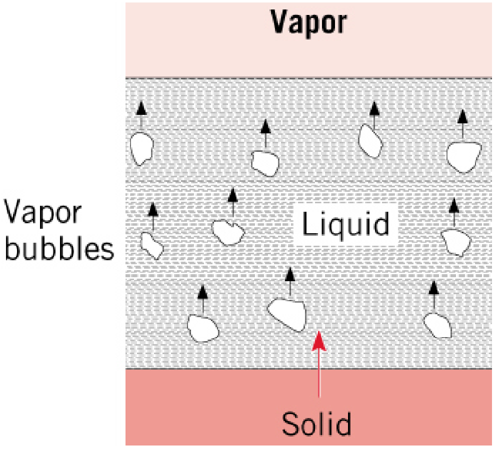
MODULE 8

BOILING AND CONDENSATION

8.1 Boiling: General considerations

- Boiling is associated with transformation of liquid to vapor at a solid/liquid interface due to convection heat transfer from the solid.
- Agitation of fluid by vapor bubbles provides for large convection coefficients and hence large heat fluxes at low-to-moderate surface-to-fluid temperature differences



- Special form of Newton's law of cooling:

$$q''_s = h(T_s - T_{sat}) = h\Delta T_e$$

where T_{sat} is the saturation temperature of the liquid, and $\Delta T_e = T_s - T_{sat})$ is the excess temperature.

8.2 Special cases

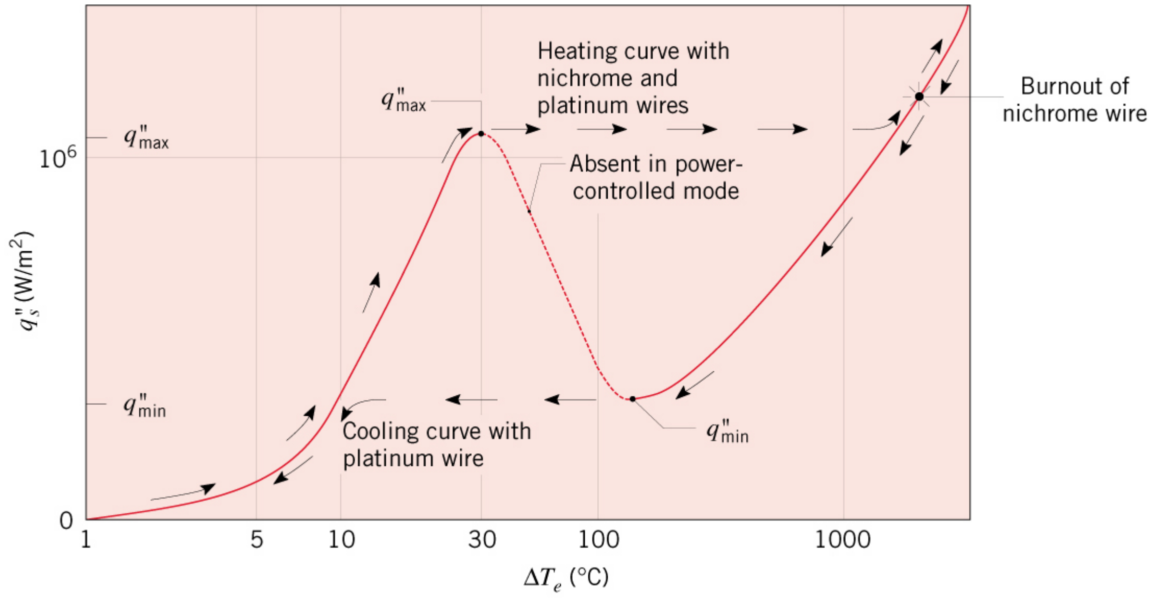
- ➢ Pool Boiling:Liquid motion is due to natural convection and bubble-induced mixing.
- ➢ Forced Convection Boiling:Fluid motion is induced by external means, as well as by bubble-induced mixing.
- ➢ Saturated Boiling:Liquid temperature is slightly larger than saturation temperature

- Subcooled Boiling:Liquid temperature is less than saturation temperature

8.3 The boiling curve

The boiling curve reveals range of conditions associated with saturated pool boiling on a q_s'' vs. ΔT_e plot.

Water at Atmospheric Pressure



Free Convection Boiling (ΔT_e<5°C)

- Little vapor formation.
- Liquid motion is due principally to single-phase natural convection.

Onset of Nucleate Boiling – ONB ($\Delta T_e \approx$5°C)

Nucleate boiling (5°C < ΔT_e<30°C)

- Isolated Vapor Bubbles (5°C < ΔT_e<10°C)

  Liquid motion is strongly influenced by nucleation of bubbles at the surface.

  h and q_s'' rise sharply with increasing ΔT_e

Heat transfer is principally due to contact of liquid with the surface (single-phase convection) and not to vaporization

- Jets and Columns (10ºC < ΔT_e <30ºC)

  Increasing number of nucleation sites causes bubble interactions and coalescence into jets and slugs.

