Unit 3rd

Date:
Page:

Heat exchanger

H.E is broadly defined as a control vol. where is heat exchange occur b/w 2 or more than 2 fluid at steady state steady flow connection

Classification of H.E

TEMA (Tublar heat exchanger manufactural association)

On the basis of heat transfer process

- Direct (mixing)
- Indirect (surface)

Direct	Indirect
cooling tower	boiler
de-superheater	Air preheater
Open feed water heater	Economiser
Jet condensor	
Jet spray	

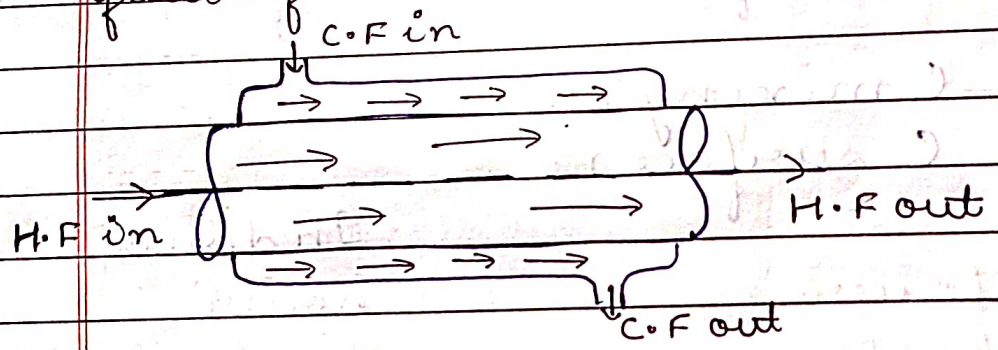
On the basis of compactness of SAD (surface area density m^2/m^3)

Non-compact	$70 \leq C \leq 500$
Medium compact	$500 \leq C \leq 700$
Compact	$C > 700$
Automobile radiator	$C \simeq 1100$
gas turbine driven engine	$C \simeq 6600$

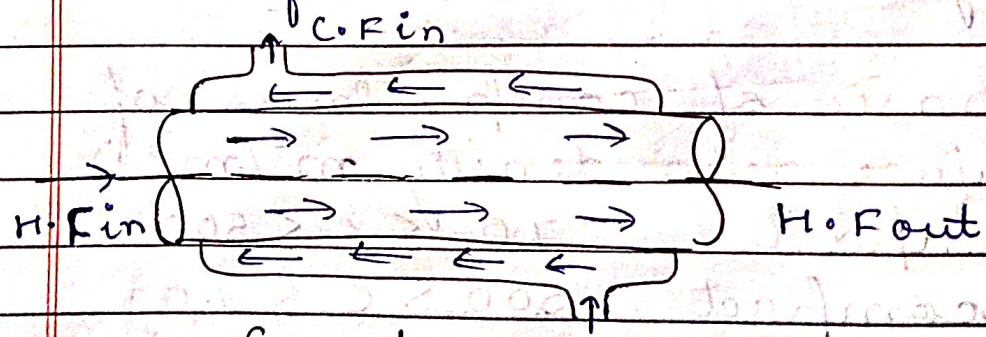
Most compact heat exchanger in the world till date is human lungs
$C \simeq 20,000$

On the basis of hot & cold fluid in heat exchanger
(Transfer type)
- Recuperative [No time slag]
- Regenerative [time slag]
(storage type H.E)

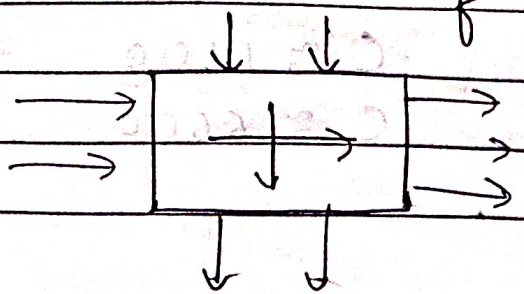
On the basis of relative direct^n of fluid flow



⇉ Parallel flow (cocurrent)
⇄ Counter flow (counter current)
⊥→ Cross flow (transverse flow)



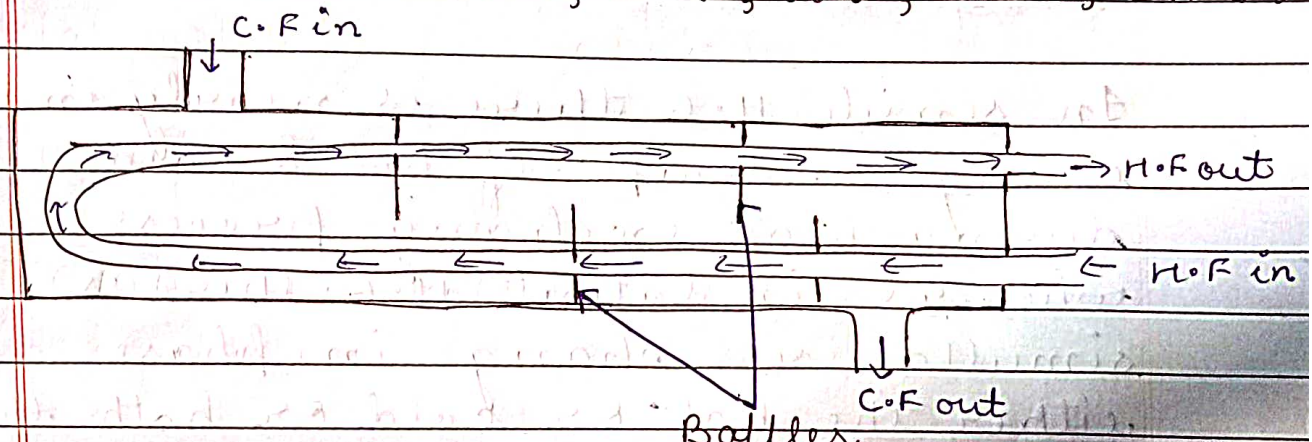
Counter flow



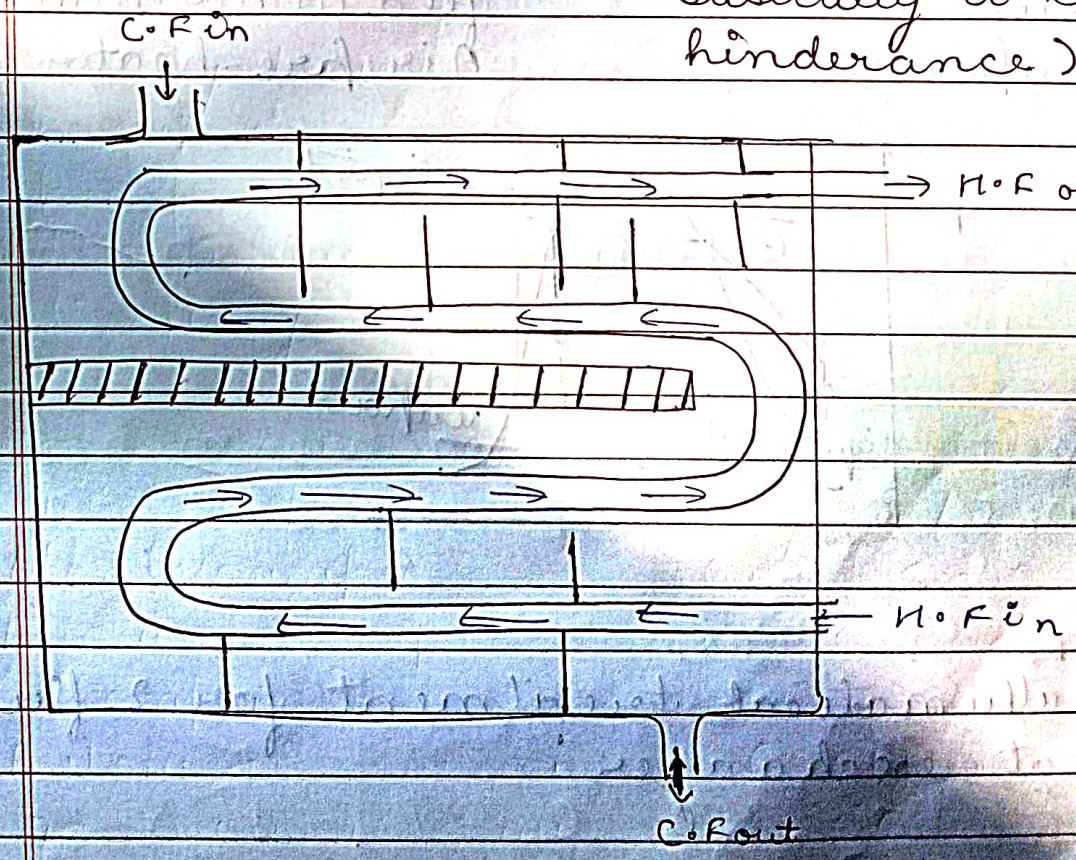
Date:
Page:

No. of passes by hot & cold fluid

- Single pass (parallel, counter, cross flow)
- Multi pass (1-shell, 2 tube ; 2-S, 4-T ; 3-S, 6-T ; ... ; n-S, 2n-T)



Baffles
(• restrict fluid flow
• increase heat exchange rate b/w 2 fluid
• Basically it create hinderance)

