mu_l}$$

On Integration we get

$$u=\frac{(\rho_f-\rho_v)g}{\mu_l}\frac{y^2}{2}+c_1y+c_2$$

Boundary Conditions $\quad u=0,\ \ y=0 \quad \Rightarrow c_2=0$

Analysis of Film Condensation-III

$$\frac{\partial u}{\partial y}=0,\ \ y=\delta\qquad\Rightarrow c_1=\frac{\rho_l-\rho_g}{\mu_l}g\delta$$

$$\Rightarrow u=\frac{(\rho_f-\rho_v)g\delta^2}{\mu_l}\left(\frac{y}{\delta}-\frac{y^2}{2\delta^2}\right)$$

- Energy Equation

$$\left(u\frac{\partial(T)}{\partial x}+v\frac{\partial(T)}{\partial y}\right)=\alpha\left(\frac{\partial^2T}{\partial y^2}\right)\qquad\Rightarrow\left(\frac{\partial^2T}{\partial y^2}\right)=0$$

Negligible

$$\Rightarrow T=c_1y+c_2$$

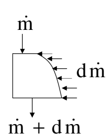
Analysis of Film Condensation-IV

Boundary Conditions $\quad T=T_W,\ \ y=0 \quad T=T_{Sat},\ \ y=\delta$

$$\Rightarrow T=T_w+(T_{sat}-T_w)\frac{y}{\delta}$$

Note that the boundary layer thickness is still unknown

This is obtained in the following manner



$$\dot m=\int_0^\delta\rho_l u\,dy \qquad \text{For unit width}$$

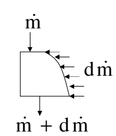
$$=\int_0^\delta\rho_l\frac{(\rho_l-\rho_v)g\delta^2}{\mu_l}\left(\frac{y}{\delta}-\frac{y^2}{2\delta^2}\right)dy$$

$$=\rho_l\frac{(\rho_l-\rho_v)g\delta^3}{3\mu_l}$$

Analysis of Film Condensation-V

$$d\dot m=\rho_l\frac{(\rho_l-\rho_v)g3\delta^2}{3\mu_l}d\delta \quad (1)$$

From Energy Balance per unit width



$$h_{fg}d\dot m=\left(k_l\left.\frac{\partial T}{\partial y}\right|_{y=\delta}\right)\Delta x=k_l\left(\frac{T_{sat}-T_w}{\delta}\right)\Delta x$$

$$d\dot m=\frac{k_l}{h_{fg}}\left(\frac{T_{sat}-T_w}{\delta}\right)\Delta x \quad (2)$$

Equating 1 and 2 we get $\quad \delta^3\frac{d\delta}{dx}=\frac{k_l\mu_l(T_{sat}-T_w)}{\rho_l(\rho_l-\rho_v)h_{fg}g}$

$$\Rightarrow\frac{\delta^4}{4}=\frac{k_l\mu_l(T_{sat}-T_w)}{\rho_l(\rho_l-\rho_v)h_{fg}g}x+c_1$$

Analysis of Film Condensation-VI

Using the Boundary Condition $\delta = 0 \;\text{ at }\; x = 0$ $\Rightarrow c_1 = 0$

$$\Rightarrow \delta = \left(\frac{4 k_l \mu_l (T_{sat} - T_w) x}{\rho_l (\rho_l - \rho_v) h_{fg}\, g} \right)^{1/4}$$

To account for sub-cooling the f0ollowing correction is made

$$h'_{fg} = h_{fg} (1 + 0.68\,\text{Ja})$$

$$\text{Where, } \text{Ja} = \frac{c_p (T_{sat} - T_w)}{h_{fg}}$$ Jacob Number

Finally,

$$h = \frac{q''}{T_{sat} - T_w} = \frac{1}{T_{sat} - T_w} k_l \frac{\partial T}{\partial y} = \frac{k_l}{T_{sat} - T_w} \frac{(T_{sat} - T_w)}{\delta} = \frac{k_l}{\delta}$$

