Module 8: Boiling

Lecture 29: Boiling Heat Transfer

The Lecture Contains:

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Introduction

For boiling, the convection coeffiecient depends on

Difference between the surface and saturation temperatures $\Delta T = [T_w - T_{sat}]$ -

The body force arising from the liquid-vapour density difference $g\ (\rho_l - \rho_v)$

The latent heat hfg -the surface tension h_{fg}

The surface tension σ

$$\text{L},\ \rho,\ c_p,\ k,\ \mu$$

$$h = (\Delta T,\ g(\rho_l - \rho_v),\ h_{fg},\ \sigma,\ L,\ \rho,\ c_p,\ k,\ \mu)$$

10 variables in 5 dimensions $(m,\ kg,\ s,\ J,\ K)$

Result in $5\ \pi$ groups

Here hL/k is Nusselt number, $\frac{c_p \Delta T}{h_{fg}}$ is Jakob number, $\mu c_p/k$, is Prandtl number and $g(\rho_l - \rho_v)L^2/\sigma^2$ is Bond number.

Previous Next

Boiling modes

Heat is transferred from solid surface to the liquid $q''_w = h(T_w - T_{sat}) = h\Delta T$. Heat transfer is strongly in inuenced by the growth of vapor bubbles

Pool Boiling

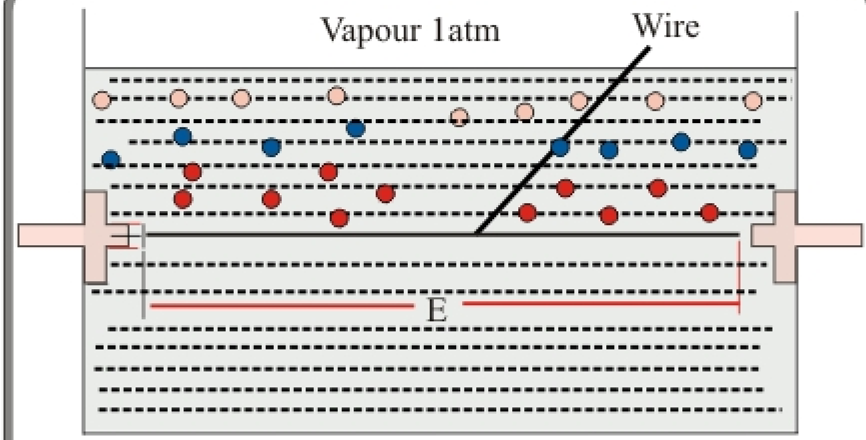

Figure 8.1: Nukiyama's power-controlled heating apparatus for demonstrating the boiling curve

Nukiyama identified different regimes of pool boiling by using a similar apparatus shown in the figure

Previous Next

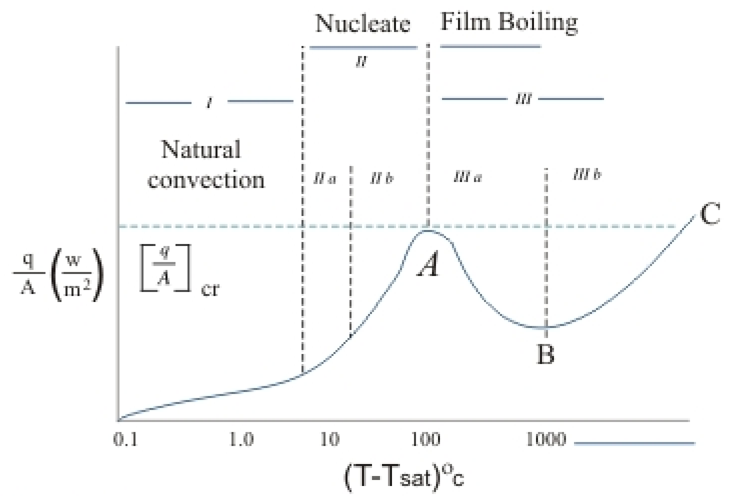

Figure 8.2 Typical boiling curve for water at one atmosphere surface heat flux $\left(\frac{q}{A}\right)$ as a function of excess temperature

The following are various regimes of Boilling :

1. Natural Convection: This phenomenon occurs at low temperatures $< 5^oC$. Heat transfer from the heated surface to the liquid in its vicinity causes the liquid to be superheated.
The superheated liquid rises to the free liquid surface by natural convection where vapor is produced by evaporation.

Previous Next

2. Nucleate Boiling: It commences with the increased difference between $(T_w - T_{sat})$

II (a): The bubbles formed are very few in number. These bubbles grow in size, separate from the heated surface and rise to the free surface.
II(b): The rate of bubble formation and number of locations where they are formed increase.

3. Film Boiling: High bubble formation rate causes them to coalesce and blanket the surface.with a vapor film.

III (a): The vapor lm is unstable and involves partial film boiling and partial nucleate boiling.
III (b): A stable lm covers the entire surface.