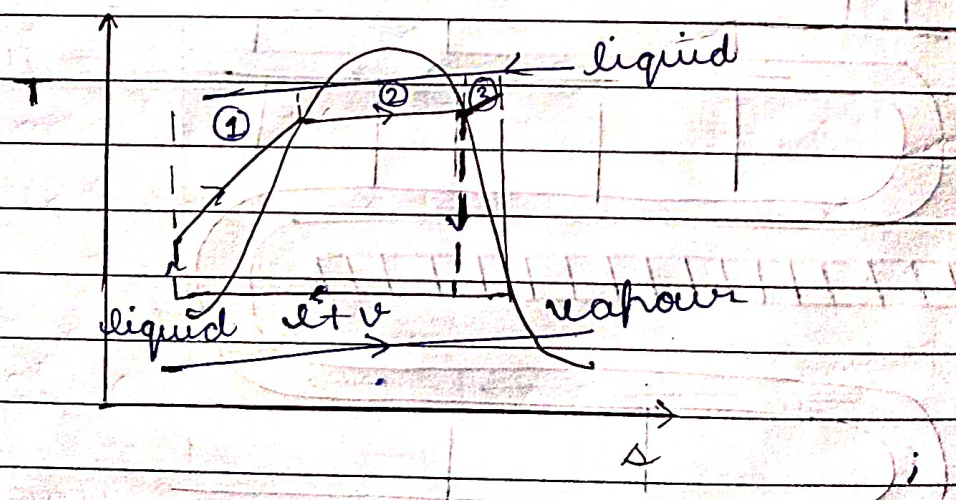


On the basis of whether or not hot & ~~clo~~ cold fluid exchange phase

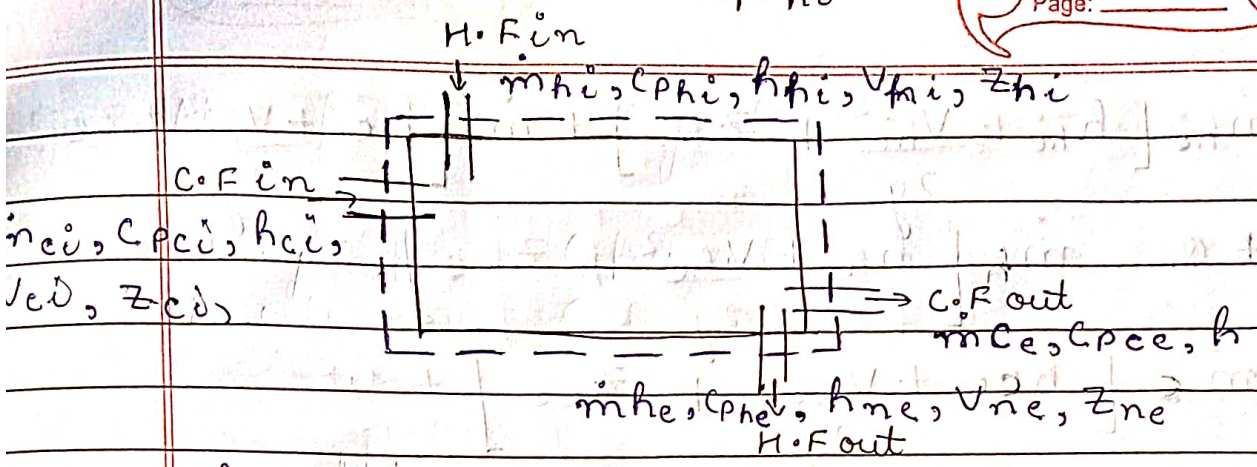
Sensible heat exchanger
Latent " "

In sensile H.E there is nearly in change in temp. of hot & cold during heat exchange process whereas in latent H.E there is simullaneous change in phase either the hot or cold or both the fluid

Latent	Sensible
Boiler	Automobile radiator
condensor	feed water heater
evaporator	Air pre-heater



Mathematical treatment for 2 fluid heat exchanger



$\dot{m}_{hi}$ (mass flow rate of heate exchanger at inlet)

C_{phi} (specific heat capacity of heat exchanger at inlet)

$\dot{m}_{he}$ (" at exit)

C_{phe} (" at exit)

h_{hi} (enthalpy of hot fluid at inlet)

Z_{hi} (potential energy of hot fluid at inlet)

V_{hi} (velocity of hot fluid at inlet)

Assumption

steady state steady flow process

$\dot{m}_{hi} = \dot{m}_{he} = \dot{m}_h$

$\dot{m}_{ci} = \dot{m}_{ce} = \dot{m}_c$

Heat exchange fluid are assumed to be thermophysical property

$C_{phi} = C_{phe} = C_{ph}$

$C_{pci} = C_{pce} = C_{pc}$

$$\dot{m}_h\left[h_{hi}\right] + \dot{m}_c h_{ci} + \frac{V_{hi}^2}{2g} + \frac{V_{ci}^2}{2g} + \dot{m}_h Z_{hi} + \dot{m}_c Z_{ci}\Big]$$

$$Q = \dot{m}_h\left[h_{he}\right] + \dot{m}_c h_{ce} + \frac{V_{he}^2}{2g} + \frac{V_{ce}^2}{2g} + Z_{ce} + Z_{he}\Big]$$

$+ W$

Date:
Page:

$$\dot{m}_{hi}\left[h_{hi}+\frac{V_{hi}^2}{2g}+z_{hi}\right]+\dot{m}_c\left[h_{ci}+\frac{V_{ci}^2}{2g}+z_{ci}\right]+Q=\dot{m}_h\left[h_{he}+\frac{V_{he}^2}{2g}+z_{he}\right]+\dot{m}_c\left[h_{ce}+\frac{V_{ce}^2}{2g}+z_{ce}\right]+w$$

Heat exchange occurs only between hot & cold fluid with no net heat crossing control surface

$Q_{cv}=0$

There is no net work transition across control surface

$w_{cv}=0$

Hot & cold fluid undergoes negligible changes in there K.E & P.E

$$\dot{m}_h h_{hi}+(\dot{m}_h h_{he})=\dot{m}_c(h_{ce})-\dot{m}_c(h_{ci})$$

$$\dot{m}_h h_{hi}-\dot{m}_h h_{he}=\dot{m}_c h_{ce}-\dot{m}_c h_{ci}$$

$$\dot{m}_h C_{ph}(T_{hi}-T_{he})=\dot{m}_c C_{pc}(T_{ce}-T_{ci})$$

$C_h=\dot{m}_h C_{ph}$

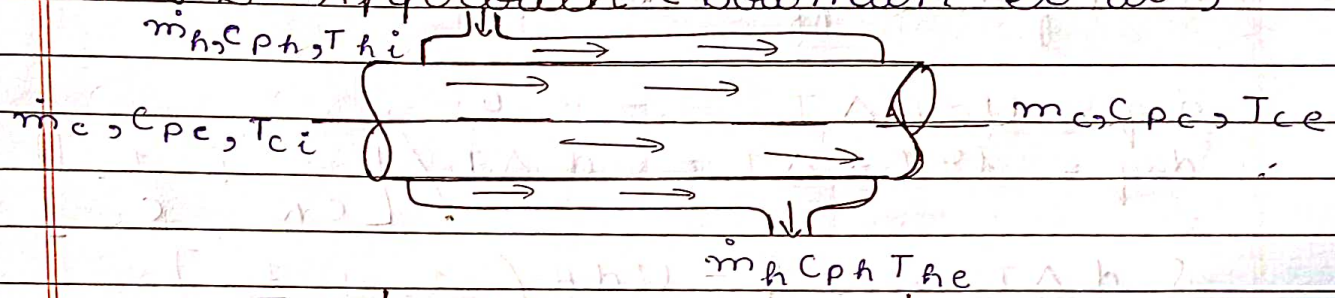
$C_c=\dot{m}_c C_{pc}$

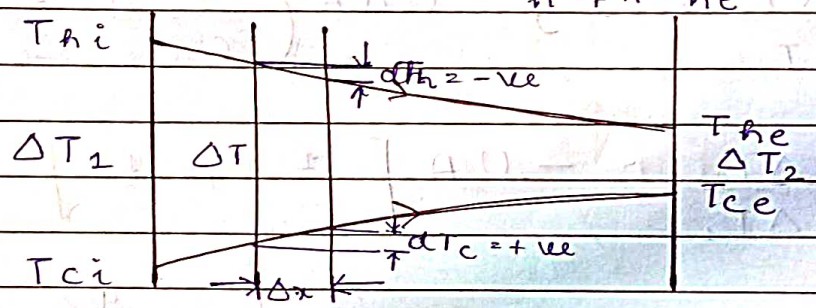
$$C_h(T_{hi}-T_{he})=C_c(T_{ce}-T_{ci})$$

Date:
Page:

From the above eq^n we can understand the energy released by hot fluid is equal to energy absorbed by cold fluid in steady state steady flow condition

LMTD Approach (Bowman et at)





As in a heat exchanger the temp. of hot fluid & cold fluid varying continuously in local axial direct^n as shown in figure. Now the ques arise at what temp. difference we calculate the rate of heat exchange as ΔT is changing

