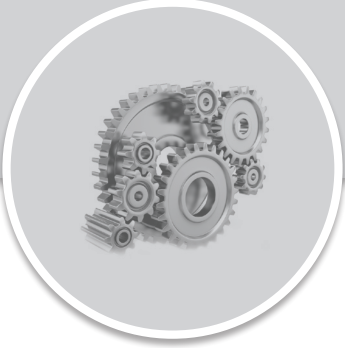
MECHANICAL ENGINEERING

Heat Transfer



Comprehensive Theory
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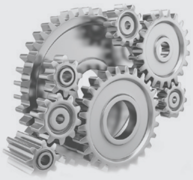

EDITIONS

First Edition : 2015
Second Edition : 2016
Third Edition : 2017
Fourth Edition : 2018
Fifth Edition : 2019
Sixth Edition : 2020
Seventh Edition : 2021
Eighth Edition : 2022
Ninth Edition : 2023

Tenth Edition : 2024

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CHAPTER

3

Steady-State Conduction with Internal Heat Generation

3.1 INTRODUCTION

A medium through which heat is conducted may involve the conversion of electrical, nuclear, or chemical energy into heat (or thermal) energy. In heat conduction analysis, such conversion processes are characterized as heat generation. For example, the temperature of a resistance wire rises rapidly when electric current passes through it as a result of the electrical energy being converted to heat at a rate of I^2R, where I is the current and R is the electrical resistance of the wire. The safe and effective removal of this heat away from the sites of heat generation (the electronic circuits) is the subject of electronics cooling, which is one of the modern application areas of heat transfer. Likewise, a large amount of heat is generated in the fuel elements of nuclear reactors as a result of nuclear fission.

Note that the heat generation is a volumetric phenomenon. That is, it occurs throughout the body of a medium. Therefore, the rate of heat generation in a medium is usually specified per unit volume and is denoted by $\dot{q}_g$ whose unit is W/m^3.

The rate of heat generation has to be controlld one; otherwise the resulting temperature growth might result in the failure of the medium. Undoubtedly temperature distribution within the medium and the rate of heat dissipation to the surrounding assume great important in the design of thermal units.

3.2 PLANE WALL WITH INTERNAL HEAT GENERATION

Let us consider a slab of thickness L, in the region $0 \le x \le L$, and of uniform thermal conductivity k. Let an electrical current passes through the slab causing a uniform heat generation of $\dot{q}_g$(W/m^3). The temperature on the two faces of the slab, T_w, will be the same because it loses the same amount of heat by convection on two sides.

Consider an element of thickness dx and cross-sectional area A.

Heat conducted in at x, $\qquad \dot{Q}_x = -kA\dfrac{dT}{dx}$

Heat conducted out at $x + dx$, $\qquad \dot{Q}_{x+dx} = -kA\dfrac{dT}{dx} - kA\dfrac{d^2T}{dx^2}dx$

Heat generated within dx, $\qquad \dot{Q}_g = \dot{q}_g A\,dx$

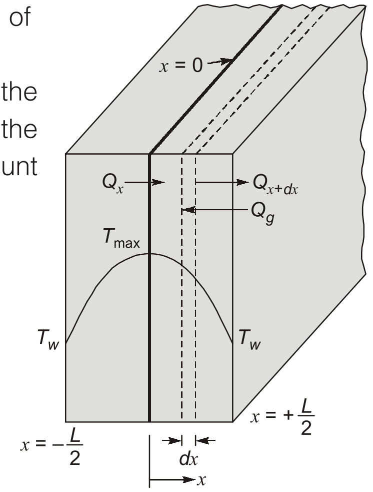


Figure: Slab with Uniform Heat Generation

As $\dot{Q}_g$ represents an energy increase in the volume element, an energy balance on the element of thickness dx yields.

