$T_s =$ constant , $Nu = \frac{hD}{k} = 3.66$

$$Nu = 3.66 + \frac{0.065 (D/L) Re Pr}{1 + 0.04 ((D/L) Pr Re)^{2/3}}$$

Enterance region

$$Nu = 1.86 \left(\frac{Re Pr D}{L} \right)^{1/3} \left(\frac{\mu_b}{\mu_s} \right)^{0.14}$$

If $Re > 10,000$ (Turbulent flow)

$$f = (0.79 \ln Re - 1.64)^{-2}$$

$$Nu = 0.125 f Re Pr^{1/3}$$

In fully developed turbulent smooth pipe,

$$f = 0.184 Re^{-0.2}$$

$Nu = 0.023 Re^{0.8} Pr^{1/3} \rightarrow 0.7 < Pr < 160$

$Re > 1000$

Colburn Eqn:

So as to correct the error in the above,

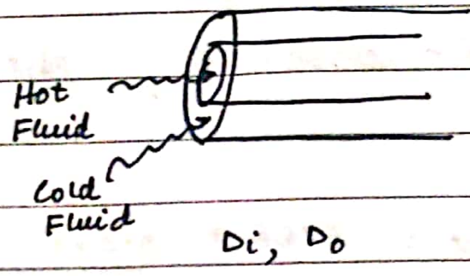
$$\left. \begin{aligned} Nu &= 0.023 Re^{0.8} Pr^{n} \\ n &= 0.4 \text{ for heating} \\ n &= 0.3 \text{ for cooling} \end{aligned} \right\} \text{Dittus Boeller Eqn.}$$

Liquid Metals ($0.004 < Pr < 0.01$)

$T_s =$ constant $\rightarrow Nu = 4.8 + 0.0156 Re^{0.085} Pr^{0.93}$

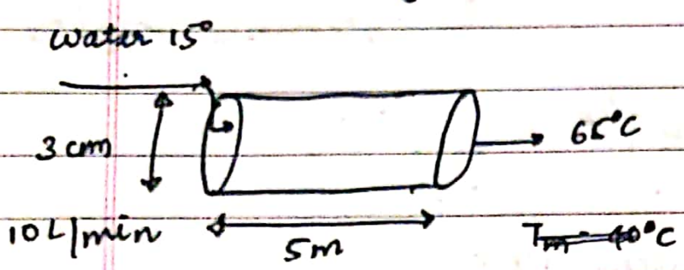
$q_s'' =$ constant $\rightarrow Nu = 6.3 + 0.0167 Re^{0.85} Pr^{0.93}$

$$D_h = \frac{4A_c}{P}$$



$$D_h = \cancel{4A} D_o - D_i$$

$$Nu_i = \frac{h_i D_h}{k} \qquad Nu_o = \frac{h_o D_h}{k}$$



ⓐ heater power

ⓑ linear ~~δ~~ Ts

$\rho = 992.1 \ kg/m^3$

$k = 0.631 \ W/m°C$

$\nu = 0.658 \times 10^{-6} \ m^2/s$

$C_p = 4179 \ J/kg°C$

$P_r = 4.32$

$\dot{m} = \rho \dot{V} = 0.165 \ kg/s$

$\dot{Q} = \dot{m} C_p \Delta T$

$= 34.6 \ kW$

$\dot{q}_s = \frac{\dot{Q}}{A_s} = 73.5 \ kW/m^2$

$\dot{q}_s = h(T_s - \overset{65°C}{T_m})$

$Re = 10900 \ \left(\frac{V_m D}{\nu}\right)$

$V = \frac{\dot{V}}{A_c} = 0.24 \ m/s$

$Nu = 0.023 Re^{0.8} P_r^{0.4}$

$= \frac{hD}{k} \quad \approx 70$

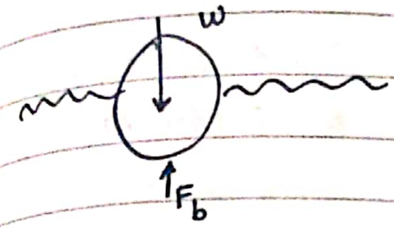
$T_s = T_m + \frac{\dot{q}_s}{h}$

$h = 1479 \ W/m^2C$

$= 65 + \frac{73500}{1497}$

$= 115°C$

Free convection (Natural convection)



$$F_{net} = (\rho_b - \rho_f)\, g\, V_{body}$$

Vol. expansion
coeff $(\beta) = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P \left[\frac{1}{K}\right]$

