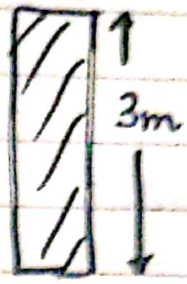
$F_f = 0.86$

Drag force $F_f = C_f A_s \frac{\rho U^2}{2}$



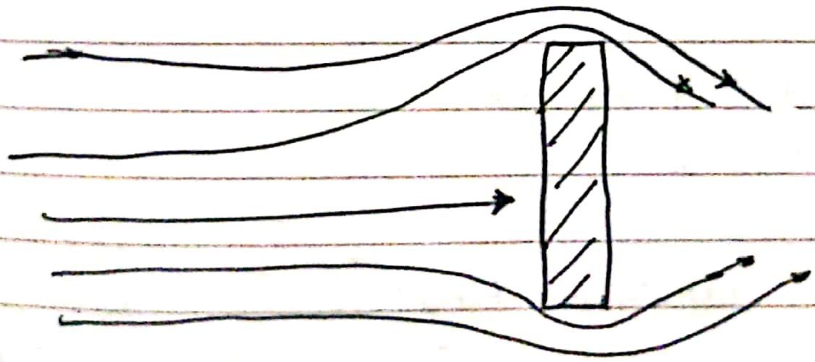
$0.86 = C_f (3 \times 2 \times 2) \frac{1.204 \times 7}{2}$

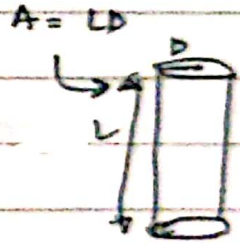
$C_f = 0.0024$

$\frac{C_f}{2} = \frac{h}{\rho C_p \vartheta} Pr^{2/3}$

$h_x = 12.7 \ W/m^2$

$C_D = C_{D,friction} + C_{D,pressure}$





The drag force is dependent on pressure and negligibly on the wall shear

$C_D = \frac{F_D}{\frac{1}{2} \rho v^2 A}$ ← Area projected to the normal surface of flow

upstream flow

$C_D = C_{D,fric} = C_f$

when plate is parallel to flow

T_s

Film Temp.

WKT, $Nu = C\, Re^m\, Pr^n$

↳ But Pr, μ changes b/w T_∞, T_s thus we use T_f, or else we can use $\left(\frac{Pr_\infty}{Pr_s}\right)^r$,

$$\left(\frac{\mu_\infty}{\mu_s}\right)^r$$

$$C_D = \frac{1}{L}\int_0^L C_{D,x}\, dx$$

$$Q = hA(T_s - T_\infty)$$

$$h = \frac{1}{L}\int_0^L h_x\, dx$$

Laminar Flow → $\bar{C_f} = \frac{1.328}{Re^{1/2}}$

$$\delta_x = \frac{5}{Re_x^{1/2}} \qquad C_{f,x} = \frac{0.664}{Re_x^{1/2}}$$

Flat Plate

$$Re_x < 5 \times 10^5$$

Turbulent Flow : $\delta_x = \frac{0.382\, x}{Re_x^{1/5}}$ → $\bar{C_f} = \frac{0.074}{Re^{1/5}}$

$$C_{f,x} = \frac{0.0592}{Re_x^{1/5}}$$

$$5 \times 10^5 \le Re_x \le 10^7$$

$$Nu_x = \frac{h_x x}{k} = 0.332\, Re_x^{0.5}\, Pr^{1/3} \qquad Pr > 0.6$$

laminar

$$Nu_x = \frac{h_x x}{k} = 0.0296\, Re_x^{0.8}\, Pr^{1/3} \qquad 0.6 \le Pr < 60$$