$\Delta T = T_h - T_c$ ---

$d\Delta T = dT_h - dT_c$ ---- 1

$dq = -\dot{m}_h C_{ph} dT_h \Rightarrow dT_h = -dq / \dot{m}_h C_{ph}$ --- 2

$dq = \dot{m}_c C_{pc} dT_c \Rightarrow dT_c = dq / \dot{m}_c C_{pc}$ ---

Date:
Page:

$$d\Delta T = \frac{-dq}{\dot{m}_h C_{ph}} - \frac{dq}{\dot{m}_c C_{pc}}$$

$$d\Delta T = -dq\left[\frac{1}{C_h} + \frac{1}{C_c}\right]$$

Assumption:
Let us considering U is overall heat transfer coefficient which is same

$$dq = U\,dA\,\Delta T \quad --- 4$$

$$dq = U\,dA\,\Delta T = d\Delta T \Big/ \left[\frac{1}{C_h} + \frac{1}{C_c}\right]$$

$$\int_1^2 \frac{d\Delta T}{\Delta T} = \int_1^2 -U\,dA\left(\frac{1}{C_h} + \frac{1}{C_c}\right]$$

$$\ln\frac{\Delta T_2}{\Delta T_1} = -UA\left[\frac{1}{C_h} + \frac{1}{C_c}\right] \quad --- 5$$

$$q = C_h(T_{hi} - T_{he}) \Rightarrow C_h = q/T_{hi} - T_{he} \quad --- 6$$

$$q = C_c(T_{ce} - T_{ci}) \Rightarrow C_c = q/T_{ce} - T_{ci} \quad --- 7$$

$$\ln\frac{\Delta T_2}{\Delta T_1} = -UA\left[\frac{T_{hi} - T_{he}}{q} + \frac{T_{ce} - T_{ci}}{q}\right]$$

$$\ln\frac{\Delta T_2}{\Delta T_1} = -\frac{UA}{q}\left[(T_{hi} - T_{ci}) - (T_{he} - T_{ce})\right]$$

$$= -\frac{UA}{q}\left[\Delta T_1 - \Delta T_2\right]$$

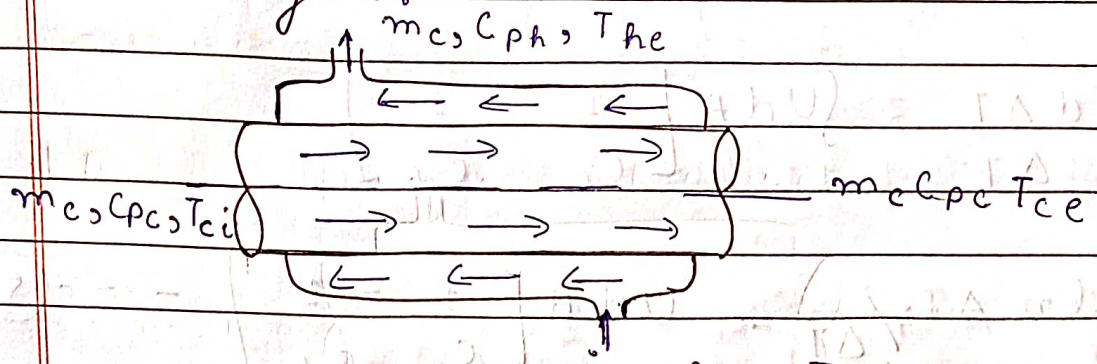
$$q = \frac{UA(\Delta T_1 - \Delta T_2)}{\ln \Delta T_1/\Delta T_2}$$

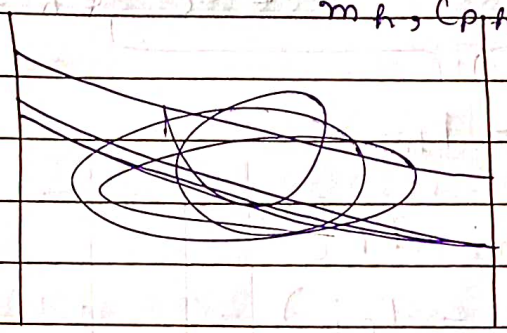
Or $$q = \frac{UA(\Delta T_2 - \Delta T_1)}{\ln \Delta T_2/\Delta T_1}$$

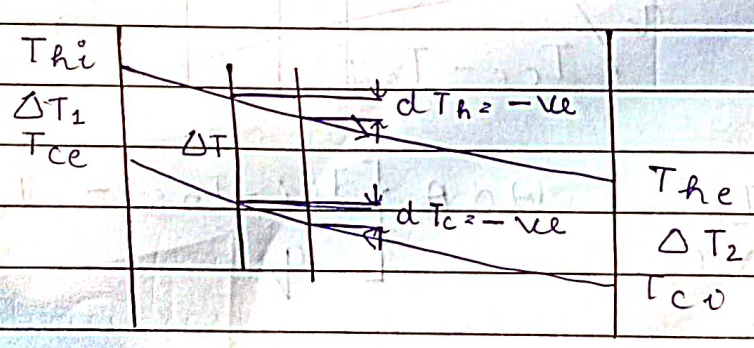
Date: _____
Page: _____

$q = UA(LMTD)$

Single pass counter flow heat exchanger.







$\Delta T = dT_h - dT_c$ --- (1)

$dq = -\dot{m}_h C_{ph} dT_h$

$dT_h = -dq / \dot{m}_h C_{ph}$ --- (2)

$dq = -\dot{m}_c C_{pc} dT_c$

$dT_c = -dq / \dot{m}_c C_{pc}$ --- (3)

$$d\Delta T = \frac{-dq}{\dot{m}_h C_{ph}} + \frac{dq}{\dot{m}_c C_{pc}}$$

$$d\Delta T = dq \left[\frac{1}{C_c} - \frac{1}{C_h} \right]$$

Date:
Page:

$$dq = U\,dA\,\Delta T \quad --- (4)$$

$$\frac{d\Delta T}{\left[\frac{1}{C_c} - \frac{1}{C_h}\right]} = U\,dA\,\Delta T$$

$$\int_1^2 \frac{d\Delta T}{\Delta T} = \int_1^2 U\,dA\left[\frac{1}{C_c} - \frac{1}{C_h}\right]$$

$$\ln \Delta T_2/\Delta T_1 = U\,dA\left[\frac{1}{C_c} - \frac{1}{C_h}\right] \quad --- (5)$$

$$q = C_h(T_{hi} - T_{he})$$

$$C_h = q/T_{hi} - T_{he} \quad --- (6)$$

$$q = C_c(T_{ce} - T_{ci})$$

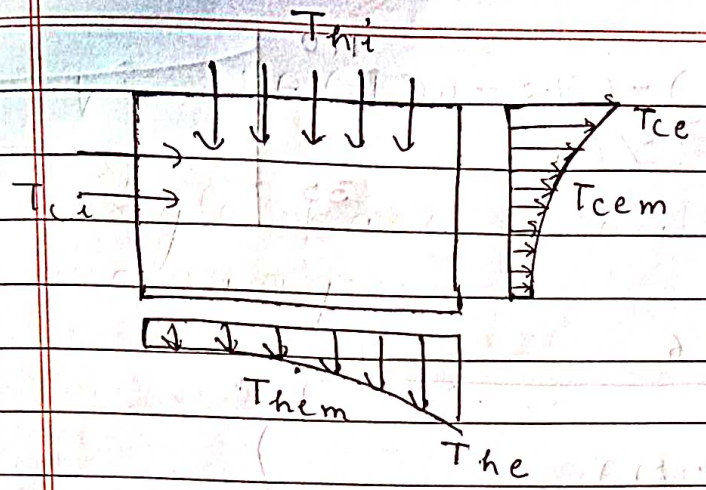
$$C_c = q/T_{ce} - T_{ci} \quad --- (7)$$

$$\ln \frac{\Delta T_2}{\Delta T_1} = U\,dA\left[\frac{T_{hi} - T_{he}}{q} - \frac{T_{ce} - T_{ci}}{q}\right]$$

$$\ln \frac{\Delta T_2}{\Delta T_1} = \frac{U\,dA}{q}\left[\frac{(T_{hi} - T_{ce}) - (T_{he} - T_{ci})}{q}\right]$$

$$q = \frac{U\,dA(\Delta T_1 - \Delta T_2)}{\ln \Delta T_2/\Delta T_1}$$

Date: _____
Page: _____



$q = UA(LMTD)$

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln \Delta T_1 / \Delta T_2}$$

$\Delta T_1 = T_{hi} - T_{hem}$

$\Delta T_2 = T_{cem} - T_{ci}$

Water flowing at a rate of 4080 Kg/h 35°C to 65°C by making use of hot engine oil entering & leaving the shell side of STHE respectively at 110°C & 75°C. The H.E is a single pass cocurrent type & uniform overall heat transfer coefficient 320 W/m²K

$C_p = 1900$ J/KgK

i) Design area to be provided H-E to handle above job

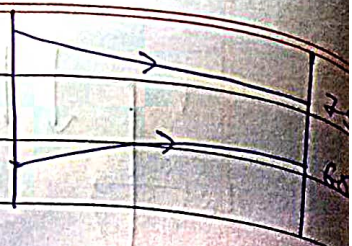
ii) What would happen to design area if one uses counter flow H-E with other parameter held fix

iii) What would happen to design area if one uses cross flow H-E with other parameter keeping fix

Comments on result.