For ideal gas

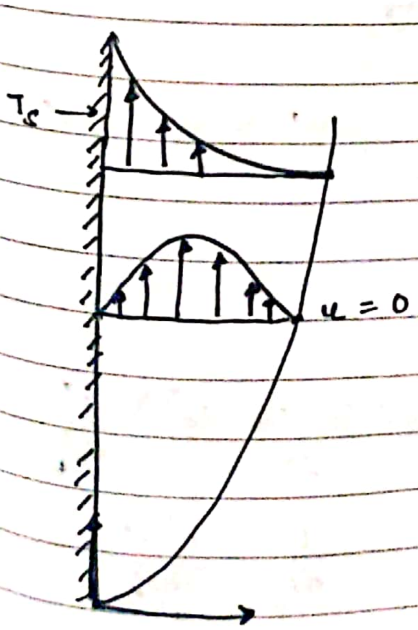
$$\rho = \frac{P}{RT} \Rightarrow \beta = \frac{1}{T}$$

$$\beta = -\frac{1}{\rho}\,\frac{\rho_\infty - \rho}{T_\infty - T} \quad (\text{At const. } P)$$

$$\rho_\infty - \rho = \rho\beta\,(T - T_\infty)$$

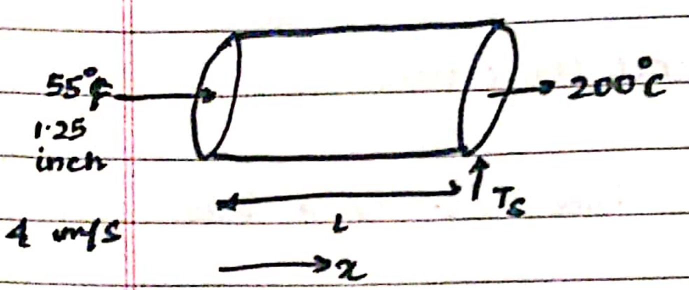
Buyoncy force $\propto \Delta\rho \propto \Delta T$ (At const. P)

larger ΔT => larger F_b ⇒ Stronger Free conv
⇓
Higher HT Rate



$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \mu\frac{\partial^2 u}{\partial y^2} - \frac{\partial P}{\partial x} - \rho g$$

$$\frac{\partial P_\infty}{\partial x} = -\rho_\infty g$$



$P_r = 3.368$

$C_p = 1 \text{ Btu}/°F$

$\nu = 0.57 \times 10^{-5} \text{ ft}^2/s$

$k = 0.374 \text{ Btu}/\text{ft } °F$

$Re = 11000 \qquad Nu = 475$

$h = 1666 \text{ Btu}/hft^2 °F \qquad q_s = h(T_s - T_e)$

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \mu\frac{\partial^2 u}{\partial y^2} + (\rho_\infty - \rho)g$$

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P$$

$\rho_\infty - \rho = \rho\beta(T - T_\infty)$ (at const - P)

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} + g\beta(T - T_\infty)$$

$$V = \frac{Re\,\nu}{L_c}$$

$L_c \leftarrow$ char. length

On non-dimensionalising,

$$x^* = \frac{x}{L_c}, \quad y^* = \frac{y}{L_c}, \quad u^* = \frac{u}{V}, \quad v^* = \frac{v}{V}$$

$$T^* = \frac{T - T_\infty}{T_s - T_\infty}$$

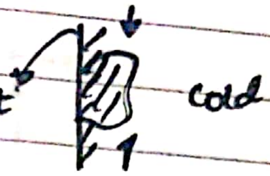
$$u^*\frac{\partial u^*}{\partial x^*} + v^*\frac{\partial u^*}{\partial y^*} = \left(\frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2}\right)\frac{T^*}{Re_L^2} + \frac{1}{Re_L}\frac{\partial^2 u^*}{\partial y^{*2}}$$