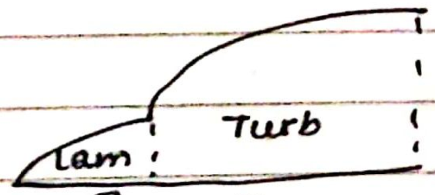
$$5\times 10^5 < Re_x \le 10^7$$

Turbulent

$$h_x \propto x^{-0.5}$$

$$\overline{Nu} = \frac{hL}{k} = 0.664\, Re_L^{1/2}\, Pr^{1/3} \qquad Re < 5\times 10^5$$

$$\overline{Nu} = \frac{hL}{k} = 0.037\, Re_L^{0.8}\, Pr^{1/3}$$



$$h = \frac{1}{L}\left[\int_0^{x_{cr}} h_{x,lam}\, dx + \int_{x_{cr}}^{L} h_{x,turb}\, dx\right]$$

$$Nu = \frac{hL}{k} = \left(0.037\, Re_L^{0.8} - 871\right) Pr^{1/3}$$

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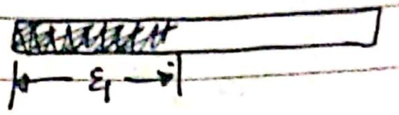
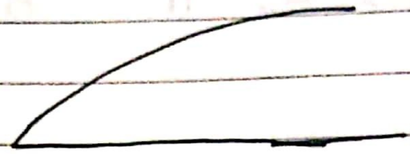


$$Nu_x = \frac{Nu_x \;(\text{for } \varepsilon_1 = 0)}{\left(1 - \left(\varepsilon_1/x\right)^{3/4}\right)^{1/3}}$$

$$= \frac{0.332 \; Re^{0.5} \; Pr^{1/3}}{\left[1 - \left(\varepsilon_1/x\right)^{3/4}\right]^{1/3}}$$



uniform Heat Flux

Laminar : $Nu_x = 0.453 \; Re_x^{1/2} \; Pr^{1/3}$

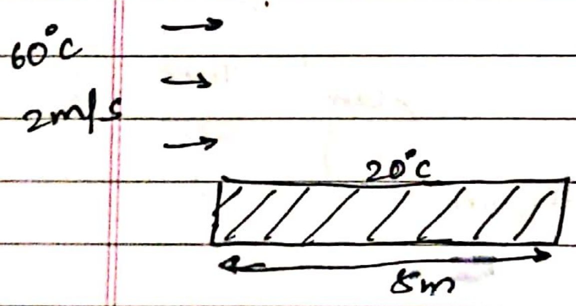
(36% change from T_s)

Turbulent : $Nu_x = 0.0308 \; Re_x^{0.8} \; Pr^{1/3}$

(4% change from T_s)

$$\dot{Q} = \dot{q}_s A$$

$$h_x (T_s - T_\infty) \Rightarrow T_s(x) = T_\infty + \frac{\dot{q}_s}{h_x}$$



Total drag force ?
Rate of heat transfer per unit width of plate

$\rho = 875 \text{ kg/m}^3$

$Pr = 2870$, $Re_L = 4 \times 10^4$ ($\rho u_\infty / L$)

