UNIT-3 PHASE CHANGE HEAT TRANSFER AND HEAT EXCHANGERS

Part - A

1. What is meant by Boiling and condensation?
The change of phase from liquid to vapour state is known as boiling.
The change of phase from vapour to liquid state is known as condensation.

2. Give the applications of boiling and condensation.
Boiling and condensation process finds wide applications as mentioned below.

1. Thermal and nuclear power plant.
2. Refrigerating systems
3. Process of heating and cooling
4. Air conditioning systems

3. **What is meant by pool boiling?**
If heat is added to a liquid from a submerged solid surface, the boiling process referred to as pool boiling. In this case the liquid above the hot surface is essentially stagnant and its motion near the surface is due to free convection and mixing induced by bubble growth and detachment.

4. What is meant by Film wise and Drop wise condensation?
The liquid condensate wets the solid surface, spreads out and forms a continuous film over the entire surface is known as film wise condensation.
In drop wise condensation the vapour condenses into small liquid droplets of various sizes which fall down the surface in a random fashion.

5. Give the merits of drop wise condensation?
In drop wise condensation, a large portion of the area of the plate is directly exposed to vapour. The heat transfer rate in drop wise condensation is 10 times higher than in film condensation.

6. What is heat exchanger?
A heat exchanger is defined as an equipment which transfers the heat from a hot fluid to a cold fluid.

7. What are the types of heat exchangers?
The types of heat exchangers are as follows

1. Direct contact heat exchangers
2. Indirect contact heat exchangers
3. Surface heat exchangers
4. Parallel flow heat exchangers
5. Counter flow heat exchangers
6. Cross flow heat exchangers
7. Shell and tube heat exchangers
8. Compact heat exchangers.

8. What is meant by Direct heat exchanger (or) open heat exchanger?
In direct contact heat exchanger, the heat exchange takes place by direct mixing of hot and cold fluids.

9. What is meant by Indirect contact heat exchanger?
In this type of heat exchangers, the transfer of heat between two fluids could be carried out by transmission through a wall which separates the two fluids.

10. What is meant by Regenerators?

In this type of heat exchangers, hot and cold fluids flow alternately through the same space. Examples: IC engines, gas turbines.

11. What is meant by Recuperater (or) surface heat exchangers?

This is the most common type of heat exchangers in which the hot and cold fluid do not come into direct contact with each other but are separated by a tube wall or a surface.

12. What is meant by parallel flow and counter flow heat exchanger?

In this type of heat exchanger, hot and cold fluids move in the same direction.

In this type of heat exchanger hot and cold fluids move in parallel but opposite directions.

13. What is meant by shell and tube heat exchanger?

In this type of heat exchanger, one of the fluids move through a bundle of tubes enclosed by a shell. The other fluid is forced through the shell and it moves over the outside surface of the tubes.

14. What is meant by compact heat exchangers?

There are many special purpose heat exchangers called compact heat exchangers. They are generally employed when convective heat transfer coefficient associated with one of the fluids is much smaller than that associated with the other fluid.

15. What is meant by LMTD?

We know that the temperature difference between the hot and cold fluids in the heat exchanger varies from point in addition various modes of heat transfer are involved. Therefore based on concept of appropriate mean temperature difference, also called logarithmic mean temperature difference, also called logarithmic mean temperature difference, the total heat transfer rate in the heat exchanger is expressed as

$Q = U A (\Delta T)m$ Where U – Overall heat transfer coefficient W/m^2K A – Area m^2

$(\Delta T)_m$ – Logarithmic mean temperature difference.

16. What is meant by Fouling factor?

We know the surfaces of a heat exchangers do not remain clean after it has been in use for some time. The surfaces become fouled with scaling or deposits. The effect of these deposits the value of overall heat transfer coefficient. This effect is taken care of by introducing an additional thermal resistance called the fouling resistance.