$$\dot{Q}_x + \dot{Q}_g = \dot{Q}_{x+dx} \qquad \text{...(3.1)}$$

or
$$-kA\frac{dT}{dx} + \dot{q}_g A\,dx = -kA\frac{dT}{dx} - kA\frac{d^2T}{dx^2}dx$$

$\Rightarrow$
$$\frac{d^2T}{dx^2} + \frac{\dot{q}_g}{k} = 0 \qquad \text{...(3.2)}$$

The first and second integration of Equation (3.2) gives respectively

$$\frac{dT}{dx} = \frac{-\dot{q}_g}{k}x + C_1 \qquad \text{...(3.3)}$$

$$T = -\frac{1}{2}\frac{\dot{q}_g}{k}x^2 + C_1 x + C_2 \qquad \text{...(3.4)}$$

Applying boundary conditions

at, $x = 0,\ \frac{dT}{dx} = 0$ and $kA\frac{dT}{dx}\Big|_{x=-\frac{L}{2}} = -kA\frac{dT}{dx}\Big|_{x=\frac{+L}{2}} = \frac{1}{2}\left(\dot{q}_g AL\right)$ ...(3.5)

and $x = \frac{L}{2}$ $\quad T = T_w$ ...(3.6)

Using the boundary condition ($x = 0$, $\frac{dT}{dx} = 0$ in Equation (3.3), we get $\quad C_1 = 0$

Thus
$$T = \frac{\dot{q}_g x^2}{2k} + C_2$$

Now using the boundary condition (3.6), $T = T_w$ at $x = \frac{L}{2}$, we get $\quad C_2 = T_w + \frac{\dot{q}_g L^2}{8k}$
Resulting in the following temperature distribution :

$$T = T_w + \frac{\dot{q}_g}{8k}\left(L^2 - 4x^2\right) \qquad \text{...(3.7)}$$

The maximum temperature, $T_{\max}$, at the centre line is obtained by putting $x = 0$ in Equation (3.7)

$$T_{\max} = T_w + \frac{\dot{q}_g L^2}{8k} \qquad \text{...(3.8)}$$

The heat flow rate,
$$Q = -kA\frac{dT}{dx}\Big|_{x=\frac{L}{2}} = -kA\left(\frac{-\dot{q}_g}{8k}\cdot\frac{8L}{2}\right) = \frac{1}{2}\dot{q}_g AL$$

If the ambient temperature is T_∞ and the heat transfer coefficient is h, then at face, $x = \frac{L}{2}$

OBJECTIVE BRAIN TEASERS

1. Heat is generated in a 0.3 cm diameter cylindrical electric heater at a rate of 150 W/cm^3. The heat flux at the surface of the heater in steady operation is_____ W/cm^2. [Correct upto 1 decimal place]

2. Heat is generated uniformly in a 4 cm diameter, 16 cm long solid bar (k = 2.4 W/m°C). The temperature at the center and at the surface of the bar are measured to be 210°C and 45°C, respectively. The rate of heat generation within the bar at steady state is_____ W. [Round off to nearest integer]

3. Hot water flows through a PVC (k = 0.092 W/mK) pipe whose inner diameter is 2 cm and outer diameter is 2.5 cm. If the temperature of the interior surface of this pipe is 15°C more than outer surface, then rate of heat transfer per unit of pipe length is
   (a) 22.8 W/m (b) 38.9 W/m
   (c) 48.7 W/m (d) 63.6 W/m

4. Heat is generated in a 8 cm diameter spherical radioactive material whose thermal conductivity is 25 W/m°C uniformly at a rate of 15 × 10^6 W/m^3. If the surface temperature of the material is measured to be 120°C, then the center temperature of the material during steady operation is______°C. [Round off to nearest integer]