$< 5 \times 10^5$

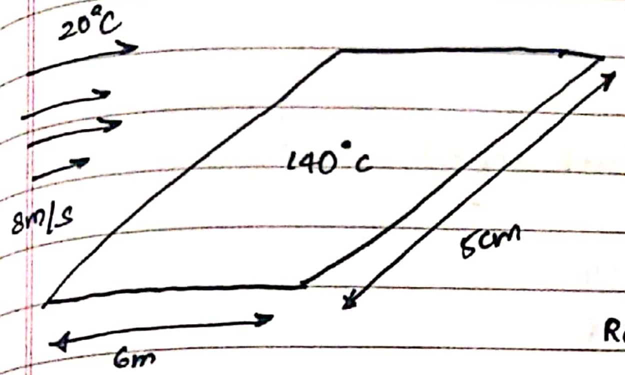
$\Rightarrow$ laminar

$$C_f = \frac{1.328}{Re_L^{0.5}} = 1.328 \times (4 \times 10^4)^{-0.5}$$

$F_D = c_f A_s \frac{\rho v^2}{2}$ $\qquad Q = hA(T_s - T_A)$

$Nu = \frac{hL}{k} \Rightarrow 0.664\, Re_L^{0.5} Pr^{1/3}$

$\Rightarrow h = \frac{k}{L} Nu$



$k = 0.029$ W/m°C

$Pr = 0.715$

$\nu = 2.1 \times 10^{-5}$ m^2/s

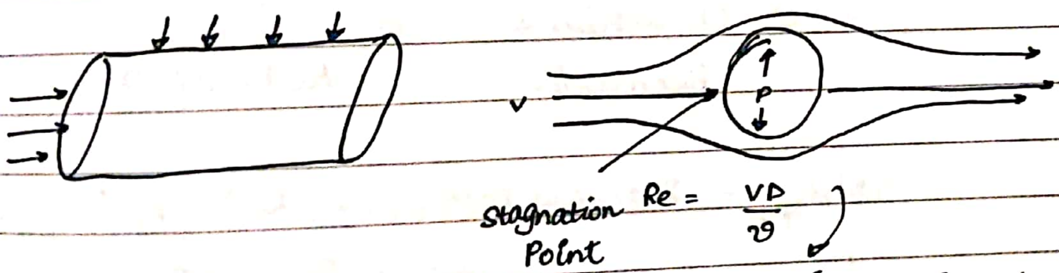
$Re_L = \frac{\rho v L}{\nu}$

$= 1.9 \times 10^6$

$\Rightarrow$ Turbulent

$Nu = (0.037\, Re^{0.8} - 871)\, Pr^{1/3}$

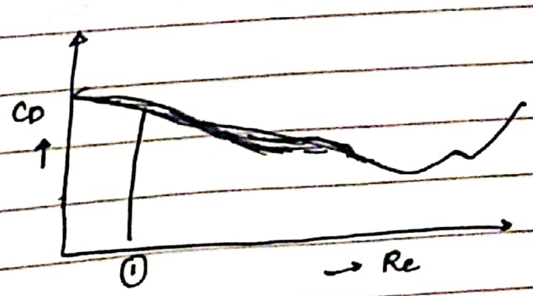
$= \frac{hL}{k}$ $\qquad Q = hA_s(T_s - T_\infty)$

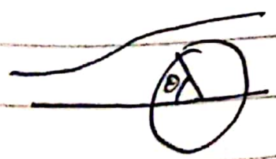


$Re = \frac{VD}{\nu}$

$Re \approx 2 \times 10^5$ (laminar)

$C_D = \frac{24}{Re}$ $\quad (Re < 1)$





Flow seperation occurs at $\theta = 80°$ for laminar and for $\theta = 140°$ for turbulent

Say $Re = 10^5$ (Laminar)

For Rough sphere $C_D = 0.1$
$\varepsilon / D = 0.0015$

Smooth sphere $C_D = 0.5$

$Re = 10^6$ (Turbulent)

RS $C_D = 0.4$
SS $C_D = 0.1$

$$F_D = C_D A \frac{\rho V^2}{2} \qquad A = \frac{\pi D^2}{4}$$

$$Nu_{cyl} = \frac{hD}{k} = 0.3 + \frac{0.62\, Re^{1/2} Pr^{1/3}}{\left[1 + \left(0.4/Pr\right)^{2/3}\right]^{1/4}} \left[1 + \left(\frac{Re}{28200}\right)^{5/8}\right]$$

↳ Churchill & Bernstein

$Re\, Pr > 0.2$

$$Nu_{sph} = 2 + \left[0.4\, Re^{1/2} + 0.06\, Re^{2/3}\right] Pr^{0.4} \left(\frac{\mu_\infty}{\mu_s}\right)^{1/4}$$

$3.5 \le Re < 80 \times 10^3$
$0.7 \le Pr < 380$

↳ White Ref

↳ Error is 30%.

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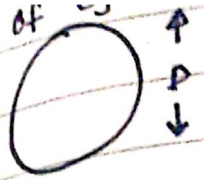
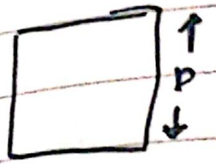
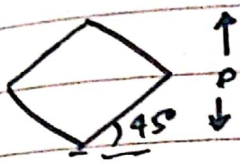
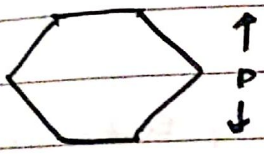
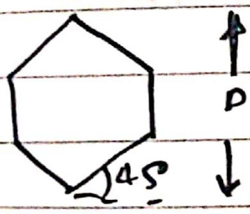
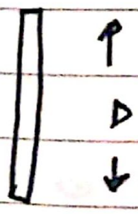
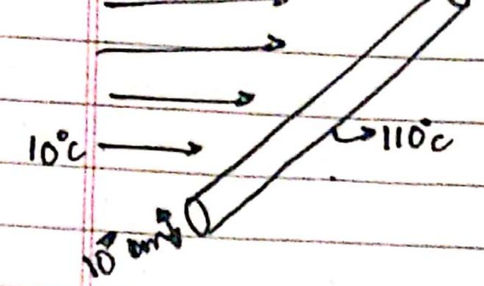
of