17. What is meant by effectiveness?

The heat exchanger effectiveness is defined as the ratio of actual heat transfer to the maximum possible heat transfer.

$$\text{Effectiveness } \varepsilon = \frac{\text{Actual heat transfer}}{\text{Maximum possible heat transfer}} = \frac{Q}{Q_{max}}$$

Part-B

1. **Water is boiled at the rate of 24 kg/h in a polished copper pan, 300 mm in diameter, at atmospheric pressure. Assuming nucleate boiling conditions calculate the temperature of the bottom surface of the pan.**

Given :

m = 24 kg / h

$$= \frac{24 \text{ kg}}{3600 \text{ s}}$$

$$\boxed{m = 6.6 \times 10^{-3} \text{kg/s}}$$

d = 300 mm = .3m

Solution:

We know saturation temperature of water is 100°C

i.e. T_{sat} = 100°C

Properties of water at 100°C

From HMT data book Page No.13

Density $\rho l = 961 \text{ kg/m}^3$

Kinematic viscosity $v = 0.293 \times 10^{-6} \text{ m}^2/\text{s}$

Prandtl number $P_r - 1.740$

Specific heat Cpl = 4.216 kj/kg K = 4216 j/kg K

Dynamic viscosity $\mu l = \rho l \times v$

$$= 961 \times 0.293 \times 10^{-6}$$

$$\boxed{\mu L = 281.57 \times 10^{-6} \text{ Ns/m}^2}$$

From steam table (R.S. Khumi Steam table Page No.4)

At 100°C

Enthalpy of evaporation hfg = 2256.9 kj/kg

$$\boxed{hfg = 2256.9 \times 10^3 \text{ j/kg}}$$

Specific volume of vapour

Vg = 1.673 m^3/kg

Density of vapour

$$\rho v = \frac{1}{vg}$$

$$\frac{1}{1.673}$$

$$\boxed{\rho v = 0.597 \ kg/m^3}$$

For nucleate boiling

$$\text{Heat flux } \frac{Q}{A} = \mu l \times hfg \left|\frac{g \times (\rho_l - \rho_v)}{\sigma}\right| \times \left|\frac{Cpl \times \Delta T}{Csf \times hfg P_r^{1.7}}\right|^3$$

We know transferred $Q = m \times hfg$

Heat transferred $Q = m \times hfg$.

$$\frac{Q}{A} = \frac{mhg}{A}$$

$$\frac{Q}{A} = \frac{6.6 \times 10^{-3} \times 2256.9 \times 10^3}{\frac{\pi}{4} d^2}$$

$$= \frac{6.6 \times 10^{-3} \times 2256.9 \times 10^3}{\frac{\pi}{4} (.3)^2}$$

$$\boxed{\frac{Q}{A} = 210 \times 10^3 \ w/m^2}$$

$\sigma =$ surface tension for liquid vapour interface

At 100°C (From HMT data book Page No.147)

$$\boxed{\sigma = 58.8 \times 10^{-3} N/m}$$

For water – copper – Csf = Surface fluid constant = 013

$\boxed{C_{sf} = .013}$ (From HMT data book Page No.145)

Substitute, μl, h_{fg}, ρl, ρv, σ, Cpl, hfg, $\frac{Q}{A}$ and P_r values in Equation (1)

(1) $\Rightarrow \quad 210 \times 10^{3} = 281.57 \times 10^{-6} \times 2256.9 \times 10^{3}$

$$\left|\frac{9.81 \times 961 - 597}{58.8 \times 10^{-3}}\right|^{0.5}$$

$$\left|\frac{4216 \times \Delta T}{.013 \times 2256.9 \times 10^{3} \times (1.74)^{1.7}}\right|^{3}$$

$\Rightarrow \quad \left|\frac{4216 \times \Delta T}{75229.7}\right| = 0.825$

$\Rightarrow \quad \Delta T(.56)^{3} = .825$

$\Rightarrow \quad \Delta T \times .056 = 0.937$

ΔT - 16.7

We know that

Excess temperature $\Delta T = T_{w} - T_{sat}$

$$16.7 = T_{w} - 100°C.$$

$\boxed{T_{w} = 116.7°C}$

2. A nickel wire carrying electric current of 1.5 mm diameter and 50 cm long, is submerged in a water bath which is open to atmospheric pressure. Calculate the voltage at the burn out point, if at this point the wire carries a current of 200A.