Scanned with CamScanner

Gr_L (Grashof No.) = $\dfrac{g\beta (T_s - T_0) L_c^3}{\nu^2}$ ← kinematic viscosity

For vertical plate, $Gr_{critical} = 10^9$ ← of order

Turbulent if $> 10^9$, in vertical Hot plane.



If $Gr/Re^2 \ll 1$, free convection dominates

If $Gr/Re^2 \gg 1$, natural convection

If $Gr/Re^2 \approx 1$, can't neglect any.

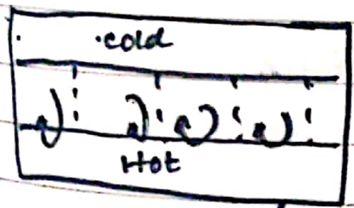
$Nu = \dfrac{hL_c}{k} = C\,(Gr_L\,Pr)^n = C\,Ra_L^n$

$C < 1$

$n = \frac{1}{4}$ laminar

$n = \frac{1}{3}$ turbulent

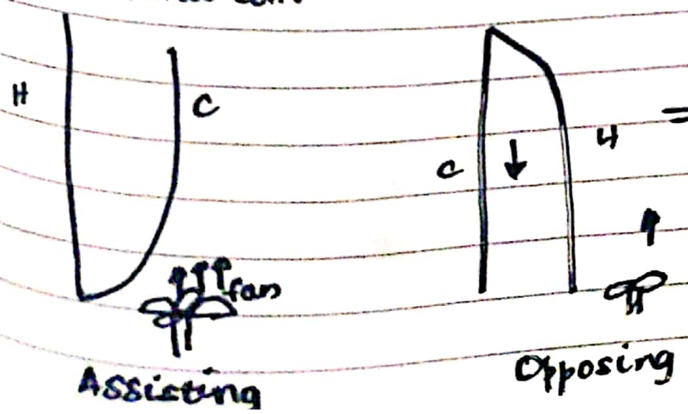
$\dot{q} = hA_s(T_s - T_\infty)$

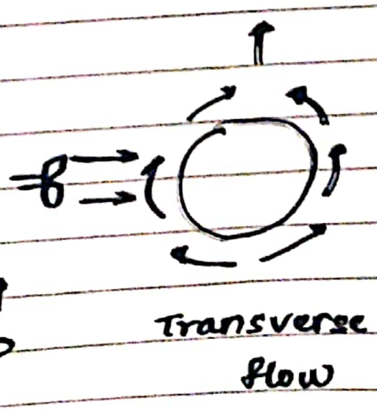


Benand cells (Only wen $Ra > 1700$)

When $Ra > 3 \times 10^5$, then cells are broken with turbulent

Natural Conv





The combined Nu number,

$$Nu_c = \left(Nu_f^n \pm Nu_n^n \right)^{1/n}$$

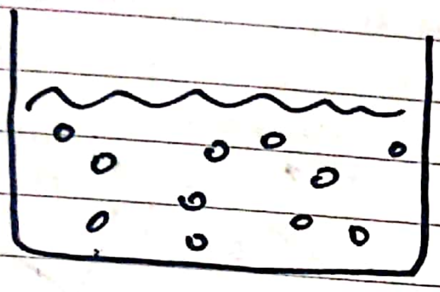
Assisting / Transverse

Opposing

$$\dot{q}_{conv} = h A_s (T_s - T_\infty)$$

Inv. prop

Boiled convection



← Boiling

Formation of the bubbles is dependent on latent heat of vap, surface tension.