	0.4 - 4	$Nu = 0.989\ Re^{0.33} Pr^{1/3}$
	4 - 40	$Nu = 0.911\ Re^{0.385} Pr^{1/3}$
	40 - 4000	$Nu = 0.683\ Re^{0.466} Pr^{1/3}$
	4000 - 40000	$Nu = 0.193\ Re^{0.618} Pr^{1/3}$
	40 000 - 400 000	$Nu = 0.027\ Re^{0.805} Pr^{1/3}$
	5000 - 100,000	$Nu = 0.102\ Re^{0.675} Pr^{1/3}$
	5000 - 100,000	$Nu = 0.246\ Re^{0.588} Pr^{1/3}$
	5000 - 100,000	$Nu = 0.153\ Re^{0.638} Pr^{1/3}$
	5000 - ~~100~~ 19,500	$Nu = 0.16\ Re^{0.638} Pr^{1/3}$
	19500 - 100,000	$Nu = 0.0385\ Re^{0.782} Pr^{1/3}$
	4000 - 15000	$Nu = 0.228\ Re^{0.731} Pr^{1/3}$
Ellipse 	2500 - 15000	$Nu = 0.248\ Re^{0.612} Pr^{1/3}$



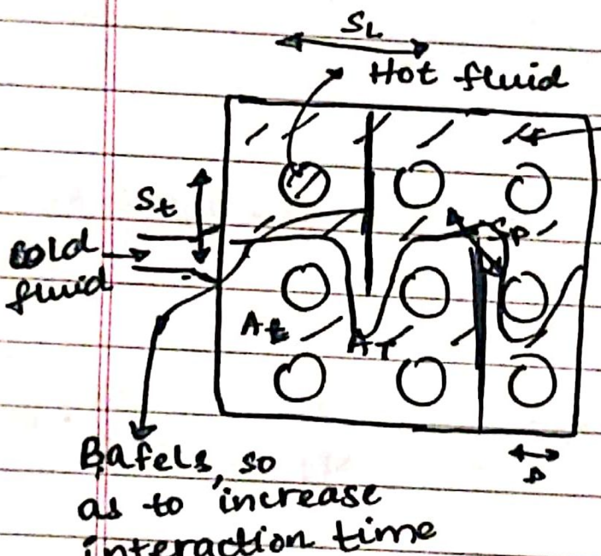
ρ_{air}
μ_{air} → $\nu_{air} = 1.896 \times 10^{-5}\ m^2/s$
k

$Re = 4.2 \times 10^4$
$Pr = 0.72$

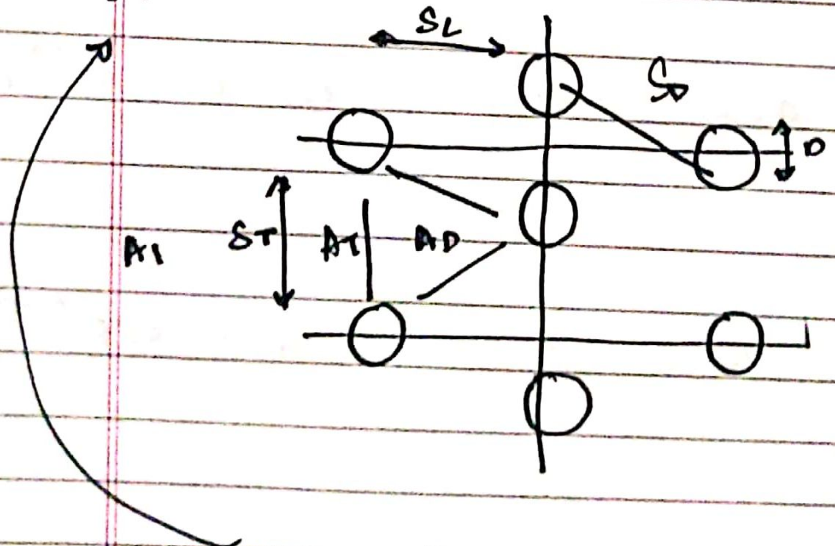
$Re \times Pr > 0.2$

$Nu = 128$
$\Rightarrow h = 35\ W/m^2\,°c$

$\dot{Q} = hA_s(T_s - T_\infty)$
$= 35\ (\pi \times 0.1)\ (110 - 10)\ W$
$= 1099$