Given :

D = 1.5mm = 1.5×10^{-3} m; L = 50 cm = 0.50m; Current I = 200A

Solution

We know saturation temperature of water is 100°C

i.e. T_{sat} = 100°C

Properties of water at 100°C

(From HMT data book Page No.11)

$\rho l = 961 \text{ kg/m}^{3}$

$v = 0.293 \times 10^{-6} \text{ m}^{2}/\text{s}$

P_{r} - 1.740

Cpl = 4.216 kj/kg K = 4216 j/kg K

$\mu l = \rho l \times v = 961 \times 0.293 \times 10^{-6}$

$\mu l = 281.57 \times 10^{-6} \text{ Ns/m}^{2}$

From steam Table at 100°C

R.S. Khurmi Steam table Page No.4

h_{fg} – 2256.9 kj/kg

$h_{fg} = 2256.9 \times 10^3$ j/kg

$v_g = 1.673 m^3/kg$

$$\rho v = \frac{1}{\nu_g} = \frac{1}{1.673} = 0.597 \ kg/m^3$$

σ = Surface tension for liquid – vapour interface

At 100°C

$\sigma = 58.8 \times 10^{-3}$ N/m (From HMT data book Page No.147)

For nucleate pool boiling critical heat flux (AT burn out)

$$\frac{Q}{A} = 0.18 \times h_{fg} \times \rho v \left[\frac{\sigma \times g \times (\rho l - \rho v)}{\rho v^2} \right]^{0.25} ----1$$

(From HMT data book Page No.142)

Substitute h_{fg}, ρl, ρv, σ values in Equation (1)

$$(1) \Rightarrow \frac{Q}{A} = 0.18 \times 2256.9 \times 10^3 \times 0.597$$

$$\left[\frac{58.8 \times 10^{-3} \times 9.81\ (961 - .597)}{.597^2} \right]^{0.25}$$

$$\boxed{\frac{Q}{A} = 1.52 \times 10^6 \ W/m^2}$$

We know

Heat transferred Q = V × I

$$\frac{Q}{A} = \frac{V \times I}{A}$$

$$1.52 \times 10^6 = \frac{V \times 200}{\pi dL} \quad \because A = \pi dL$$

$$1.52 \times 10^6 = \frac{V \times 200}{\pi \times 1.5 \times 10^{-3} \times .50}$$

$$\boxed{V = 17.9 \text{ volts}}$$

3. **Water is boiling on a horizontal tube whose wall temperature is maintained ct 15°C above the saturation temperature of water. Calculate the nucleate boiling heat transfer coefficient. Assume the water to be at a pressure of 20 atm. And also find the change in value of heat transfer coefficient when**

1. **The temperature difference is increased to 30°C at a pressure of 10 atm.**
2. **The pressure is raised to 20 atm at Δ T = 15°C**

Given :

Wall temperature is maintained at 15°C above the saturation temperature.

$T_w = 115°C. \quad \because T_{sat} = 100°C \; T_w = 100 + 15 = 115°C$

= p = 10 atm = 10 bar

case (i)

$\Delta T = 30°C; \; p = 10 \text{ atm} = 10 \text{ bar}$

case (ii)

p = 20 atm = 20 bar; ΔT - 15°C

Solution:

We know that for horizontal surface, heat transfer coefficient

$h = 5.56 (\Delta T)^3$ From HMT data book Page No.128

$h = 5.56 (T_w - T_{sat})^3$

$= 5.56 (115 - 100)^3$

$$\boxed{h = 18765 \text{ w/m}^2\text{K}}$$

Heat transfer coefficient other than atmospheric pressure

$h_p = hp^{0.4}$ From HMT data book Page No.144

$= 18765 \times 10^{0.4}$

$$\text{Heat transfer coefficient } h_p = 47.13 \times 10^3 \, W/m^2K$$

Case (i)

P = 100 bar ΔT = 30°C From HMT data book Page No.144

Heat transfer coefficient

$$h = 5.56\,(\Delta T)^3 = 5.56(30)^3$$

$$h = 150 \times 10^3 \, W/m^2K$$

Heat transfer coefficient other than atmospheric pressure

$h_p = hp^{0.4}$

$$= 150 \times 10^3 (10)^{0.4}$$

$$h_p = 377 \times 10^3 \, W/m^2K$$

Case (ii)