Date:
Page:

i) $L.M.T.D = \dfrac{(110-35)-(75-65)}{\ln 75/10}$



$= \dfrac{65}{2.0149}$

$= 32.2596$

$q = UA(L.M.T.D)$

$q = \dot{m}_c C_{pc}(T_{ce} - T_{ci})$

$= \dfrac{4080 \times 1000}{3600} \times 4.1805 \times 30$

$= 142.137\ kW$

$q = UA(L.M.T.D)$

$142.137 \times 10^3 = 320 \times A \times 32.2596$

$A = 13.7687\ m^2$

ii) $L.M.T.D = \dfrac{45-40}{\ln 45/40}$

$= \dfrac{5}{0.11778}$

$= 42.4509$

$q = UA(L.M.T.D)$

$10^3 \times 142.137 = 320 \times A \times 42.4509$

$A = 10.46\ m^2$

iii) $L.M.T.D = \dfrac{60 - 57.5}{\ln 60/57.5}$

$= \dfrac{2.5}{0.04255}$

$= \cancel{166.221768}\ 58.74$

$q = 320 \times A \times \cancel{166.221768}\ 58.74$

$142137 / 320 \times 58.74 = A$

$A = 7.56\ m^2$

Though the expression for N.T.U for parallel, counter & cross flow but L.M.T.D are different.

Infact for given terminal temp. for two fluids $(L.M.T.D)_{parallel} < (L.M.T.D)_{counter} < (L.M.T.D)_{cross}$

design area of $A_{parallel} < A_{counter} < A_{cross}$

Area of cross flow.

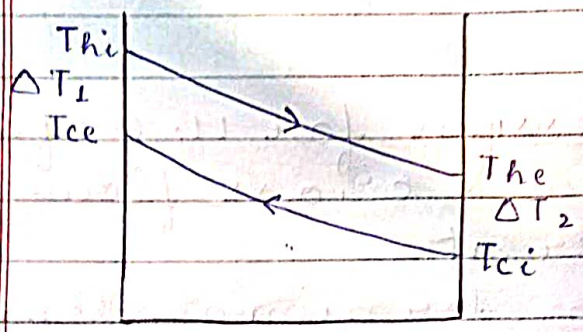
Find the % ↑ or ↓ for 3 heat exchanger

Date:
Page:

Same heat capacity

$C_c = C_h$

$(T_{hi} - T_{he}) = (T_{ce} - T_{ci})$



$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}}$$

(It can be indeterminant)

AMTD (Arithmetic mean temperature difference) $= \frac{1}{2}(\Delta T_1 + \Delta T_2) = \Delta T_1 = \Delta T_2$

$q = UA\Delta T_1$

Or $q = UA\Delta T_2$

L.MTD can be applicable if you know either 4 or 3 or 2 temp. you know but for 2 known temp. you have to use hit & trials method which is quite lengthy.

So for simplifying this ~~this~~ we use effectiveness - no. of transfer unit

ε - NTU (1962)

Effectiveness in heat exchange

It is defined as the ratio of actual rate of heat transfer possible in H.E to the thermodynamic limit of maximum heat transfer

Date:
Page:

$$\epsilon = \frac{q_{actual}}{q_{max^m}} = \frac{C_c(T_{ce} - T_{ci})}{C_{min}(T_{hi} - T_{ci})} = \frac{C_c(T_{hi} - T_{he})}{C_{min}(T_{hi} - T_{ci})}$$

$$HCR = \frac{C_{max}}{C_{min}}$$

NTU

Ratio of heat capacity of to th min heat capacity of flowing fluid

$$\frac{UA}{C_{min}}$$

For single pass parallel flow heat exchanger

$$d\Delta T = dT_h - dT_c \quad --- (1)$$

$$d\Delta T = \frac{-dq}{C_{ph}} - \frac{dq}{C_{pc}}$$

$$d\Delta T = -dq\left[\frac{1}{C_{ph}} + \frac{1}{C_{pc}}\right]$$

$$d\Delta T = -UA\Delta T\left[\frac{T_{hi} - T_{he}}{q} + \frac{T_{ce} - T_{ci}}{q}\right]$$

$$\int_{T_1}^{T_2} \frac{d\Delta T}{\Delta T} = -\frac{UA}{a}(\Delta T_1 - \Delta T_2)$$

$$\ln\frac{\Delta T_2}{\Delta T_1} = -UA(\Delta T_1 - \Delta T_2)$$

$$q = \frac{UA(\Delta T_1 - \Delta T_2)}{\ln\left[\Delta T_1/\Delta T_2\right]}$$

Date:
Page:

$$\frac{\Delta T_2}{\Delta T_1} = e^{-UA\left[\frac{1}{C_c}+\frac{1}{C_h}\right]}$$

$$\frac{T_{he}-T_{ce}}{T_{hi}-T_{ci}} = e^{-UA\left[\frac{1}{C_c}+\frac{1}{C_h}\right]} \quad --- (5)$$

$$q = C_h(T_{hi}-T_{he}) = C_c(T_{ce}-T_{ci})$$

$$T_{he} = T_{hi} - \frac{C_c}{C_h}(T_{ce}-T_{ci}) \quad --- (6)$$

$$\frac{T_{hi} - \frac{C_c}{C_h}(T_{ce}-T_{ci}) - T_{ce}}{T_{hi}-T_{ci}} = e^{-UA\left[\frac{1}{C_c}+\frac{1}{C_h}\right]}$$

Adding & subtracting T_{ci} in numerator of left side

$$\frac{T_{hi} - T_{ci} + T_{ci} - \frac{C_c}{C_h}(T_{ce}-T_{ci}) - T_{ce}}{T_{hi}-T_{ci}} = e^{-UA\left[\frac{1}{C_c}+\frac{1}{C_h}\right]}$$

$$1 + \frac{T_{ci} - \frac{C_c}{C_h}(T_{ce}-T_{ci}) - T_{ce}}{T_{hi}-T_{ci}} = e^{-UA\left[\frac{1}{C_c}+\frac{1}{C_h}\right]}$$

$$\frac{1 - e^{-UA\left[\frac{1}{C_c}+\frac{1}{C_h}\right]}}{1 + \frac{C_c}{C_h}} \quad \frac{C_c}{C_{min}}$$

Date: _____
Page: _____

$$\frac{1 + (T_{ce} - T_{ci})\left[\frac{-C_c}{C_h} - 1\right]}{(T_{hi} - T_{ci})} = e^{-UA\left[\frac{1}{C_c}+\frac{1}{C_h}\right]}$$

$$\frac{1 - (T_{ce} - T_{ci})\left[\frac{C_c}{C_h} + 1\right]}{(T_{hi} - T_{ci})} = e^{-UA\left[\frac{1}{C_c}+\frac{1}{C_h}\right]}$$

$$\frac{C_c}{C_{min}} \frac{(T_{ce} - T_{ci})}{(T_{hi} - T_{ci})} = \frac{1 - e^{-UA\left[\frac{1}{C_c}+\frac{1}{C_h}\right]}}{\left[\frac{C_c}{C_h} + 1\right]} \quad --- (7)$$

Now by definition of effectiveness

$$\epsilon = \frac{1 - e^{-UA\left[1/C_c + 1/C_h\right]}}{\left[\frac{C_c}{C_h} + 1\right]} \times \frac{C_c}{C_{min}}$$

$$\epsilon = \frac{1 - e^{-UA\left[\frac{1}{C_c}+\frac{1}{C_h}\right]}}{\left[\frac{C_{min}}{C_h} + \frac{C_{min}}{C_c}\right]} \quad --- (8)$$

From the definetion of NTU

$$\epsilon = \frac{1 - e^{-NTU\left[\frac{C_{min}}{C_c} + \frac{C_{min}}{C_h}\right]}}{\left[\frac{C_{min}}{C_c} + \frac{C_{min}}{C_h}\right]} \quad --- (8)$$

There are two cases

Date:
Page:

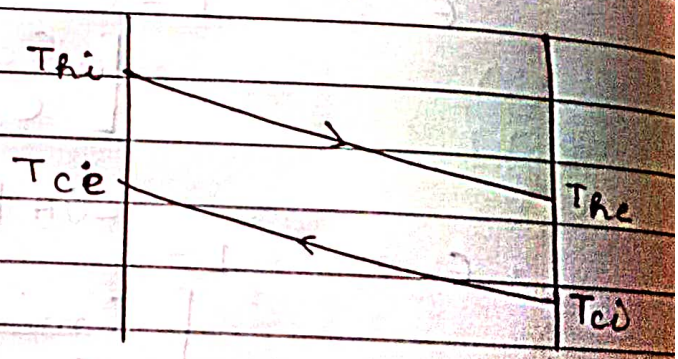
1. $C_c \rightarrow C_{min}$ $\quad C_h \rightarrow C_{max}$

$$\epsilon = \frac{1 - e^{-NTU\left[1 + \frac{C_{min}}{C_{max}}\right]}}{\left[1 + \frac{C_{min}}{C_{max}}\right]} \quad --- (10)$$

2. $C_c \rightarrow C_{max}$ $\quad C_h \rightarrow C_{min}$

$$\epsilon = \frac{1 - e^{-NTU\left[1 + \frac{C_{min}}{C_{max}}\right]}}{\left[1 + \frac{C_{min}}{C_{max}}\right]} \quad --- (11)$$

2. ϵ of H.E counter flow (single pass)



Date:

Page:

Date:
Page:

Hot chemical products of ~~concentrate~~ const. pressure specific heat 2500 J/Kgk at a terminal temperature 600°C flow at a rate 30kg/s in co-current heat exchanger. These products are used to heat of const pressure specific heat 4200 J/Kgk entering at a temp. 100°C into the exchanger same as that of chemical product. Calculate for 50 m² heat exchange area and overall heat transfer coefficient 1500 W/m²K. The temperature at exit for both fluid is