← Shell & tube heat Exchanger



staggered

$S_D = \sqrt{S_L^2 + S_T^2}$

$A_T = (S_T - D)\,L$
$A_1 = S_T L$

$$Re_D = \frac{\rho V D}{\mu}$$

$$\rho V_1 A_1 = \rho V_m A_T$$

$$V S_T = V_{max} (S_T - D)$$

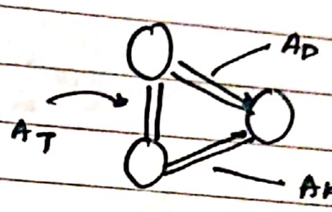
$$V_m = \frac{S_T}{S_T - D} V_\infty$$

For staggered

$$A_1 = S_T L$$

$$A_T = (S_T - D) L$$

$$A_D = (S_D - D) L$$



If $2A_D > A_T \longrightarrow V_m = \frac{S_T}{S_T - D} V_\infty$

If $2A_D < A_T \longrightarrow V_m = \frac{S_T}{2(S_D - D)} V_\infty$

$$S_D = \sqrt{S_L^2 + \left(\frac{S_T}{2}\right)^2}$$

$$Nu_D = \frac{hD}{k} = C Re_D^m Pr^n \left(\frac{Pr}{Pr_s}\right)^{0.25}$$

$T_m = \frac{T_i + T_e}{2}$ ← For T_s (P_s)

For no. of tubes (N_L) < 16,

$$Nu_{D,N_L} = F \, Nu_D$$

(From table)

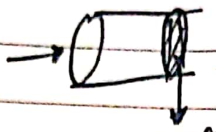
$Q = hA\Delta T \rightarrow T_s - T_m \rightarrow (T_i + T_e)/2$

$$\Delta T_m = \frac{(T_s - T_e) - (T_s - T_i)}{\ln\left(\frac{T_s - T_e}{T_s - T_i}\right)} = \frac{\Delta T_e - \Delta T_i}{\ln\left(\frac{\Delta T_e}{\Delta T_i}\right)}$$

$$Q = hA_s \, \Delta T_m = \dot{m} C_p \, \Delta T \quad \Delta T \to (T_e - T_i)$$

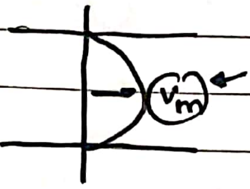
$$A_s = N_L \pi D L$$

Flow in pipe / duct / tube / conduit



Properities vary only in the direction of fluid

Steady (const. prop. of bulk avg.)



considered for Re calculation

$$\dot{m} = \rho V_m A_c = \int \rho \, V(r,x) \, dA_c$$

$$V_m = \frac{\int_{A_c} \rho V(r,x) \, dA_c}{\rho A_c}$$

$$= \frac{\int_0^R \rho \, V(r,x) \, 2\pi r \, dr}{\rho \, \pi R^2}$$

$$V_m = \frac{2}{R^2} \int_0^R V(r,x) \, r \, dr$$

$$E_{fluid} = \dot{m} C_p T_m$$

$$= \int_{\dot{m}} C_p \, dT \, \delta\dot{m}$$

$$E_f = \int_{A_c} \rho C_p T v \, dA_c$$

$$T_m = \int_{\dot m} c_p T \delta \dot m \Big/ \dot m c_p$$

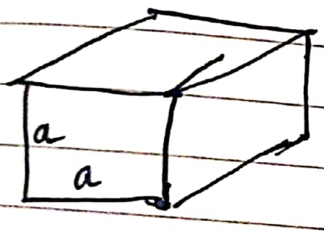
$$\dot m = \rho V_m (\pi R^2)$$

$$T_m = \frac{2}{V_m R^2} \int_0^R T(r,x)\, v(r,x)\, r \, dr$$

$$T_b = \frac{(T_{m,i} + T_{m,e})}{2}$$

↑

T_{bulk} (consider this for calculations)