Evaporation — liq. / vapour Interface

60% RH, 20°c, water evaporates → 2.3 kPa = psat

→ v.p = ~~1.4~~ 1.4 kPa

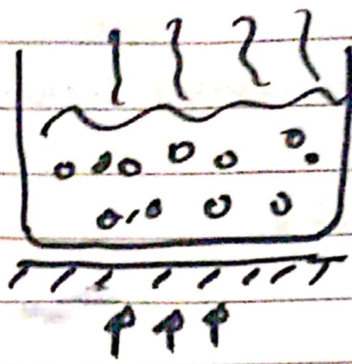
Boiling → Solid / liq. interface

$T_s >> T_{sat}$

$$q_b = h (T_s - T_{sat}) = h \, \Delta T_{excess} \quad (W/m^2)$$

Pool boiling - No bulk motion of flow

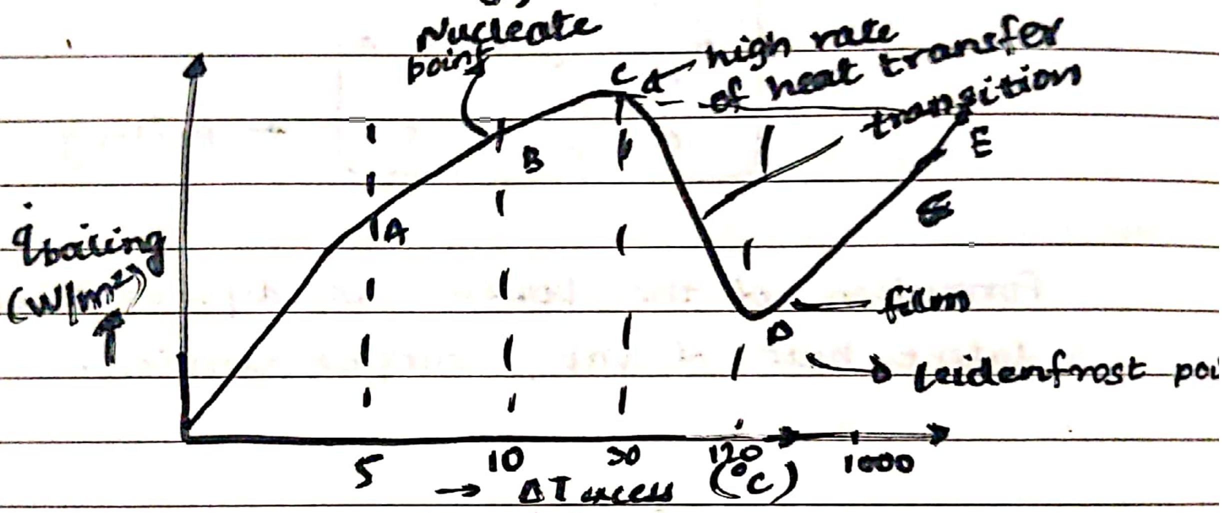
Flow boiling - Forced convection induced boiling.