$C_c = m_c C_{pc}$
$= 30 \times 4200$
$= 126000$ W/K
$= 126$ KW/K

$C_h = m_h C_{ph}$
$= 30 \times 2500$
$= 75000$ W/K
$= 75$ KW/K

$C_{max} = 126$ KW/K

$C_{min} = 75$ KW/K

$$NTU = \frac{UA}{C_{min}}$$
$$= \frac{1500 \times 50}{75000}$$
$$= 1$$

$$\epsilon = \frac{1 - e^{-1\left[1 + \frac{75}{126}\right]}}{1 + \frac{75}{126}}$$

$= 0.7971 / 1.5952$
$= 0.49967$

Date:
Page:

Date:
Page:

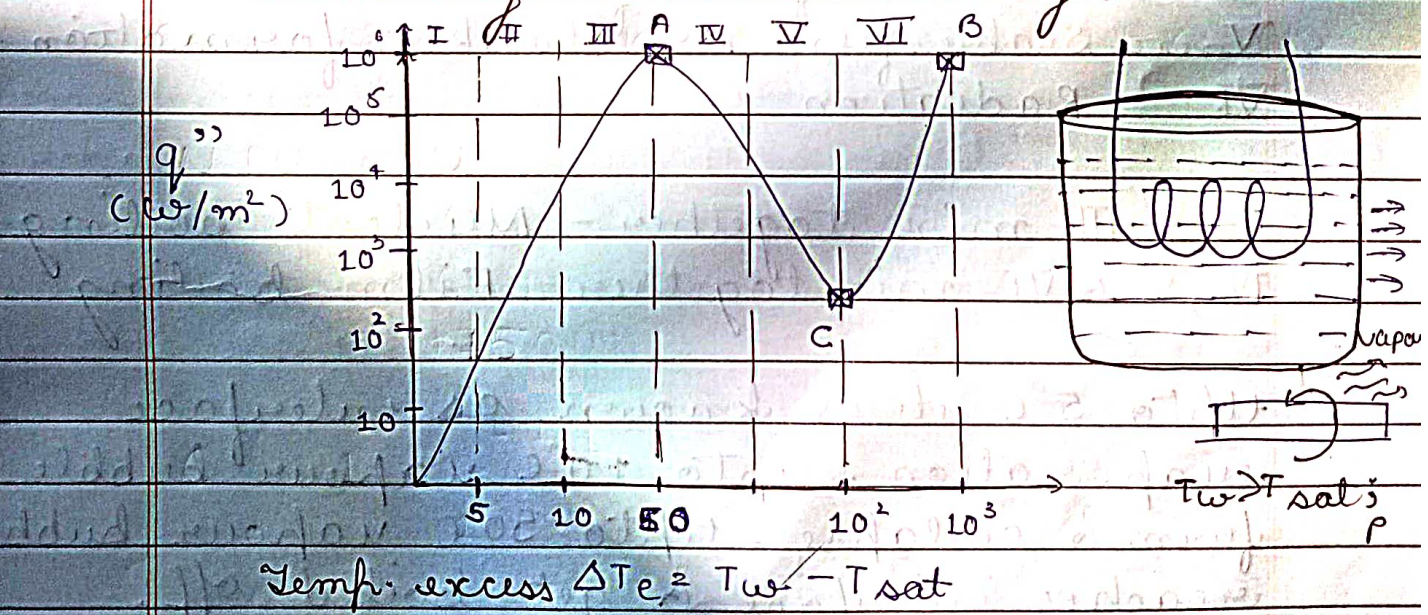
Boiling and Condensation

1. Boiling : It is a convection H.T process in which liquid undergoes change in its phase into vapour when it comes in contact with solid surface i.e $T > T_{saturation}$ of liquid corresponding to the given pressure

Classify different boiling phenomena? with suitable examples (5 for each)

- Subcooled or local boiling
- saturated or bulk boiling
- Flow or forced boiling
- Pool or submerged or free boiling

Pool boiling curve (S. Nukiyama)



- Nukiyama conducted experiment on pool boiling by taking an electrical resistance nicron heating element

emerged in liquid water (at saturation temp) by varying surface temp & measuring heat flux.
Basically he varies ohmic resistance of heating element & thus varying ΔT_e & make measurement for boiling heat flux.
He ploted pool boiling curve with boiling heat flux as a funct^n of temp. excess.

I - interphase evaporation
II - Vapour bubble forms & collapse in liquid
III - vapour bubble reaches interface & get boiled off
IV - Unstable film formation
V - Stable film or blanket formation
VI - Radiation

II & III mix together - Nucleat boiling
IV, V & VI mix together - Film boiling

Upto 5°C it is known as interface evaporation. upto 10°C vapour bubble form & collapse. Upto 50°C vapour bubble reaches interface & get boiled off.
Film is nothing but vapour bubble formation is very much in no.
It acts as an insulating blanket.

Date:
Page:

Nucleat boiling is the resins in all episode because we get 10^6 at $50^\circ C$ after that at $1000^\circ C$

A : Boiling crises point, max^m heat flux point, critical heat flux point, peak heat flux point, burn out point.

Boiling crises because boiling process beyond that point is unstable unless point B is reached.

The temp. at Point B is extremely high & normally the ~~boiling~~ melting point of the solid. So, if the heating of metallic surface is not limited to point A it is possible the metal may get damaged or it may even melt

Point C is known as Leidenfrost & minimum heat flux point

Empirical co-relations (Rosenhow's relation)

Rosenhow's gives the boiling heat flux

$$q''_{boiling} = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2} \left[\frac{C_{pl}\,\Delta T_e}{C_{sf}\, h_{fg}\, Pr_l^{n}}\right]^{3} \quad \text{--- (1)}$$

C_{sf} is empirical const. whose values depend on the nature of surface fluid combination & surface roughness.

$n = 1$ for water

$n = 1.7$ for other liquids

Zuber relation for peak & critical heat flux

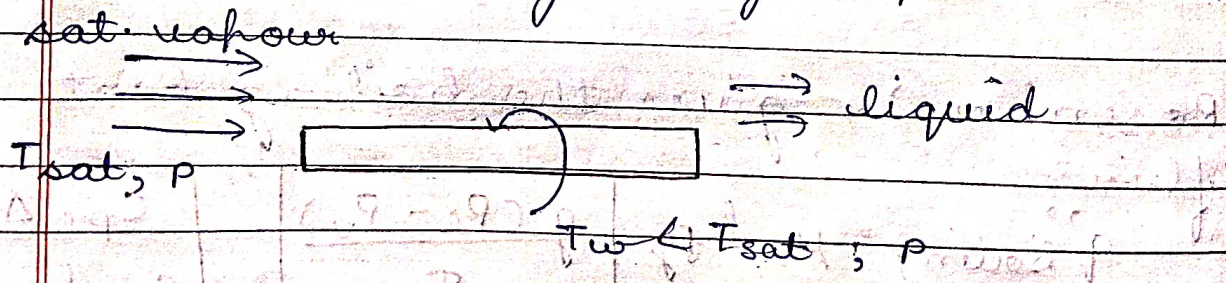
$$C.H.F = q''_{max} = 0.179\, h_{fg}\, \rho_v \left[\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^2}\right]^{1/4}$$

Zuber - Berensor relation

$$M.H.F = q''_{min} = 0.09\, h_{fg}\, \rho_v \left[\frac{\sigma g (\rho_l - \rho_v)}{(\rho_l + \rho_v)^2}\right]^{1/4}$$

Condensation

It is a convection heat transfer process in which a saturated vapour undergoes change in its phase into liquid when it comes in contact with solid surface i.e at a temp. lower than the saturated temp. of the liquid corresponding to given pressure.

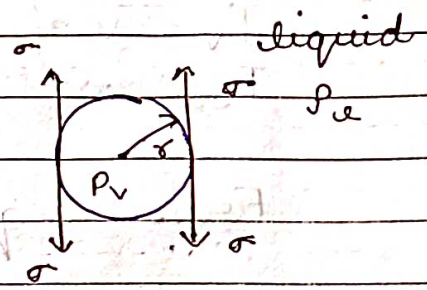


Date: _____
Page: _____

Boiling

* Bubble formation

It is assumed that it is spherical in shape.



Pressure force on bubble must be equal to surface tension at vapour liquid interface.

$$\pi r^2 (P_v - P_l) = 2\pi r \cdot \sigma$$

$$P_v - P_l = \frac{2\sigma}{r} \quad \text{---} (1)$$

P_v = vapour pressure inside bubble
P_l = liquid pressure over liquid bubble
σ = surface tension on

A vapour is perfect gas (this is an assumption), hence you can apply clayperon eq^n

$$\frac{dP}{P} = \frac{h_{fg}}{RT^2} dT \quad \text{---} (2)$$

$$PV = mRT$$

$$P = \rho RT$$

$$\rho_v = P/RT \quad \text{---} (3)$$

Perfect gas

From eq 2 & 3

$$\frac{dP}{dT} = \frac{\rho RT}{RT^2} h_{fg}$$

$$\frac{dP}{dT} = \frac{\rho_v h_{fg}}{T}$$

$$\frac{P_v - P_l}{T_v - T_{sat}} = \frac{h_{fg} \rho_v}{T} \quad \text{---} (4)$$

T_v = vapour temp. inside bubble
T_{sat} = sat. temp. inside bubble at P_v

From eq (1) & eq (4)

$$\frac{2\sigma}{r(T_v - T_{sat})} = \frac{h_{fg}\rho_v}{T}$$

$$T_v - T_{sat} = \frac{2\sigma}{r} \times \frac{T}{h_{fg}\rho_v} \quad \text{--- eq (5)}$$

$$T_v - T_{sat} = \frac{2\sigma}{r} \times \frac{T^2 \times R}{h_{fg} P}$$

eq (5) shows that if $T_e - T_{sat} > T_v - T_{sat}$ the bubble of radius r will grow otherwise it will collapse.
where T_e = temp. of surrounding of bubble

Condensation

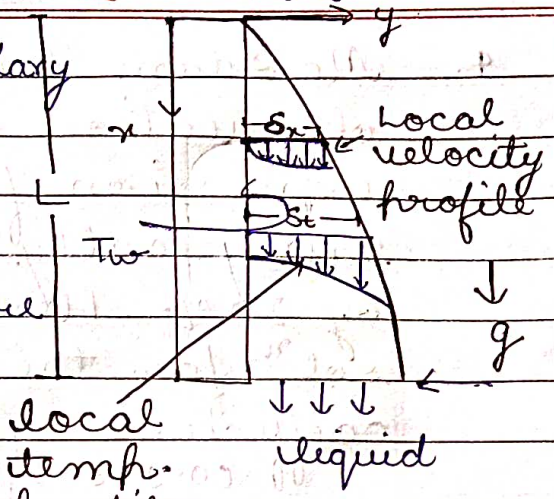
Differentiate dropwise & filmwise condensation with some suitable examples.