(D) → Hydraulic Diameter (D_h)

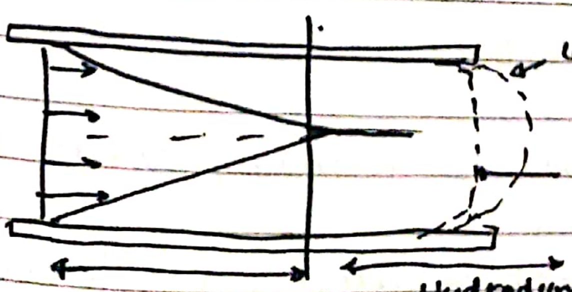
$$D_h = \frac{\text{weightage cross-sec.}}{\text{weightage perimeter}} = \frac{4A_c}{P}$$

$$= \frac{4 \, \pi D^2/4}{\pi D} = D$$

Re < 2300 laminar

2300 < Re < 10k Transistion

Re > 10k Turbulent



When flow is both hydrodynamically fully developed and thermally fully developed, the flow is called a fully developed flow

For hydrodynamically fully developed flow,

$$\frac{\partial v(r,x)}{\partial x} = 0 \implies v = v(r)$$

For thermally fully developed flow,

$$\frac{\partial}{\partial x}\left[\frac{T_s(x) - T(r,x)}{T_s(x) - T_m(x)}\right] = 0$$

$$\dot{q}_s = h_x (T_s - T_m)$$
$$= k \left.\frac{\partial T}{\partial r}\right|_{r=R}$$

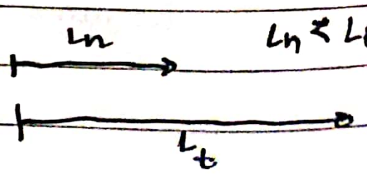
$$h_x = \frac{1}{(T_s - T_m)} \left(k \left.\frac{\partial T}{\partial r}\right|_{r=R} \right)$$

h_x → Independent of x

$$\frac{\partial}{\partial r}\left(\frac{T_s - T}{T_s - T_m}\right) = \frac{-\left(\frac{\partial T}{\partial r}\right)_{r=R}}{T_s - T_m} \neq f(x)$$