P = 20 bar; ΔT = 15°C

Heat transfer coefficient h = 5.56 $(\Delta T)^3$ = 5.56 $(15)^3$

$$h = 18765 \, W/m^2K$$

Heat transfer coefficient other than atmospheric pressure

$h_p = hp^{0.4}$

= 18765 $(20)^{0.4}$

$$h_p = 62.19 \times 10^3 \, W/m^2K$$

4. **A vertical flat plate in the form of fin is 500m in height and is exposed to steam at atmospheric pressure. If surface of the plate is maintained at 60°C. calculate the following.**

1**. The film thickness at the trailing edge**

2. Overall heat transfer coefficient

3. Heat transfer rate

4. The condensate mass flow rate.

Assume laminar flow conditions and unit width of the plate.

Given :

Height ore length L = 500 mm = 5m

Surface temperature T^{w} = 60°C

Solution

We know saturation temperature of water is 100°C

i.e. T_{sat} = 100°C

(From R.S. Khurmi steam table Page No.4

h_{fg} = 2256.9kj/kg

$h_{fg} = 2256.9 \times 10^3$ j/kg

We know

$$\text{Film temperature } T_f = \frac{T_w + T_{sat}}{2}$$

$$= \frac{60 + 100}{2}$$

$$\boxed{T_f = 80°C}$$

Properties of saturated water at 80°C

(From HMT data book Page No.13)

ρ - 974 kg/m^3

$v = 0.364 \times 10^{-6}\ m^2/s$

$k = 668.7 \times 10^{-3} W/mk$

$\mu = p \times v = 974 \times 0.364 \times 10^{-6}$

$\mu = 354.53 \times 10^{-6} Ns/m^2$

1. Film thickness δ_x

We know for vertical plate

Film thickness

$$\delta x = \left(\frac{4 \mu K \times x \times (T_{sat} - T_w)}{g \times h_{fg} \times \rho^2} \right)^{0.25}$$

Where

X = L = 0.5 m

$$\delta_x = \frac{4 \times 354.53 \times 10^{-6} \times 668.7 \times 10^{-3} \times 0.5 \times 100 - 60}{9.81 \times 2256.9 \times 10^3 \times 974^2}$$

$$\delta_x = 1.73 \times 10^{-4} m$$

2. Average heat transfer coefficient (h)

For vertical surface Laminar flow

$$h = 0.943 \left[\frac{k_3 \times \rho^2 \times g \times h_{fg}}{\mu \times L \times T_{sat} - T_w} \right]^{0.25}$$

The factor 0.943 may be replace by 1.13 for more accurate result as suggested by Mc Adams

$$1.13 \left(\frac{(668.7 \times 10^{-3})^3 \times (974)^2 \times 9.81 \times 2256.9 \times 10^3}{354.53 \times 10^{-6} \times 1.5 \times 100 - 60} \right)^{0.25}$$

$$h = 6164.3 \ W/m^2 k.$$

3. Heat transfer rate Q

We know

$$Q = hA(T_{sat} - T_w)$$

$$= h \times L \times W \times (T_{sat} - T_w)$$

$$= 6164.3 \times 0.5 \times 1 \times 100\text{-}60$$

$$\boxed{Q = 123286 \text{ W}}$$

4. Condensate mass flow rate m

We know

$$Q = m \times h_{fg}$$

$$m = \frac{Q}{h_{fg}}$$

$$m = \frac{1.23.286}{2256.9 \times 10^3}$$

$$\boxed{m = 0.054 \text{ kg/s}}$$

5. Steam at 0.080 bar is arranged to condense over a 50 cm square vertical plate. The surface temperature is maintained at 20°C. Calculate the following.

a. **Film thickness at a distance of 25 cm from the top of the plate.**
b. **Local heat transfer coefficient at a distance of 25 cm from the top of the plate.**
c. **Average heat transfer coefficient.**
d. **Total heat transfer**
e. **Total steam condensation rate.**
f. **What would be the heat transfer coefficient if the plate is inclined at 30°C with horizontal plane.**

Given :

Pressure P = 0.080 bar

Area A = 50 cm × 50 cm = 50 × 050 = 0.25 m^2

Surface temperature T_w = 20°C

Distance x = 25 cm = .25 m

Solution

Properties of steam at 0.080 bar

(From R.S. Khurmi steam table Page no.7)