5. Harvested grains, like wheat, undergo a volumetric exothermic reaction while they are being stored. This heat generation causes these grains to spoil or even start fire if not controlled properly. Wheat (k = 0.5 W/mK) is stored on the ground (effectively an adiabatic surface) in 5 m thick layers. Air at 20°C contacts the upper surface of this layer of wheat with h = 3 W/m^{2}K. The temperature distribution inside this layer is given by
$$\frac{T-T_s}{T_0-T_s} = 1-\left(\frac{x}{L}\right)^2$$
where T_s is the upper surface temperature, T_0 is the lower surface temperature, x is measured upwards from the ground, and L is the thickness of the layer. When the temperature of the upward surface is 24°C, what is the temperature of the wheat next to the ground?
   (a) 39°C (b) 51°C
   (c) 72°C (d) 84°C

6. A solar heat flux $\dot{q}_s$ is incident on a sidewall whose thermal conductivity is k, solar absorptivity is α_s, and convective heat transfer coefficient is h. Taking the positive x direction to be towards the sky and disregarding radiation exchange with the surroundings surface, the correct boundary condition for this sidewall surface is
   (a) $-k\dfrac{dT}{dx} = \alpha_s \dot{q}_s$
   (b) $-k\dfrac{dT}{dx} = h(T-T_\infty)$
   (c) $-k\dfrac{dT}{dx} = h(T-T_\infty) = \alpha_s \dot{q}_s$
   (d) $h(T-T_\infty) = \alpha_s \dot{q}_s$

7. Which one of the following is the correct expression for one-dimensional, steady-state, constant thermal conductivity heat conduction equation for a cylinder with heat generation?
   (a) $\dfrac{1}{r}\dfrac{\partial}{\partial r}\left(rk\dfrac{\partial T}{\partial r}\right) + \dot{q}_{gen} = \rho c\dfrac{\partial T}{\partial t}$
   (b) $\dfrac{1}{r}\dfrac{\partial}{\partial r}\left(r\dfrac{\partial T}{\partial r}\right) + \dfrac{\dot{q}_{gen}}{k} = \dfrac{1}{\alpha}\dfrac{\partial T}{\partial t}$
   (c) $\dfrac{1}{r}\dfrac{\partial}{\partial r}\left(r\dfrac{\partial T}{\partial r}\right) = \dfrac{1}{\alpha}\dfrac{\partial T}{\partial t}$
   (d) $\dfrac{1}{r}\dfrac{\partial}{\partial r}\left(r\dfrac{dT}{dr}\right) + \dfrac{\dot{q}_{gen}}{k} = 0$

■■■■

ANSWER KEY

1. (11.3) 2. (796) 3. (b) 4. (280)
5. (d) 6. (c) 7. (d)

$$\frac{dT}{dx} = 0 + (T_0 - T_s)\left\{0 - \frac{2x}{L^2}\right\}$$

$$\left(\frac{dT}{dx}\right)_{x=L} = (T_0 - T_s)\left\{0 - \frac{2 \cdot L}{L^2}\right\}$$

$$= \frac{(T_s - T_0) \cdot 2}{L}$$

$$Q_{\text{conducted}} = Q_{\text{convected}}$$

$$-k \times \left.\frac{dT}{dx}\right|_{x=L} = 12$$

$$\frac{-0.5 \times [T_s - T_0] \times 2}{5} = 12$$

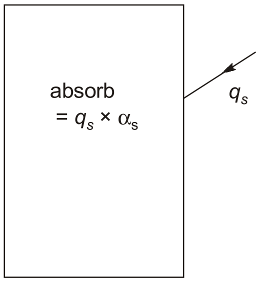
$$\frac{-0.5 \times [24 - T_0] \times 2}{5} = 12$$

$$24 - T_0 = \frac{-5 \times 12}{2 \times 0.5}$$

$$24 - T_0 = -60$$

$$T_0 = 24 + 60 = 84°\text{C}$$

6. (c)



$$\therefore \quad q_s \alpha_s = h(T - T_\infty) = \frac{-k \times dT}{dx}$$

Total heat absorbed will be conducted to the other end and then will be convected to surrounding.