When $Pr \approx 1$, boundary layers are almost same

When $Pr >> 1$, velocity BL is much ahead of thermal BL



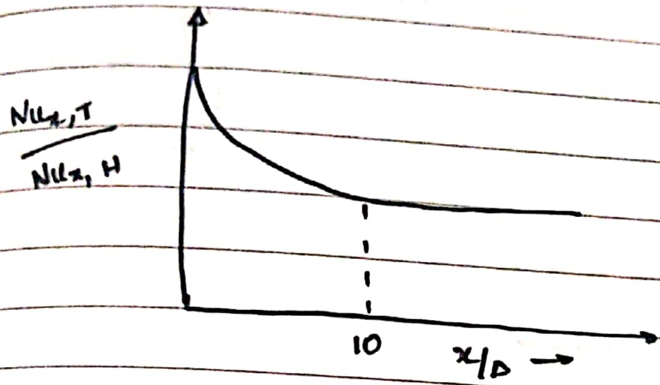
$L_h \lesssim L_t$ } $Pr >> 1$

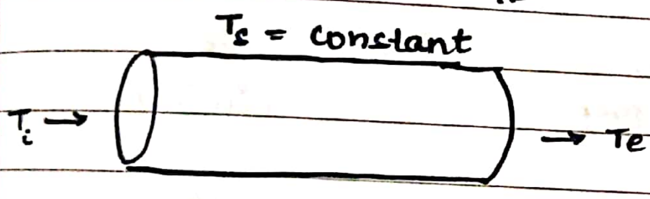
$L_{h,lam} = 0.05\, Re\, D$

$L_{t,lam} = 0.05\, Re\, Pr\, D$
$= Pr\, L_{h,lam}$

$L_{h,Turb} = 1.359\, Re^{1/4}$

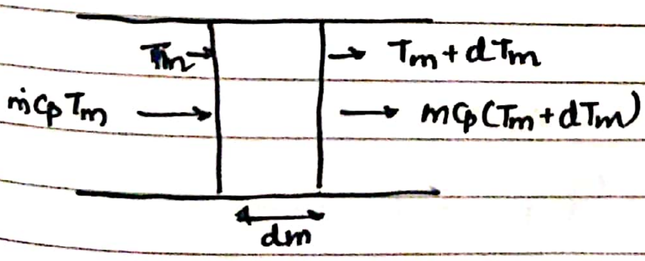
$L_{h,Turb} \approx L_{t,Turb} \approx 10D$ ← Entery Affect





$\dot{Q} = h A_s \Delta T_{avg}$

$\Delta T_{avg} = T_s - T_b$
$= \dfrac{\Delta T_i + \Delta T_e}{2}$



$\delta \dot{Q} = h(T_s - T_m)\, dA$

$\dot{m} C_p\, dT_m = h(T_s - T_m)\, dA_s$

$dA_s = P\, dx$ @ $x = 0$, $T_m = T_i$

$dT_m = -d(T_s - T_m)$ @ $x = L$, $T_m = T_e$

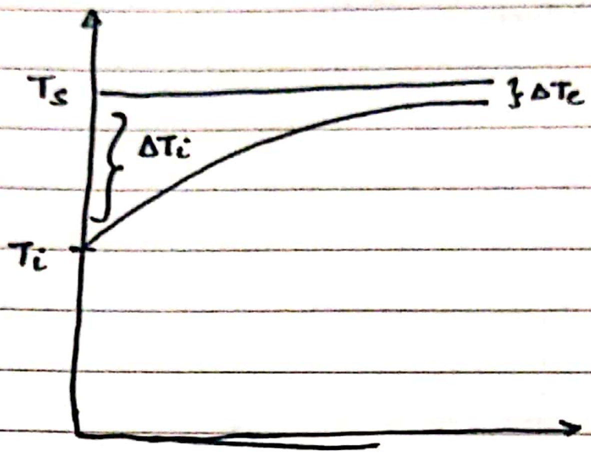
$$\frac{d(T_s - T_m)}{T_s - T_m} = -\frac{hP}{\dot{m} C_p}\, dx$$

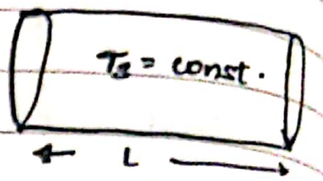
$$\ln\left(\frac{T_s - T_{me}}{T_s - T_i}\right) = -\frac{hA_s}{\dot{m}C_p}$$

$$T_e = T_s - (T_s - T_i)\, e^{-hA_s/\dot{m}C_p}$$

NTU ← No. of transfer units

$$\therefore \; T_m = T_s - (T_s - T_i)\, e^{-(hPx/\dot{m}C_p)}$$





NTU = $\frac{hA_s}{\dot{m}C_p}$	T_e (in °c)
0.01	20.8
0.1	27.6
1.0	70.6
5.0	99.5
10	100°

Selection of equipment plays a major role

$$\dot{m}C_p = \frac{-hA_s}{\ln\left(\frac{T_s - T_e}{T_s - T_i}\right)}$$

$$Q = hA_s\,\Delta T_{avg}$$
$$= \dot{m}C_p\,(T_i - T_e)$$

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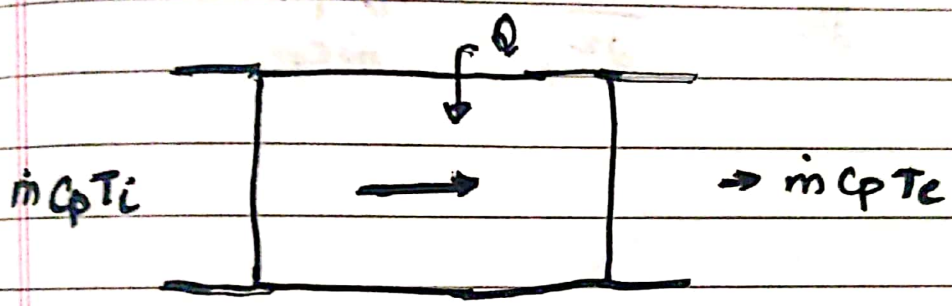
$$\cancel{h A_s} \Delta T_{avg} = -\frac{\cancel{h A_s} (T_i - T_e)}{\ln\left(\frac{T_s - T_e}{T_s - T_i}\right)}$$