$T_{satj/kg} = 41.53°C$

$h_{fg} = 2403.2kj/kg = 2403.2 \times 10^{3} j/kg$

We know

$$\text{Film temperature } T_f = \frac{T_w + T_{sat}}{2}$$

$$= \frac{20+41.53}{2}$$

$$\boxed{T_f = 30.76°C}$$

Properties of saturated water at 30.76°C = 30°C

From HMT data book Page No.13

$\rho - 997 \ kg/m^3$

$\nu = 0.83 \times 10^{-6} \ m^2/s$

$k = 612 \times 10^{-3} W/mK$

$\mu = p \times v = 997 \times 0.83 \times 10^{-6}$

$\mu = 827.51 \times 10^{-6} Ns/m^2$

a. Film thickness

We know for vertical surfaces

$$\delta x = \left(\frac{4\mu K \times x \times (T_{sat} - T_w)}{g \times h_{fg} \times \rho^2} \right)^{0.25}$$

(From HMT data book Page No.150)

$$\delta_x = \frac{4 \times 827.51 \times 10^{-6} \times 612 \times 10^{-3} \times .25 \times (41.53 - 20)100}{9.81 \times 2403.2 \times 10^3 \times 997^2}$$

$$\delta_x = 1.40 \times 10^4 m$$

b. Local heat transfer coefficient h_x Assuming Laminar flow

$$h_x = \frac{k}{\delta x}$$

$$h_x = \frac{612 \times 10^{-3}}{1.46 \times 10^{-4}}$$

$$\boxed{hx = 4{,}191\ W/m^2K}$$

c. Average heat transfer coefficient h

(Assuming laminar flow)

$$h = 0.943 \left[\frac{k^3 \times \rho^2 \times g \times h_{fg}}{\mu \times L \times T_{sat} - T_w} \right]^{0.25}$$

The factor 0.943 may be replaced by 1.13 for more accurate result as suggested by Mc adams

$$h = 0.943 \left[\frac{k^3 \rho^2 g\ h_{fg}}{\mu \times L \times T_{sat} - T_w} \right]^{0.25}$$

Where L = 50 cm = .5 m

$$h = 1.13 \left| \frac{(612 \times 10^{-3})^3 \times (997)^2 \times 9.81 \times 2403.2 \times 10^3}{827.51 \times 10^{-6} \times .5 \times 41.53 - 20} \right|^{0.25}$$

$$h = 5599.6\ W/m^2k$$

d. Heat transfer (Q)

We know

$Q = hA(T_{sat} - T_w)$

$h \times A \times (T_{sat} - T_w)$

$= 5599.6 \times 0.25 \times (41.53 - 20$

$Q = 30.139.8\ W$

e. Total steam condensation rate (m)

We know

Heat transfer

$Q = m \times h_{fg}$

$$m = \frac{Q}{h_{fg}}$$

$$m = \frac{30.139.8}{2403.2 \times 103}$$

$m = 0.0125\ kg/s$

f. If the plate is inclined at θ with horizontal

$h_{inclined} = h_{vertical} \times \sin\theta^{1/4}$

$h_{inclined} = h_{vertical} \times (\sin 30)^{1/4}$

$h_{inclined} = 5599.6 \times \left(\frac{1}{2}\right)^{1/4}$

$h_{inclined} = 4.708.6\ W/m^2k$

Let us check the assumption of laminar film condensation

We know

$$\text{Reynolds Number } R_e = \frac{4m}{w\mu}$$

where

W = width of the plate = 50cm = .50m

$$R_e = \frac{4 \times .0125}{0.50 \times 827.51 \times 10^{-6}}$$

$$R_e = 120.8 < 1800$$

So our assumption laminar flow is correct.

6. A condenser is to designed to condense 600 kg/h of dry saturated steam at a pressure of 0.12 bar. A square array of 400 tubes, each of 8 mm diameter is to be used. The tube surface is maintained at 30°C. Calculate the heat transfer coefficient and the length of each tube.