7. (d)

$$\frac{1}{r} \cdot \frac{d}{dr} \cdot \left\{r \cdot \frac{dT}{dr}\right\} + \frac{q_G}{k} = 0$$

$$\frac{1}{r} \cdot \frac{d}{dr}\left\{r \cdot \frac{dT}{dr}\right\} + \frac{e_{\text{gen}}}{k} = 0$$

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CONVENTIONAL BRAIN TEASERS

Q.1 A copper conductor having inner and outer radii 1.5 cm and 2.5 cm respectively is carrying a current density of 4800 amperes/cm^2. The conductor is internally cooled and a constant temperature of 75°C is maintained at the inner surface and there is no heat transfer through insulation surrounding the conductor. Determine:

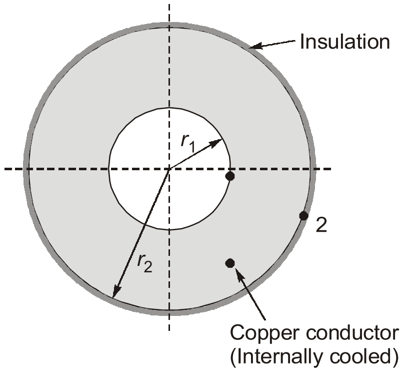
(i) The maximum temperature of the conductor and the radius at which it occurs.

(ii) The internal heat transfer rate per unit length.

For copper conductor, Take $k = 380$ W/mK and resistivity, $\rho = 2 \times 10^{-8}\ \Omega$ m.

Solution:

Given: $r_1 = 1.5$ cm, $r_2 = 2.5$ cm, Current density, $J = 4800$ amp/cm^2, $k = 380$ W/mK, $\rho = 2 \times 10^{-8}\ \Omega$m, $t_1 = 75°$C.



CHAPTER

10

Boiling and Condensation

10.1 INTRODUCTION

Thermodynamics states that when the temperature of a liquid at a specified pressure is raised to the saturation temperature, T_{sat} at that pressure, boiling occurs. Likewise when the temperature of a vapour is lowered to T_{sat}, condenstion occurs.

In this chapter, we focus on convection processes associated with the change in phase of a fluid. In particular, we consider processes that can occur at a solid–liquid or solid–vapor interface, namely, boiling and condensation. For these cases, latent heat effects associated with the phase change are significant. The change from the liquid to the vapor state due to boiling is sustained by heat transfer from the solid surface; conversely, condensation of a vapor to the liquid state results in heat transfer to the solid surface.

Since they involve fluid motion, boiling and condensation are classified as forms of the convection mode of heat transfer. However, they are characterized by unique features. Because there is a phase change, heat transfer to or from the fluid can occur without influencing the fluid temperature. In fact, through boiling or condensation, large heat transfer rates may be achieved with small temperature differences. In addition to the latent heat h_{fg}, two other parameters are important in characterizing the processes, namely, the surface tension σ at the liquid–vapor interface and the density difference between the two phases. This density difference induces a buoyancy force, which is proportional to $(\rho_l - \rho_v)$. Because of combined latent heat and buoyancy-driven flow effects, boiling and condensation heat transfer coefficients and rates are generally much larger than those characteristic of convection heat transfer without phase change.

Evaporation occurs at the liquid-vapor interface when the vapor pressure is less than the saturation pressure of the liquid at a given temperature.

Boiling, on the other hand, occurs at the solid-liquid interface when a liquid is brought into contact with a surface maintained at a temperature T_s sufficiently above the saturation temperature T_{sat}, of the liquid.

Heat transfer coefficients 'h' associated with boiling and condensation are typically much higher than those encountered in other forms of convection processes that involve a single phase.