Analysis of Film Condensation-VII

$$\Rightarrow Nu_x = \frac{hx}{k_l} = \frac{x}{\delta} = \left(\frac{\rho_l (\rho_l - \rho_v) h'_{fg}\, g x^3}{k_l \mu_l (T_{sat} - T_w)} \right)^{1/4}$$

$$Nu_x = 0.707 \left(\frac{\rho_l (\rho_l - \rho_v) h'_{fg}\, g x^3}{k_l \mu_l (T_{sat} - T_w)} \right)^{1/4}$$

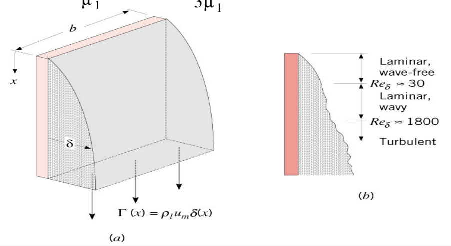
Just as in natural convection, we can show that

$$\overline{Nu}_L = \frac{4}{3} Nu_L = 0.943 \left(\frac{\rho_l (\rho_l - \rho_v) h'_{fg}\, g L^3}{k_l \mu_l (T_{sat} - T_w)} \right)^{1/4}$$

Analysis of Film Condensation-VIII

- Effects of Turbulence
  - Three flow regimes may be identified and delineated in terms of a Reynolds number defined as

$$\Rightarrow Re_\delta = \frac{4 \rho_l \bar{u} \delta}{\mu_l} = \frac{4 g \rho_l (\rho_l - \rho_v) \delta^3}{3 \mu_l^2}$$



Analysis of Film Condensation-IX

Laminar Region $Re_\delta < 30$

$$\frac{\overline{h}_L (\nu_l^2 / g)^{1/3}}{k_l} = 1.47 (Re_\delta)^{-1/3}$$

Wavy Laminar Region $30 < Re_\delta < 1800$

$$\frac{\overline{h}_L (\nu_l^2 / g)^{1/3}}{k_l} = \frac{Re_\delta}{1.08 (Re_\delta)^{1.22} - 5.2}$$

Turbulent Region $Re_\delta > 1800$

$$\frac{\overline{h}_L (\nu_l^2 / g)^{1/3}}{k_l} = \frac{Re_\delta}{8750 + 58\, Pr_l^{-0.5} (Re_\delta^{0.75} - 253)}$$

Analysis of Film Condensation-X

- Calculation procedure:

To use the equations in the previous slide, we first use the relation

$$\dot{m} = \frac{\overline{h}_L W \times L (T_{sat} - T_w)}{h'_{fg}}$$

$$\text{Since } Re_\delta = \frac{4 \dot{m} L}{W \times L \mu_l} = \frac{4 \dot{m}}{W \mu_l} = \frac{4}{\mu_l} \frac{\overline{h}_L L (T_{sat} - T_w)}{h'_{fg}}$$

$$\Rightarrow \overline{h}_L = \frac{Re_\delta\, h'_{fg}\, \mu_l}{4 L (T_{sat} - T_w)}$$

Thus, the left hand side of the equations in previous slide can also be expressed in terms of Reynolds number and known parameters. Hence we can solve for Re_δ, and hence for $\overline{h}_L$

Analysis of Film Condensation-XI

- A single tube or sphere:

$$\overline{h}_D = C \left(\frac{\rho_l (\rho_l - \rho_v) k_l^3 h'_{fg}\, g}{\mu_l (T_{sat} - T_w) D} \right)^{1/4}$$

Tube: C = 0.729 Sphere: C = 0.826

- Vertical Tier of N-tubes:

$$\overline{h}_{D,N} = 0.729 \left(\frac{\rho_l (\rho_l - \rho_v) k_l^3 h'_{fg}\, g}{N \mu_l (T_{sat} - T_w) D} \right)^{1/4}$$