Given :

$$m = 600 \text{ kg/h} = \frac{600}{3600} \text{kg/s} = 0.166 \text{ kg/s}$$

$$m = 0.166 \text{ kg/s}$$

Pressure P – 0.12 bar   No. of tubes = 400

$$\text{Diameter } D = 8mm = 8 \times 10^{-3} m$$

$$\text{Surface temperature } T_w = 30°C$$

Solution

Properties of steam at 0.12 bar   From R.S. Khurmi steam table Page No.7

$$T_{sat} = 49.45°C$$

$$h_{fg} = 2384.3 \text{ kj/kg}$$

$$h_{fg} = 2384.9 \times 10^3 \text{ j/kg}$$

We know

$$\text{Film temperature } T_f = \frac{T_w + T_{sat}}{2}$$

$$= \frac{30 + 49.45}{2}$$

$$T_f = 39.72°C = 40°C$$

Properties of saturated water at 40°C

From HMT data book Page No.13

ρ - 995 kg/m^3

$\nu = .657 \times 10^{-6}$ m^2/s

k = 628.7×10^{-3} W/mk

$\mu = \rho \times \nu = 995 \times 0.657 \times 10^{-6}$

$\mu = 653.7 \times 10^{-6}$ Ns/m^2

with 400 tubes a 20 × 20 tube of square array could be formed

i.e. $N = \sqrt{400} = 20$

N = 20

For horizontal bank of tubes heat transfer coefficient.

$$h = 0.728 \left[\frac{K^3 \rho^2 g\ h^{fg}}{\mu\ D\ (T_{sat} - T_w)} \right]^{0.25}$$

From HMT data book Page No.150

$$h = 0.728 \left[\frac{(628 \times 10^{-3})^3 \times (995)^2 \times 9.81 \times 2384.3 \times 10^3}{653.7 \times 10^{-6} \times 20 \times 8 \times 10^{-3} \times (49.45 - 30)} \right]^{0.25}$$

h = 5304.75 W/m^{2}K

We know

Heat transfer

$Q = hA(T_{sat} - T_w)$

No. of tubes = 400

$Q = 400 \times h \times \pi \times D \times L \times (T_{sat} - T_w)$

$Q = 400 \times 5304.75 \times \pi \times 8 \times 10^{-3} \times 1\ (49.45\text{-}30)$

$Q = 1.05 \times 10^6 \times L$........1

We know

$Q = m \times h_{fg}$

$= 0.166 \times 2384.3 \times 103$

$Q = 0.3957 \times 10^6$ W

$= 0.3957 \times 10^6 = 1.05 \times 10^6 L$

L = 0.37 m

Problems on Parallel flow and Counter flow heat exchangers

From HMT data book Page No.135

Formulae used

1. Heat transfer $Q = UA\,(\Delta T)_m$

Where

U – Overall heat transfer coefficient, W/m^2K

A – Area, m^2

$(\Delta T)_m$ – Logarithmic Mean Temperature Difference. LMTD

For parallel flow

$$(\Delta T)_m = \frac{(T_1 - t_1) - (T_2 - t_2)}{\ln\left[\dfrac{T_1 - t_1}{T_2 - t_2}\right]}$$

In Counter flow

$$(\Delta T)_m = \frac{(T_1 - t_1) - (T_2 - t_2)}{\ln\left[\dfrac{T_1 - t_1}{T_2 - t_2}\right]}$$

Where

T_1 – Entry temperature of hot fluid °C T_2 – Exit temperature of hot fluid °C

T_1 – Entry temperature of cold fluid °C T_2 – Exit temperature of cold fluid °C

2. Heat lost by hot fluid = Heat gained by cold fluid

$$\mathbf{Q_h = Q_c}$$

$$m_h C_{ph} (T_1 - T_2) = m_c C_{pc} (t_2 - t_1)$$

M_h – Mass flow rate of hot fluid, kg/s

M_c – Mass flow rate of cold fluid kg/s

C_{ph} – Specific heat of hot fluid J/kg K

C_{pc} – Specific heat of cold fluid J/kg L

3. Surface area of tube

$A = \pi D_1 L$

Where D_1 Inner din

4. $\mathbf{Q = m \times h_{fg}}$

Where h_{fg} – Enthalpy of evaporation j/kg K

5. Mass flow rate

$m = \rho AC$