$$\therefore \quad \Delta T_{avg} = \Delta T_{LMTD}$$

$$\Delta T_{LMTD} = \frac{T_i - T_e}{\ln\left(\frac{T_s - T_e}{T_s - T_i}\right)}$$

$$\Delta T_{LMTD} = \frac{\Delta T_e - \Delta T_i}{\ln\left(\frac{\Delta T_e}{\Delta T_i}\right)}$$



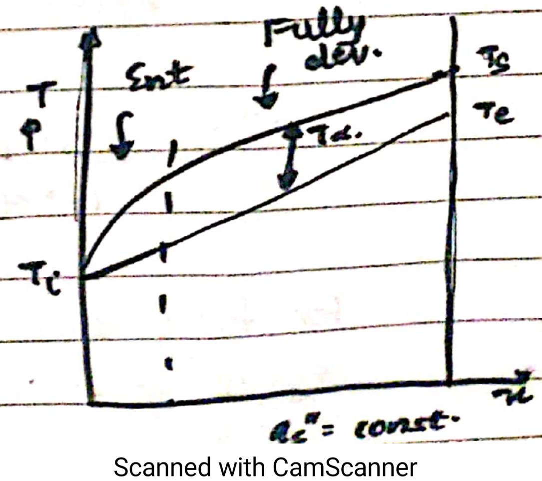
$$Q = \dot{m} c_p (T_e - T_i)$$

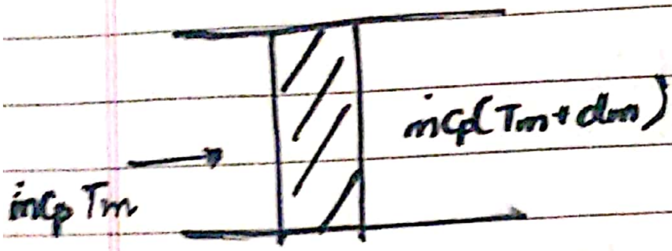
$$\dot{q}_s = h_x (T_s - T_m)$$

$$\dot{Q} = \dot{q}_s A_s (T_e - T_i)$$

$$T_e = T_i + \frac{\dot{q}_s A_s}{\dot{m} c_p} \qquad \dot{q}_s = h (T_s - T_m)$$

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

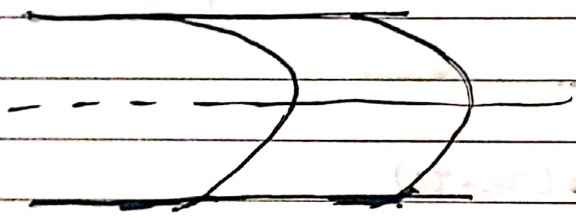




$$\frac{\partial}{\partial x}\left(\frac{T_s - T}{T_s - T_m}\right) = 0$$

$$\Rightarrow \frac{\partial T_s}{\partial x} - \frac{\partial T}{\partial x} = 0 \Rightarrow \frac{\partial T_s}{\partial x} = \frac{\partial T}{\partial x}$$

$$\frac{\partial T_s}{\partial x} = \frac{\partial T}{\partial x} = \frac{\partial T_m}{\partial x} = \frac{\dot{q}_s p}{\dot{m}c_p} \Rightarrow \text{const.}$$



laminar flow

$$v(r) = 2V_m\left(1 - \frac{r^2}{R^2}\right)$$

At $r = 0$, $V_{max} = 2V_m$

$$\Delta P = \underbrace{f}_{64/Re}\frac{L}{D}\frac{\mu V_m^2}{2}$$

$$\dot{V} = \frac{\pi D^4 \Delta P}{128\mu L}$$

For fully developed laminar flow, when $\dot{q}_s$ is const.

$\dot{q}_s = h(T_s - T_m)$ $\quad Nu = 4.36 \leftarrow$ const.

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

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

Enterance region

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

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