At 1 atm, for example, liquid water in contact with a solid surface at 110°C boils

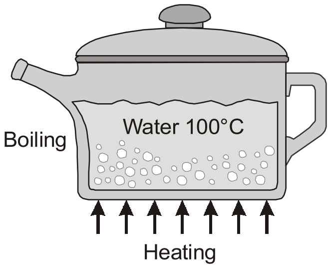


Figure: Boiling Heat Transfer

EXAMPLE : 10.6

Hot coffee in a cup is allowed to cool. Its cooling rate is measured and found to be greater than the value calculated by conduction, convection and radiation measurement. The difference is due to

(a) properties of coffee changing with temperature
(b) currents of air flow in the room
(c) underestimation of the emissivity of coffee
(d) evaporation

Solution: (d)

Hot coffee in a cup is allowed to cool. While measuring its cooling rate evaporation is considered so its value is greater than the value calculated by conduction, convection and radiation.

EXAMPLE : 10.7

Consider the following statements:

If a surface is pockmarked with a number of cavities, then as compared to a smooth surface

1. radiation will increase.
2. nucleate boiling will increase.
3. conduction will increase.
4. convection will increase.

Which of these statements are correct?

(a) 1, 2 and 3
(b) 1, 2 and 4
(c) 1, 3 and 4
(d) 2, 3 and 4

Solution: (b)

Radiation will increase $Q \propto A$, surface convection will increase $Q \propto A$, surface nucleate boiling will increase as pocket will be the favourable sites for onset of nucleation.

EXAMPLE : 10.8

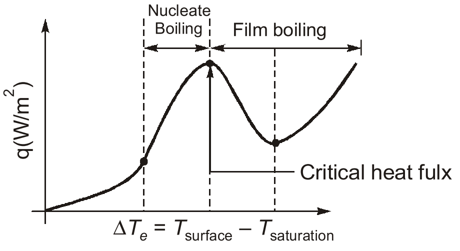
Assertion (A): If the excess temperature in pool boiling over a horizontal surface is increased above the value corresponding to the critical heat flux, the temperature difference between the surface and liquid increases but heat flux decreases sharply.

Reason (R): With increasing excess temperature beyond the value corresponding to the critical heat flux, a stage is reached when the rate of formation of bubbles is so high that they start to coalesce and blanket the surface with a vapour film.

(a) Both A and R are individually true and R is the correct explanation of A
(b) Both A and R are individually true but R is not the correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

Solution: (a)

The trend of increase of heat flux with increase in excess temperature is observed upto critical heat flux point only. This is due to the fact that the bubble formation is very rapid and the bubbles blanket the heating surface and prevent the incoming fresh liquid from taking their place.



10.2.2 Flow Boiling

In *flow boiling*, the fluid is forced to move by an external source such as a pump as it undergoes a phase-change process. The boiling in this case exhibits the combined effects of convection and pool boiling. The flow boiling is classified as *external* and *internal flow* boiling depending on whether the fluid is forced to flow over a heated surface or inside a heated tube.

External flow boiling over a plate or cylinder is similar to pool boiling, but the added motion increases both the nucleate boiling heat flux and the critical heat flux considerably, as shown in figure below.

Internal flow boiling is much more complicated in nature because there is no free surface for the vapor to escape, and thus both the liquid and the vapor are forced to flow together. The two-phase flow in a tube exhibits different flow boiling regimes, depending on the relative amounts of the liquid and the vapor phases. This complicates the analysis even further.

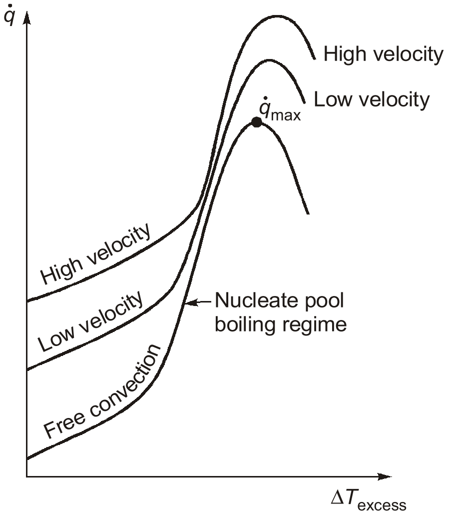


Figure: The effect of forced convection on external flow boiling for different flow velocities

The different stages encountered in flow boiling in a heated tube are shown in figure below together with the variation of the heat transfer coefficient along the tube.