Pool boiling → Subcooled boiling, Saturated boiling

Subcooled boiling, $T_b < T_{sat}$

Saturated boiling, $T_b = T_{sat}$



Nucleate point - bubbles are moving up

At C - critical / max heat flux

then CD is transition B.P

From pt. D - film boiling

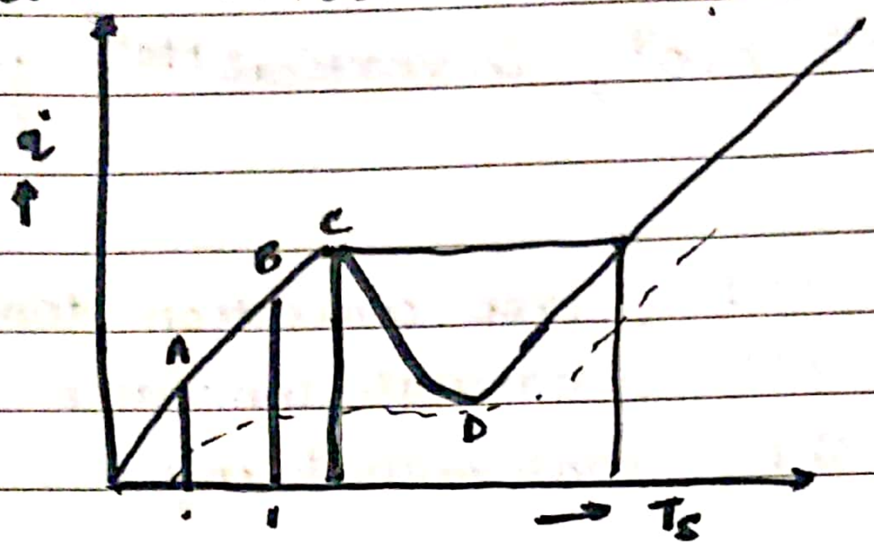
$$Nu = f\left[Pr,\ \frac{\rho g(\rho_l - \rho_v)L^3}{\mu^2},\ Ja,\ Bo\right]$$

Ja → Jacob no.

Bo → Bond no.

$$Ja = \frac{c_p \Delta T}{\cancel{h_{fg}}\ L_v} \qquad Bo = \frac{g(\rho_l - \rho_v)L}{\sigma}$$

Boiled Convection



A → natural convection boiling

(A→B) → Change from natural to nucleid boiling

BC → Bubbles detach from the surface and comes up to the surface

C → Critical heat flux

D → level

$$\dot{q}_{nuc} = \mu \, h_{fg} \left[\frac{g(\rho_l - \rho_g)}{\sigma} \right]^{1/2} \left[\frac{c_p (T_s - T_{sat})}{C_{sf} \, h_{fg} \, Pr_l^{\,n}} \right]^3$$

const. depends on fluid and surface const.

$$\dot{q}_{max} = C_{cr} \, h_{fg} \left[\sigma g \rho_v^2 (\rho_l - \rho_v) \right]^{1/4}$$

$$\dot{q}_{rad} = \varepsilon \sigma (T_s^4 - T_{sat}^4) \qquad T_{av} = \left(\frac{T_s + T_{sat}}{2} \right)$$

$$\dot{q}_{total} = \dot{q}_{film} + \frac{3}{4} \dot{q}_{rad}$$

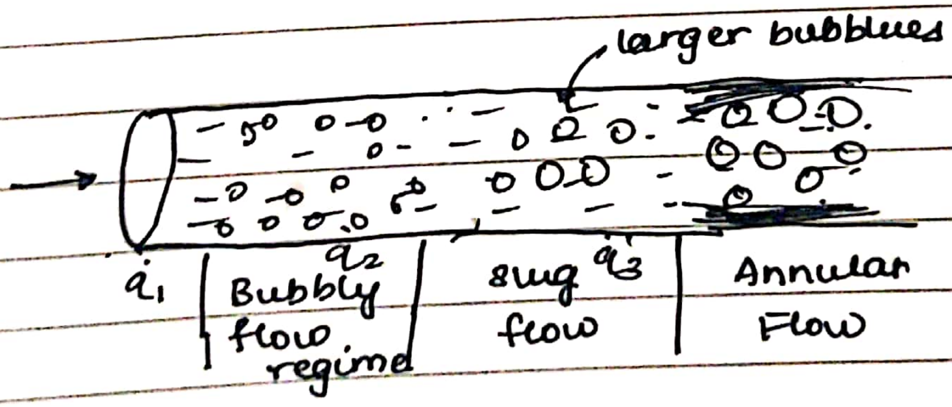
$C_{cr} \rightarrow$ Depends on shape / material ~~of the~~

Flow boiling $\longrightarrow$ Internal

$\downarrow$

External

Internal



$$\dot{q}_{total} = \dot{q}_1 + \dot{q}_2 + \dot{q}_3$$