Nilhen - Nusselt theory for filmwise condensation

This theory discuss the laminar filmwise C° over isothermal vertical flat plate

Date: sat vapour
Page:

VBL / Hydrodynamic boundary layer



Assumption:
saturated vapour is pure dry saturated & free from the air

the flow of condensate film is assumed to laminar
L.V.P is assumed to be parabolic
L.T.P is " " " linear
Thermophysical property of condensate liquid is assumed to be const.

1. The analytical solⁿ for thickness of condensate film at given x from leading edge

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

2. Local value of condensation heat transfer coefficient

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

3. Average heat transfer coefficient

$$\bar{h}_x = 0.943 \left[\frac{g \rho_l (\rho_l - \rho_v) h_{fg} k_l^3}{4\mu_l (T_{sat} - T_w) L}\right]^{1/4}$$

4. Mc Adam based on experimental observation concluded that the above expression for h_x given by Nusselt analytically underestimate the results by 20%. Hence Mc Adam refine the sol^n for the average heat transfer coefficient

$$\bar{h}_x = 1.1316 \left[\frac{g \rho_l (\rho_l - \rho_v) h_{fg} k_l^3}{4 \mu_l (T_{sat} - T_w) L} \right]^{1/4}$$

(0.943 × 1.2)

5. To calculate the mass rate of condensation

$$\dot{q}_{cond} = \bar{h} S (T_{sat} - T_w)$$

$S \rightarrow (L \times w) \times 2$

$$\dot{q}_{cond} = \dot{m}_{cond} h_{fg}$$

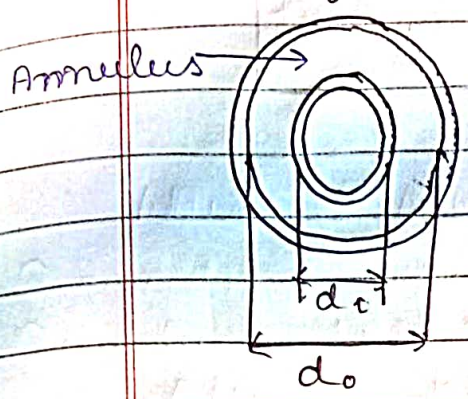
A wire of 1.2 mm dia and 200 mm length is submerged horizontally in water at 7 bar. The wire carries a current of 135 ampere within applied voltage 2.18 Volt. If the surface of wire is maintained at 200°C, calculate heat flux & boiling heat transfer coefficient. At 7 bar saturation temp is 164.97°C

Date:
Page:

Saturated steam i.e pure & free from air & other condensate at a temp. 90°C corresponding to given Pressure condense comprises in steam condensor comprise in single verticle tube of outside dia 2.5 cm on its outer surface. The surface temp. of tube is maintained at 70°C, Calculate the design height of the tube of condensor if it is required to condense 20 kg/hr of steam

Forced convection

Equivalent dia for pressure drop and heat flow



d_i - External dia of inner pipe

d_o - Inner dia of outer pipe

$$D_{eq} = \frac{4 \times A}{P}$$

$$D_{eq} = \frac{\cancel{4} \times \frac{\pi}{\cancel{4}} (d_o^2 - d_i^2)}{\pi d_o + \pi d_i}$$

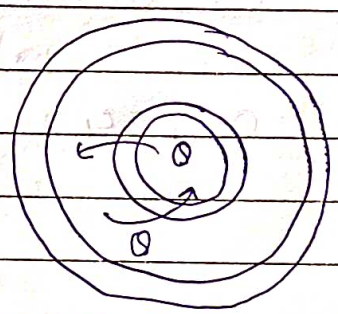
$$(D_{eq})_{\text{pressure drop}} = d_o - d_i$$

Equivalent dia for heat transfer

$$D_{eq} = \frac{4 \times A}{P}$$

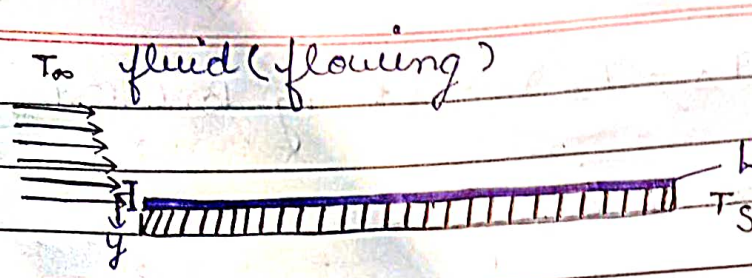
$$= \frac{4 \times \frac{\pi}{4} (d_o^2 - d_i^2)}{\pi d_i}$$

$$= \frac{d_o^2 - d_i^2}{d_i}$$



Date:
Page:

$T_s > T_\infty$



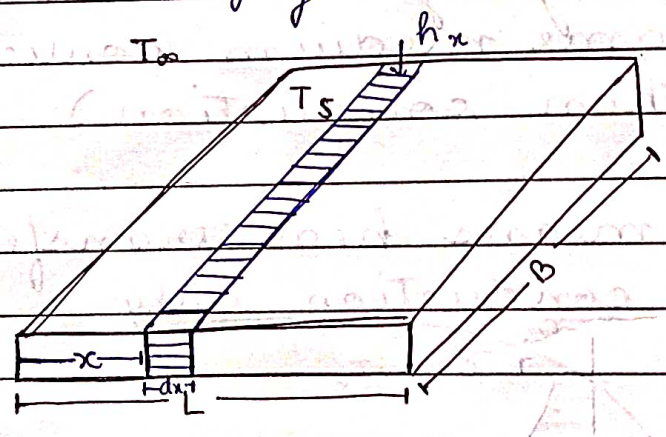
$Q_{\substack{conduction \\ plate}} = Q_{cond_y} = Q_{convection}$

$$-k_p A \frac{\partial T}{\partial y}\Big|_{y=0} = -k_f A \frac{\partial T}{\partial y}\Big|_{y=0} = h_{avg} A \Delta T$$

$$k_p A \frac{\partial T}{\partial y}\Big|_{y=0} = k_f A \frac{\partial T}{\partial y}\Big|_{y=0} = h A (T_s - T_\infty)$$

$$k_f \cancel{A} \frac{\partial T}{\partial y}\Big|_{y=0} = h_{avg} \cancel{A} (T_s - T_\infty)$$

$$h_{avg} = k_f \frac{\partial T}{\partial y}\Big|_{y=0} \Big/ (T_s - T_\infty)$$



h_x = local heat transfer coefficient

$$Q = h_{avg} L \cdot B (T_s - T_\infty)$$

$$\int dq = \int_0^L h_x B \, dx \, (T_s - T_\infty)$$

$$Q = \int_0^L h_x B \, dx \, (T_s - T_\infty) = h_{avg} L \cdot B (T_s - T_\infty)$$

$$\int_0^L h_x \cancel{P} dx (T_s - \cancel{T_\infty}) = \bar{h}_{avg} \cancel{P} L (T_s - \cancel{T_\infty})$$

$$\int_0^L h_x dx = \bar{h}_{avg} L$$

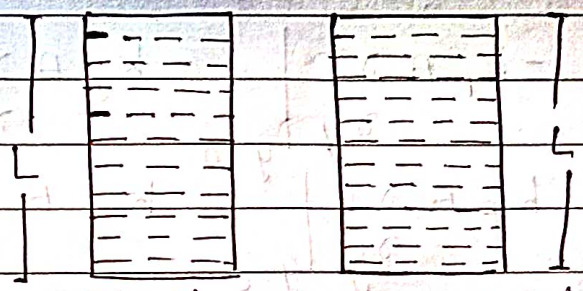
$$\boxed{\bar{h}_{avg} = \int_0^L h_x dx / L}$$

26/11/22

Nusselt Number :

$$\frac{Q_{convection}}{Q_{conduction}} = \frac{h \cancel{A} \Delta T}{K \cancel{A} \Delta T / L}$$

$$Nu = \frac{hL}{K}$$



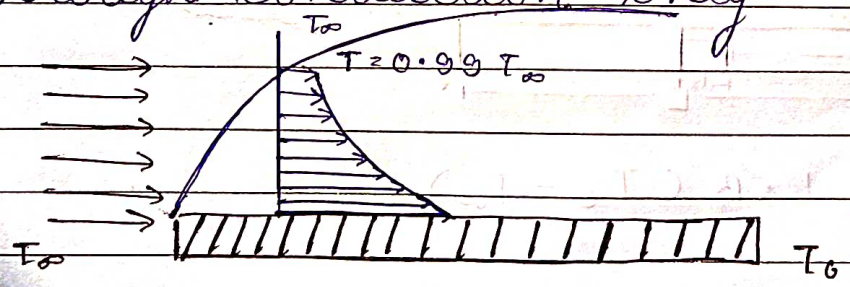
Stationary fluid (conduction) $Q = KA \frac{\Delta T}{L}$

Fluid in motion (convection) $Q = hA\Delta T$

It is defined as ratio of heat convected to the heat conducted for same fluid.