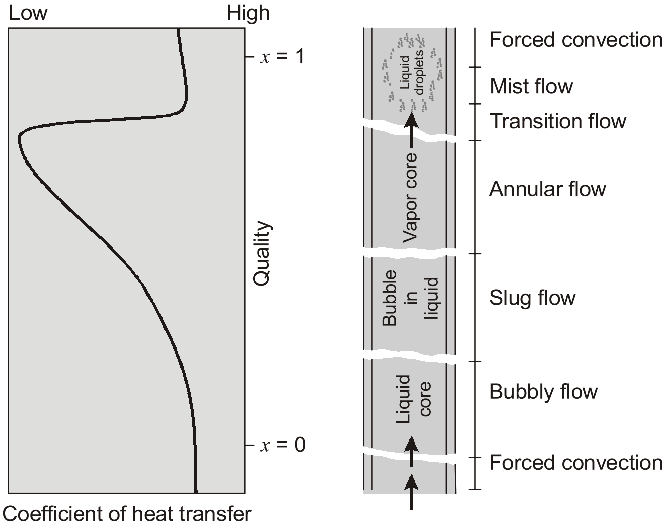


Figure: Different flow regimes encountered in flow boiling in a tube under forced convection

- Initially, the liquid is subcooled and heat transfer to the liquid is by *forced convection* (assuming no subcooled boiling). Then bubbles start forming on the inner surface of the tube, and the detached bubbles are drafted into the mainstream. This gives the fluid flow a bubbly appearance, and thus the name *bubbly flow regime*.
- As the fluid is heated further, the bubbles grow in size and eventually coalesce into slugs of vapor. Up to half of the volume of the tube in this *slug-flow regime* is occupied by vapor.
- After a while the core of the flow consists of vapor only, and the liquid is confined only in the annular space between the vapor core and the tube walls.

  This is the *annular-flow regime*, and very high heat transfer coefficients are realized in this regime.
- As the heating continues, the annular liquid layer gets thinner and thinner, and eventually dry spots start to appear on the inner surfaces of the tube. The appearance of dry spots is accompanied by a sharp decrease in the heat transfer coefficient. This *transition regime* continues until the inner surface of the tube is completely dry.

- Any liquid at this moment is in the form of droplets suspended in the vapor core, which resembles a mist, and we have a mist-flow regime until all the liquid droplets are vaporized.
- At the end of the mist-flow regime we have saturated vapor, which becomes superheated with any further heat transfer.

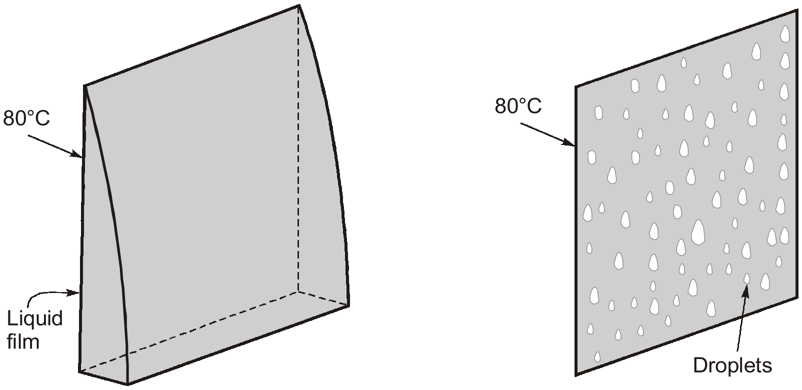
10.3 CONDENSATION HEAT TRANSFER

Condensation occurs when the temperature of a vapor is reduced *below* its saturation temperature T_{sat}. This is usually done by bringing the vapor into contact with a solid surface whose temperature T_s is *below* the saturation temperature T_{sat} of the vapor. But condensation can also occur on the free surface of a liquid or even in a gas when the temperature of the liquid or the gas to which the vapour is exposed is below T_{sat}. In the latter case, the liquid droplets suspended in the gas form a fog.