The temperature difference is of the order of 1000^oC and the radiative transfer across the vapor film is significant.

In the region I, **the heat flux is proportional to n where n is slightly greater than unity (1.3).**

When the transition from natural convection to nucleate boiling occurs, heat flux starts to increase more rapidly with the temperature difference, the value of n increasing to about 3**.** At the end of region II, the boiling curve reaches a peak **(point A).**

In III (a), inspite of increasing temperature difference, the heat flux decreases because the thermal resistance to heat flow increases with the formation vapor film.

At the end of III (a), heat flux passes through a minimum **(point B).** It starts increasing with $(T_w - T_{sat})$ only when stable film boiling begins and radiation becomes significantly important.

Previous Next

It is of interest to know how the temperature of the heating surface changes as the heat flux is steadily increased from zero. Upto point A,
nucleate boiling occurs and the temperature of the heating surface is obtained by reading o the value $(T_w - T_{sat})$ from the boiling curve and adding to the value of T_{sat}. If the heat flux is increased a little beyond the value at A, the temperature of the surface shoots up to the value corresponding to point C. For many surfaces, the temperature at **C** is high enough to cause the material to melt. Thus in many practical situations, it is undesirable to cross this value.

This value is therefore of significance in engineering and is called the ***critical or peak heat flux.***

Correlations in Pool Boiling

1. Natural convection saturated pool boiling

$$\frac{q}{A} = \frac{k}{D}(T_w - T_{sat})\left\{0.36 + \frac{0.518(Ra_D)^{1/4}}{[1+(0.559/Pr)^{9/16}]^{4/9}}\right\} \quad 10^{-6} < Ra_D < 10^9$$

$$\frac{q}{A} = \frac{k}{D}(T_w - T_{sat})\left\{0.60 + \frac{0.387(Ra_D)^{1/6}}{[1+(0.559/Pr)^{9/16}]^{8/27}}\right\}^2 \quad 10^9 < Ra_D < 10^{12}$$

.All liquid properties are evaluated at $\frac{(T_w+T_{sat})}{2}$

2. Nucleate saturated pool boiling:

$$\frac{C_{pl}(T_w - T_{sat})}{h_{fg}} = C_{sf}\left[\frac{(q/A)}{\mu_l h_{fg}}\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}\right]^{1/3} (Pr)^n$$

Previous Next

Boiling

n = 1.0 for water and 1.7 for other liquids.
C_{sf} **= another constant**

Platinum-water and Copper-water, **the value is 0.013.**
Nickel-water and Brass-water, the **value is 0.006**

3. Peak heat flux in saturated pool boiling

(Developed by Kutateladze and Zuber)

$$\frac{q}{A} = \frac{\pi}{24} h_{fg} \rho_v \left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2}\right]^{1/4} \left[\frac{\rho_l + \rho_v}{\rho_l}\right]^{1/2}$$

$$\frac{q}{A} = \frac{\pi}{24} h_{fg} \rho_v^{1/2} \left[\sigma g(\rho_l - \rho_v)\right]^{1/4}$$

If $L[g(\rho_l - \rho_v)/\sigma]^{1/2} \geq$ 2:7 where **L** is the characteristic dimension of the heater **.**

$\frac{q}{A} = 0.149\ h_{fg}\ \rho_v^{1/2} \left[\sigma\ g(\rho_l - \rho_v)\right]^{1/4}$ Due to **Lienhard and Dhir**

For horizontal **cylinder of radius R**

$$\frac{q}{A} = f(L') \left\{\frac{\pi}{24} h_{fg} \rho_v^{1/2} \left[\sigma g(\rho_l - \rho_v)\right]^{1/4}\right\}$$

where, $f(L') = 0.89 + 2.27\ exp\ (-3.44\sqrt{L'})$ and $L' = R[g(\rho_l - \rho_v)/\sigma]^{1/2}$

Previous Next

4. Film saturated pool boiling

(i) Minimum heat flux

$$q^{"}_{min} = C\rho_v h_{fg}\left[\frac{g\sigma(\rho_l-\rho_v)}{\rho_l+\rho_v)}\right]^{1/4}$$

where c=0.62

(ii) Stable film boiling

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

$h'_{fg} = h_{fg} + 0.4C_{p,v}(T_w - T_{sat})$; $C_{p,v}$ evaluated at $(T_w - T_{sat})/2$

for $T_w \geq 300^oC, \bar{h}^{4/3} = \bar{h}^{4/3}_{conv} + \bar{h}_{rad}\bar{h}^{1/3}$

If $\bar{h}_{rad} < \bar{h}_{conv} \Rightarrow \bar{h} = \bar{h}_{conv} + \frac{3}{4}\bar{h}_{rad}$ and $\bar{h}_{rad}$ is approximated as $\bar{h}_{rad} = \frac{\varepsilon\sigma(T_w^4 - T_{sat}^4)}{(T_w - T_{sat})}$ where

ε = emissivity and σ = Stefan Boltzmann constant

Previous Next