  Liquid/surface contact is impaired.

  q''_s continues to increase with ΔT_e while *h* begins to decrease

Critical Heat Flux - CHF, ($\Delta T_e \approx$ 30ºC)

- Maximum attainable heat flux in nucleate boiling.

$q''_{\max} \approx 1$ MW/m^2 for water at atmospheric pressure.

Potential Burnout for Power-Controlled Heating

- An increase in q''_s beyond $q''_{\max}$ causes the surface to be blanketed by vapor and its temperature to spontaneously achieve a value that can exceed its melting point
- If the surface survives the temperature shock, conditions are characterized by film boiling

Film Boiling

- Heat transfer is by conduction and radiation across the vapor blanket
- A reduction in q''_s follows the cooling the cooling

  curve continuously to the Leidenfrost point corresponding to the minimum heat flux $q''_{\min}$ for film boiling.
- A reduction in q''_s below $q''_{\min}$ causes an abrupt reduction in surface temperature to the nucleate boiling regime

Transition Boiling for Temperature-Controlled Heating

- Characterised by continuous decay of q''_s (from $q''_{\max}$ to $q''_{\min}$) with increasing ΔT_e
- Surface conditions oscillate between nucleate and film boiling, but portion of surface experiencing film boiling increases with ΔT_e
- Also termed unstable or partial film boiling.

8.4 Pool boiling correlations

Nucleate Boiling

- Rohsenow Correlation, clean surfaces only, ±100% errors

$$q''_s = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{c_{p,l}\, \Delta T_e}{C_{s,f}\, h_{fg}\, \mathrm{Pr}_l^n} \right)^3$$

$$C_{s,f}, n \rightarrow \text{ Surface/Fluid Combination}$$

Critical heat flux:

$$q''_{\max} = 0.149 h_{fg} \rho_v \left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4}$$

Film Boiling

$$\overline{Nu}_D = \frac{\bar{h}_{conv} D}{k_v} = C \left[\frac{g(\rho_l - \rho_v) h'_{fg} D^3}{\nu_v k_v (T_s - T_{sat})} \right]^{1/4}$$

Geometry	C
Cylinder(Hor.)	0.62
Sphere	0.67

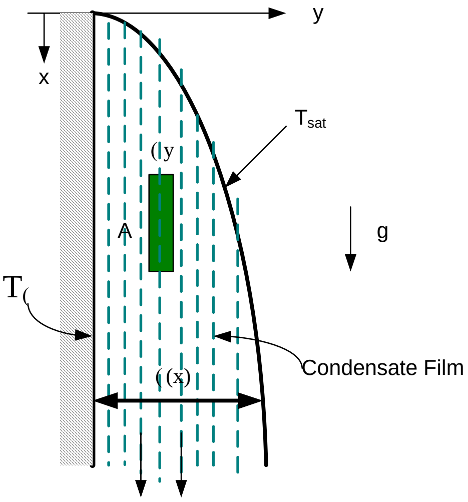
8.5 Condensation: General considerations

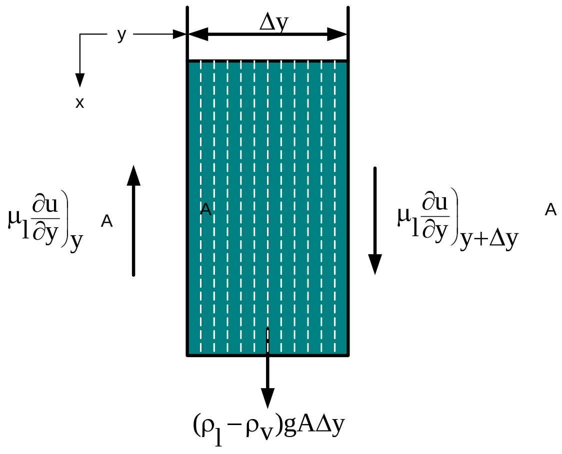
- Condensation occurs when the temperature of a vapour is reduced below its saturation temperature
- Condensation heat transfer

  Film condensation

  Dropwise condensation
- Heat transfer rates in dropwise condensation *may be as much as 10 times higher* than in film condensation

8.6 Laminar film condensation on a vertical wall





$$\delta(x) = \left[\frac{4xk_l(T_{sat} - T_w)\nu_l}{h_{fg}g(\rho_l - \rho_v)}\right]^{1/4}$$

$$h(x) = \left[\frac{h_{fg}g(\rho_l - \rho_v)k_l^3}{4x(T_{sat} - T_w)\nu_l}\right]^{1/4}$$

Average coeff. $\bar{h}_L = 0.943\left[\frac{h_{fg}\,g(\rho_l - \rho_v)k_l^3}{L(T_{sat} - T_w)\nu_l}\right]^{1/4}$

where L is the plate length.

Total heat transfer rate : $q = \bar{h}_L A(T_{sat} - T_w)$

Condensation rate : $\dot{m} = \frac{q}{h_{fg}} = \frac{\bar{h}_L A(T_{sat} - T_w)}{h_{fg}}$