Two distinct forms of condensation observed are *film condensation* and *dropwise condensation. In* ***film condensation*** *condensation*, the condensate wets the surface and forms a liquid film on the surface that slides down under the influence of gravity. The thickness of the liquid film increases in the flow direction as more vapor condenses on the film. This is how condensation normally occurs in practice.

- **Dropwise condensation**, characterized by countless droplets of varying diameters on the condensing surface instead of continuous liquid film, is one of the most effective mechanisms of heat transfer and extremely large heat transfer coefficient can be achieved by this mechanism.

  In dropwise condensation, the small droplets that form at the nucleation sites on the surface grow as a result of continued condensation, coalesce into large droplets, and slide down when they reach a certain size. Clearing the surface and exposing it to vapour. There is no liquid film in this case to resist heat transfer. As a result, with dropwise condensation, heat transfer coefficient can be achieved that are more than 10 times larger than those associated with film condensation.



(a) Film condensation (b) Dropwise condensation

Figure: When a vapor is exposed to a surface at a temperature below T_{sat}, condensation in the form of a liquid film or individual droplets.

EXAMPLE : 10.9

Assertion (A): Dropwise condensation is associated with higher heat transfer rate as compared to the heat transfer rate in film condensation.

Reason (R): In drop condensation there is free surface through which direct heat transfer takes place.

(a) Both A and R are individually true and R is the correct explanation of A
(b) Both A and R are individually true but R is not the correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

Solution: (a)

EXAMPLE : 10.10

Assertion (A): Even though dropwise condensation is more efficient, surface condensers are designed on the assumption of filmwise condensation as a matter of practice.

Reason (R): Dropwise condensation can be maintained with the use of promoters like oleic acid.

(a) Both A and R are individually true and R is the correct explanation of A
(b) Both A and R are individually true but R is not the correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

Solution: (b)

Dropwise condensation is difficult to maintain during operation of device. So condenser design are always based on film condensation (heat transfer coefficient is smaller for film condensate).

EXAMPLE : 10.11

Saturated steam is allowed to condense over a vertical flat surface and the condensate film flows down the surface. The local heat transfer coefficient for condensation

(a) remains constant at all locations of the surface
(b) decreases with increasing distance from the top of the surface
(c) increases with increasing thickness of condensate film
(d) increases with decreasing temperature differential between the surface and vapour.

Solution: (b)

As the distance or thickness of condensate film increases the heat transfer decreases which is truly indicative of decrease in heat transfer coefficient. This is the reason we promote dropwise condensation.

EXAMPLE : 10.12

Consider the following statements regarding condensation heat transfer:

1. For a single tube, horizontal position is preferred over vertical position for better heat transfer.
2. Heat transfer coefficient decreases if the vapour stream moves at high velocity.
3. Condensation of steam on an oily surface is dropwise.
4. Condensation of pure benzene vapour is always dropwise.

Which of these statements are correct?

(a) 1 and 2 (b) 1 and 3
(c) 2 and 4 (d) 3 and 4

Solution: (b)

Horizontal position promotes dropwise condensation and thickness of film formed is less. That is the reason condenser tubes are always kept horizontal. Heat transfer coefficient will increase if velocity of vapour stream increased as apart from latent heat exchange, the sensible heat exchange will be enhanced.