It is always greater than 1.
(For same medium convection is faster than conduction)

Nu = 1 means heat transfer takes place through conduction only



$T_0 > T_\infty$

Thermal boundry layer
The region above plate in which temp. variation or temp. gradient

exist is known as thermal boundary layer. (Temp. difference b/w fluid & plate)

Hydrodynamic boundary layer (due to viscosity in fluid)

Velocity profile $\frac{u}{U}$	δ	$\bar{C}_f$ (average skin friction)
$\frac{u}{U} = \frac{y}{\delta}$	$\frac{3.46x}{\sqrt{Re_x}}$	$\frac{1.155}{\sqrt{Re_L}}$
$\frac{u}{U} = 2\left(\frac{y}{\delta}\right) - \left(\frac{y}{\delta}\right)^2$	$\frac{5.48x}{\sqrt{Re_x}}$	$\frac{1.46}{\sqrt{Re_L}}$
$\frac{u}{U} = \frac{3}{2}\left(\frac{y}{\delta}\right) - \frac{1}{2}\left(\frac{y}{\delta}\right)^3$	$\frac{4.64x}{\sqrt{Re_x}}$	$\frac{1.292}{\sqrt{Re_L}}$
$\frac{u}{U} = \sin\left[\frac{\pi}{2}\frac{y}{\delta}\right]$	$\frac{4.795x}{\sqrt{Re_x}}$	$\frac{1.31}{\sqrt{Re_L}}$
	$5x/\sqrt{Re_x}$	$1.328/\sqrt{Re_L}$

Blasius exact sol^n

$$\frac{5x}{\sqrt{Re_x}} \qquad \frac{1.328}{\sqrt{Re_L}}$$

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

A velocity profile for laminar boundary is given in following form

$$\frac{u}{U} = 2\left(\frac{y}{\delta}\right) - \left(\frac{y}{\delta}\right)^2$$

Find the thickness of boundary layer at end of 1.5 m long & 1 m wide

Date:
Page:

when placed in water flowing with a velocity of 0.12 m/s. Calculate the value of co-efficient of drag. μ: 0.001 Ns/m^2

$$\frac{5.48x}{\sqrt{Re_x}}$$

$$Re = \frac{\rho v D}{\mu}$$

$$= \frac{1000 \times 0.12 \times 1.5}{0.001}$$

$$\sqrt{Re_x} = 424.26$$

$$\frac{5.48 \times 1.5}{424.26}$$

0.01937 m

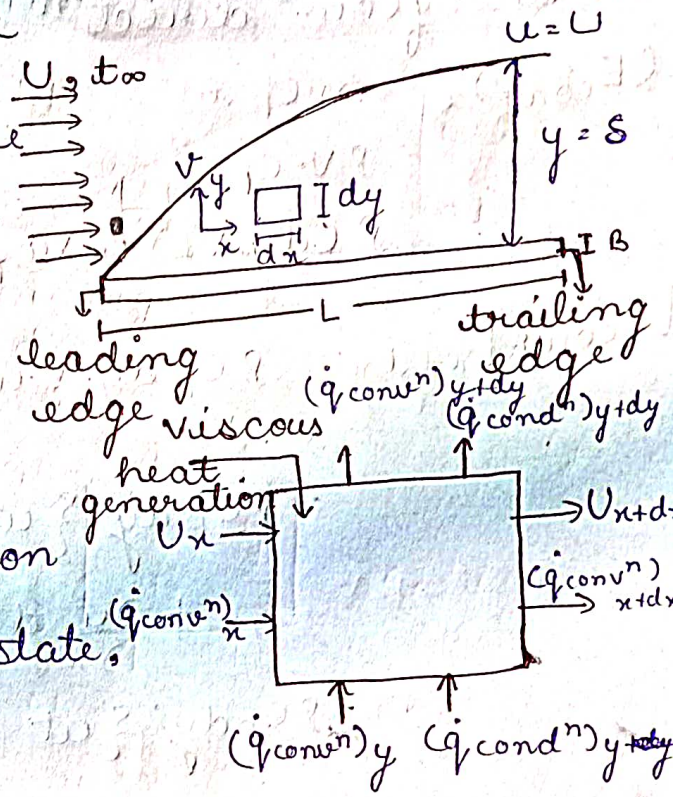
19.37 mm

$$\frac{1.46}{\sqrt{Re_L}}$$

$$\frac{1.46}{424.26}$$

0.00344

Energy equation of thermal boundary layer over flat plate



Consider control volume (dx.dy.1 unit) in the boundary layer so that end effects are negligible. Applying principle of conservation of energy for steady state condition, we have:

$$(E_{conv^n})_x + (E_{conv^n})_y + (E_{cond^n})_y + V.H.G =$$

$$(E_{conv^n})_{x+dx} + (E_{conv^n})_{y+dy} + (E_{cond^n})_{y+dy}$$

$$\{(E_{conv^n})_x - (E_{conv^n})_{x+dx}\} + \{(E_{conv^n})_y - (E_{conv^n})_{y+dy}\} + \{(E_{cond^n})_y - (E_{cond^n})_{y+dy}\} + V.H.G = 0$$

$$d\{(E_{conv^n})_x + (E_{conv^n})_y + (E_{cond^n})_y\} + V.H.G = 0$$

Assumptions:

1. Steady, incompressible flow
2. Properties of fluid evaluated at film temp. $\left(t_f = \frac{t_\infty - t_s}{2}\right)$ are constant.

3. The body forces, viscous heating & cond^n in the flow direct^n is negligible

$$(E_{conv})_x = m C_p t$$
$$= \rho V C_p t$$
$$= \rho (dy \times 1) u \times C_p \times t \quad ---(ii)$$

$$[E_{conv}]_{x+dx} = \rho C_p dy \left\{ u + \frac{\partial u}{\partial x} dx \right\} \left\{ t + \frac{\partial t}{\partial x} dx \right\}$$

$$= \rho C_p dy \left\{ ut + \frac{\partial t}{\partial x} dx \cdot u + \frac{\partial u}{\partial x} dx \cdot t + \frac{\partial u}{\partial x} dx \cdot \frac{\partial t}{\partial x} dx \right\}$$

$$= \rho C_p dy \left\{ ut + u \cdot \frac{\partial t}{\partial x} dx + t \frac{\partial u}{\partial x} dx + O(\text{due to small quantity}) \right\}$$

$$(E_{conv})_x - (E_{conv})_{x+dx} =$$
$$- \rho C_p dy \left\{ u \cdot \frac{\partial t}{\partial x} dx + t \frac{\partial u}{\partial x} dx \right\}$$
$$- \rho C_p dy\, dx \left\{ \frac{\partial t}{\partial x} \cdot u + \frac{\partial u}{\partial x} t \right\} \quad ---\ I$$

$$(E_{conv})_y = m C_p t$$
$$= \rho V C_p t$$
$$= \rho (dx \cdot 1) C_p t u$$
$$= \rho \cdot dx \cdot v \cdot C_p t \quad ---(iii)$$

$$[E_{conv}]_y - [E_{conv}]_{y+dy} = - \rho C_p dx\, dy \left\{ \frac{\partial t}{\partial y} \cdot v + \frac{\partial v}{\partial y} t \right\} \quad ---\ II$$

Adding I & II

$$- \rho C_p dx\, dy \left\{ \frac{\partial t}{\partial x} \cdot u + \frac{\partial u}{\partial x} \cdot t + \frac{\partial t}{\partial y} \cdot v + \frac{\partial v}{\partial y} \cdot t \right\}$$

$$(E_{cond^n})_y = - kA \frac{\partial t}{\partial y}$$
$$= - k\, dx \cdot 1 \frac{\partial t}{\partial y}$$

$$- k\, dx \frac{\partial t}{\partial y}$$

$$(E_{cond^n})_{y+dy} = -k\,(dx \cdot 1)\left[\frac{\partial t}{\partial y} + \frac{\partial}{\partial y}\left\{\frac{\partial t}{\partial y}\right\} dy\right]$$

$$(E_{cond^n})_y - (E_{cond^n})_{y+dy} =$$

$$= -k\,dx\left[\cancel{\frac{\partial t}{\partial y}} - \cancel{\frac{\partial t}{\partial y}} - \frac{\partial^2 t}{\partial y^2} dy\right]$$

$$= +k\,dx \frac{\partial^2 t}{\partial y^2} dy$$

$$= k\,dx \cdot dy \cdot \frac{\partial^2 t}{\partial y^2}$$

Viscous heat generation (V.H.G)

to relative motion of fluid in the boundary layer (fluid on the top phase in moves faster than fluid on bottom phase) there will be viscous effect which will cause generation of heat

$$VHG = \frac{\text{shear stress, } \tau_0 \times \text{Area}}{\text{which it act}} \times \text{distance travelled}$$

$$= \mu \frac{\partial u}{\partial y} \times dx \cdot 1 \times \frac{\partial u}{\partial y} dy$$

$$= \mu \left[\frac{\partial u}{\partial y}\right]^2 dx \cdot dy \quad ---$$

$$-\rho C_p\, dx\, dy \left\{\frac{\partial t}{\partial x} \cdot u + \frac{\partial u}{\partial x} \cdot t\right\} - \rho C_p\, dy\, dx$$

$$\left\{v \cdot \frac{\partial t}{\partial y} + \frac{\partial v}{\partial y} \cdot t\right\} + k\, dx\, dy \cdot \frac{\partial^2 t}{\partial y^2} +$$

$$\mu \left[\frac{\partial u}{\partial y}\right]^2 dx \cdot dy = 0$$

$$-\rho C_p \left\{ u\frac{\partial t}{\partial x} + t\cdot\frac{\partial u}{\partial x} + v\frac{\partial t}{\partial y} + t\cdot\frac{\partial v}{\partial y} \right\} +$$

$$k\frac{\partial^2 t}{\partial y^2} + \mu\left[\frac{\partial u}{\partial y}\right]^2 = 0$$