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IMPORTANT POINTS TO REMEMBER

- Boiling occurs when a liquid is in contact with a surface maintained at a temperature T, sufficiently above the saturation temperature T_{sat} of the liquid.
- Boiling is classified as pool boiling or flow boiling depending on the presence of bulk fluid motion.
- Boiling is called pool boiling in the absence of bulk fluid flow and flow boiling is further classified as subcooled boiling and saturated boiling depending on the bulk liquid temperature. Boiling is said to be subcooled or local when the temperature of the main body of the liquid is below the saturation temperature T_{sat} and saturated (or bulk) when the temperature of the liquid is equal to T_{sat}.
- Boiling exhibits different regimes depending on the value of the excess temperature ΔT_{excess}. Four different boiling regimes are observed – natural convection boiling, nuclear boiling, transition boiling, and film boiling.
- The rate of evaporation and the rate of heat transfer in nuclear boiling increases with increasing ΔT_{excess} and reaches a maximum at some point. The heat flux at this point is called the critical (or maximum) heat flux, $\dot{q}_{max}$.
- Two distinct forms of condensation are observed in nature, film condensation and dropwise condensation. In film condensation, the condensate wets the surface and forms a liquid film on the surface that slides down under the influence of gravity. In dropwise condensation, the condensed vapor forms countless droplets of varying diameters on the surface instead of a continuous film.

OBJECTIVE BRAIN TEASERS

Q.1 It is desired to operate engineering devices
(a) beyond the critical heat flux region
(b) in the film boiling region
(c) at the critical heat flux point
(d) nucleated region

Q.2 The dancing of water droplet on hot surface is explained by the phenomenon of
(a) nucleated boiling
(b) free convection
(c) film boiling
(d) radiation

Q.3 Dropwise condensation occurs on a .... surface.
(a) oily (b) smooth
(c) glazed (d) coated **[MSQ]**

Q.4 The heat flux in nucleate boiling varies in accordance with
(a) h_{fg} (b) $(h_{fg})^{0.5}$
(c) $(h_{fg})^3$ (d) $1/(h_{fg})^2$

Q.5 Consider the following statements regarding boiling heat transfer:
1. The peak of the boiling curve indicates the critical heat flux and the burnout point.
2. This point also indicates the onset of departure from nucleate boiling.
3. It is desired to operate the heat transfer surface close to this value, but is dangerous to exceed it.
4. At Leidenfrost point, heat transfer is maximum.

Which of the above statements are correct?
(a) 1 and 2 (b) 2 and 3
(c) 1, 2 and 3 (d) All of these

Q.6 Match **List-I** with **List-II** and select the correct answer using the codes given below the lists:

List-I	**List-II**
A. Pool boiling	**1.** Temperature of heating surface exceeds the saturation temperature of liquid.
B. Bulk boiling	**2.** Temperature of liquid less than saturation temperature.
C. Sub cooled	**3.** Temperature of liquid boiling greater than saturation temperature

Codes:

	A	B	C
(a)	1	2	3
(b)	2	1	3
(c)	3	1	2
(d)	1	3	2

Q.7 Match **List-I** with **List-II** and select the correct answer using the codes given below the lists:

List-I
A. LMTD correction is applied in case of....heat exchanger.
B. Dropwise condensation occurs on ....surfaces.
C. Grashof number has significant in heat transfer by.....
D. Least value of Prandtl number can be expected in case of.......

List-II
1. Highly polished
2. Cross flow
3. Liquid metals
4. Free convection

Codes:

	A	B	C	D
(a)	2	1	4	3
(b)	1	2	3	4
(c)	4	3	2	1
(d)	3	4	2	1

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ANSWER KEY

1. (d) 2. (c) 3. (a, d) 4. (d) 5. (c)
6. (d) 8. (a)

HINTS & EXPLANATIONS

5. (c)
At Leidenfrost point, heat transfer is minimum.

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