Continuity eq^n: $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$

$$-\rho C_p \{ u\,\partial t$$

$$u\frac{\partial t}{\partial x} + v\frac{\partial t}{\partial y} = \alpha\frac{\partial^2 t}{\partial y^2} + \frac{\mu}{\rho C_p}\left(\frac{\partial u}{\partial y}\right)^2$$

This eq^n is required differential energy eq^n for flow passed a flat plate. If VHG is neglected (when the value of u is relatively low & difference of temp. b/w free stream & the plate is small) [of the order of 40°C]

$$u\frac{\partial t}{\partial x} + v\frac{\partial t}{\partial y} = \frac{\partial^2 t}{\partial y^2}$$

The energy eq^n is similar to momentum eq^n

Prevost Theory of thermal radiation

Energy emitted by any one of the body is balanced by another body & on another hand if bodies are at 2 different temp. than there is net propogation of thermal radiation from hotter to colder on account of fact that rate of emission from hotter bodies dominate the rate of absorption from incident radiation of neighbouring body.

Thermal radiation

- Theory of propogation of thermal radiation (Clark Maxwell)
- Theory of quantum mechanics (Max Plank)

Electromagnetic wave theory

It states that all bodies in the universe are pervaded by hypothetical ether & species of a given body on account of change in electron configuration on them setup vibration in ether medium which results in continuous electromagnetic waves that travels ~~whe~~ with speed of light & get incident on colder body.

$\mu = \frac{C_0}{C} = 2.9979 \times 10^8 \ m/s$

$\mu = 1$ [for all engineering gas

$\mu = 1.5$ [glass & water]

Max Plank

This theory contradict the clark maxwell theory & stated the propogation of thermal radiation is not continuous but instant. It is discreate in the form of carriers or packets of energy called quanta each quanta of energy is called photon.

$$E = h\nu_0 = h\frac{c_0}{\lambda} \quad \text{---(i)}$$

1 Photon

ν_0 → frequency of radiation (hz)

h = Plank's constant

$= 6.62 \times 10^{-34}$ Js

$E = h\nu_0 = mc^2$ [using Einstein mass energy eq^n] ---(ii)

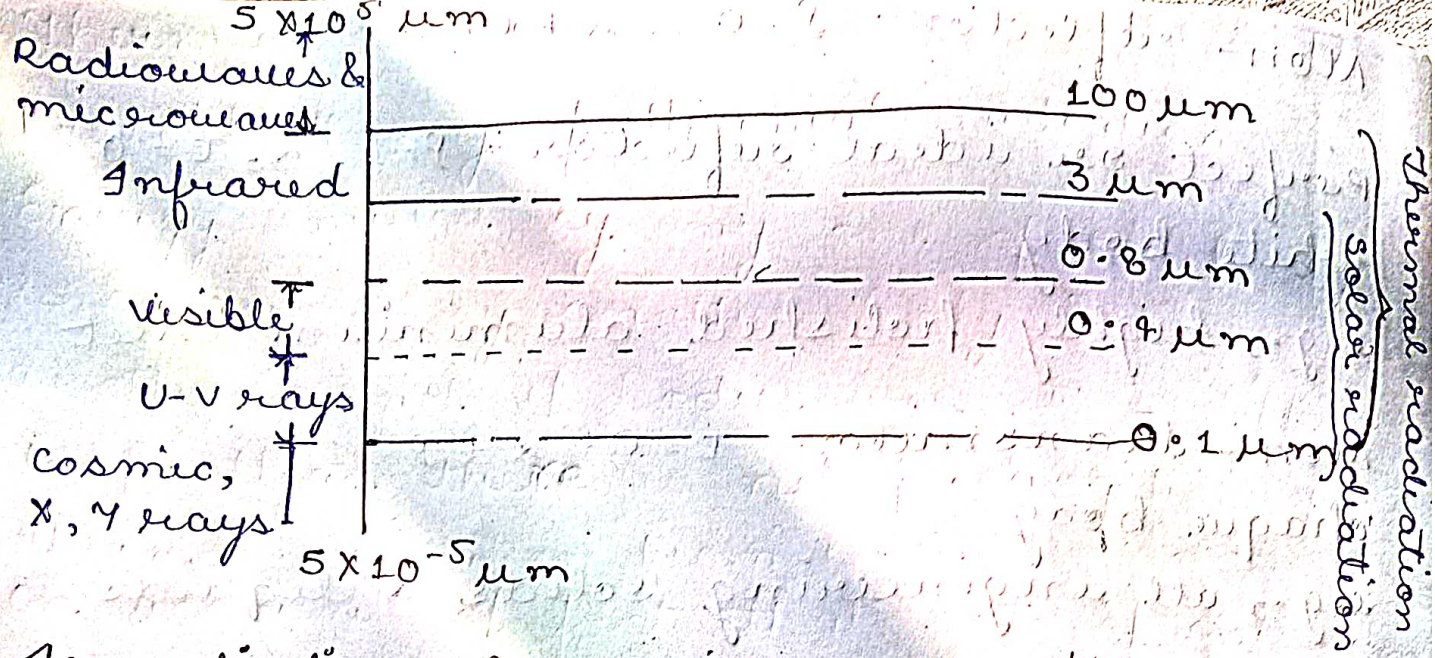
equate (i) & (ii)

$$hc_0/\lambda = mc_0^2$$

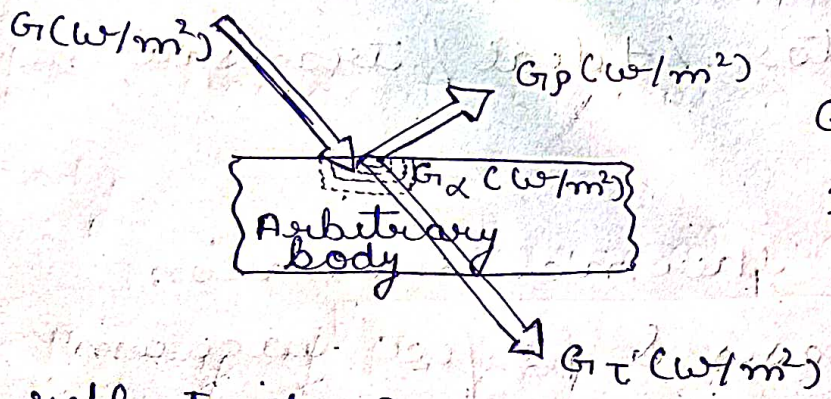
$$\frac{h}{\lambda} = mc$$

$$p = h/\lambda$$

Wavelength spectrum of thermal radiation



Irradiation & Incident radiation



$$G = G_\rho + G_\alpha + G_\tau$$

$$1 = \frac{G_\rho}{G} + \frac{G_\alpha}{G} + \frac{G_\tau}{G}$$

$$0 \leq \alpha, \rho, \tau \leq 1$$

$$\alpha + \rho + \tau = 1$$

reflectivity, ρ

absorbivity, α

transmitivity, τ

Different kind of bodies

1) Black body : $\alpha = 1$; $\rho, \tau = 0$

It is known as perfect absorber

Non-absorber : $\alpha = 0$, $\rho + \tau = 1$

Eg ; lamp black soot → very fine particles of carbon whose dia in micron

$\alpha = 0.99$

Black paint : $\alpha = 0.85$

white paper : It is black body

Crushed ice :

Non-reflector : $\rho = 0$, $\alpha + \tau = 1$

Perfect or ideal reflector : $\rho = 1$, $\alpha, \tau = 0$
white body
e.g., highly polished aluminium sheet

Non-transmitor $\tau = 0$ $\alpha + \rho = 1$
opaque body
e.g., all engineering solids & liquids are opaque

Perfect-transmitor / Ideal / transparent body
$\tau = 1$, $\rho + \alpha = 0$
It transmit all thermal radiation
e.g., all engg. gases & perfect vacuum

Write short notes on spectral or monochromatic emissi power.

Wein's law.
Rayleigh Jeans law.
Max-Plank distribution law.
} statement & relation

Total hemispherical emissipower.

Concept of black body

Prove that total or hemispherical emissipower varies with fourth power of absolute temp. of body

Concept of emissivity & emittance

Kirchoff's law

Prove that total emissive power of diffuse surface is equal to πI → intensity of radiation