BOILING & CONDENSATION

Course Contents

8.1 Introduction

- 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 vapor is lowered to saturation temperature (T_{sat}), ***Condensation*** occurs.
- Boiling and Condensation are considered to be forms of convection heat transfer since they involve fluid motion, such as the rise of the bubbles to the top and the flow of condensate to the bottom.
- Boiling and Condensation differ from other forms of convection, in that they depend on the latent heat of vaporization (h_{fg}) of the fluid and the surface tension (σ) at the liquid vapor interface, in addition to the properties of the fluid in each phase.
- During a phase change, large amount of heat (due to large latent heat of vaporization released or absorbed) can be transferred essentially at constant temperature.
- The phenomenon's are quite difficult to describe due to change in fluid properties (density, specific heat, thermal conductivity, viscosity, etc.) and due to considerations of surface tension, latent heat of vaporization, surface characteristics and other features of two phase flow.
- Heat transfer co-efficient h associated with boiling and condensation are typically much higher than those encountered in other forms of convection processes that involve a single phase.

8.2 Boiling

- Boiling is the convective heat transfer process that involves a phase change from liquid to vapor state.
- Boiling is a liquid to vapor phase change process just like evaporation, but there are significant differences between the two. ***Evaporation*** occurs at the liquid–vapor interface when the vapor pressure is less than the saturation pressure of the liquid at a given temperature. Examples of evaporation are: drying of clothes, the evaporation of sweat to cool human body and the rejection of waste heat in wet cooling towers. Note that evaporation involves no bubble formation or bubble motion.
- ***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. At 1 atm, for example, liquid water in contact with a solid surface at 110°C will boil since the saturation temperature of water at 1 atm is 100°C.

- Heat is transferred from the solid surface to the liquid, and the appropriate form of Newton's law of cooling is, $q = h(T_s - T_{sat}) = h\Delta T_e$

  Where, $\Delta T_e = (T_s - T_{sat})$ is termed the excess temperature.
- The boiling process is characterized by the rapid formation of vapor bubbles at the solid–liquid interface that detach from the surface when they reach a certain size and attempt to rise to the free surface of the liquid.

Applications of Boiling

- ✓ Steam production.
- ✓ Absorption of heat in refrigeration and Air-conditioning systems.
- ✓ Greater importance has recently been given to the boiling heat transfer because of developments of nuclear reactors, space-crafts and rockets, where large quantities of heat are produced in a limited space and are to be dissipated at very high rates.

8.3 Types of Boiling

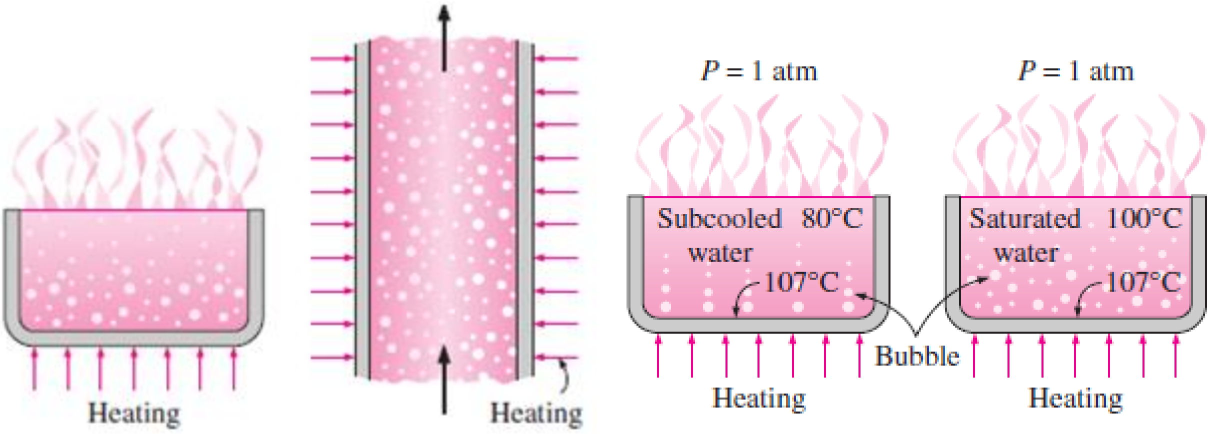
A. Classification of boiling on the basis of the presence of bulk fluid motion

1. Pool Boiling

- The liquid above the hot surface is stationary.
- The only motion near the surface is because of free convection and the motion of the bubbles under the influence of buoyancy.
- The pool boiling occurs in steam boilers. Pool boiling of a fluid can also be achieved by placing a heating coil in the fluid.

2. Forced Convection Boiling / Flow Boiling

- The fluid motion is induced by external means such as pump.
- The liquid is pumped and forced to move in a heated pipe or over a surface in a controlled manner.
- The free convection and the bubble induced mixing also contribute towards the fluid motion.



(a) Pool Boiling *(b) Flow Boiling* *(c) Sub-cooled Boiling* *(d) Saturated Boiling*

Fig. 8.1 Classification of boiling

B. Classification of boiling on the basis of the presence of bulk liquid temperature

1. Sub-cooled or Local Boiling

- The temperature of liquid is below the saturation temperature and boiling takes place only in vicinity of the heated surface.

- The vapor bubbles travel a short path and then vanish; apparently they condense in the bulk of the liquid which is at a temperature less than a boiling point or saturation temperature.

2. Saturated Boiling

- The temperature of the liquid exceeds the saturation temperature.

- The vapor bubbles generated at the solid surface(solid-liquid interface) are transported through the liquid by buoyancy effects and eventually escape from the surface (liquid-vapor interface).

- The actual evaporation process then sets in.

8.4 Boiling Regimes

- Whether the boiling phenomenon corresponds to pool boiling or forced circulation boiling, there are some definite regimes of boiling associated with progressively increasing heat flux.

- Nukiyama (1934) was the first to identify different regimes of pool boiling using the apparatus of Fig. 8.2. These different regimes can be illustrated by considering an electrically heated horizontal nichrome/Platinum wire submerged in a pool of liquid at saturation temperature.

- Fig. 8.3 shows the relationship between heat flux and the temperature excess (T_s – T_{sat}); Where,

T_s = Temperature of the hot surface

T_{sat} = Saturation temperature corresponding to the pressure at which the liquid is being evaporated.

- The heat flux is easily controlled by voltage drop across a wire of fixed resistance.
- Although the boiling curve given in Fig. 8.3 is for water, the general shape of the boiling curve remains the same for different fluids.
- Different boiling regimes are:
  A. Natural Convection Boiling
  B. Nucleate Boiling
  C. Film Boiling

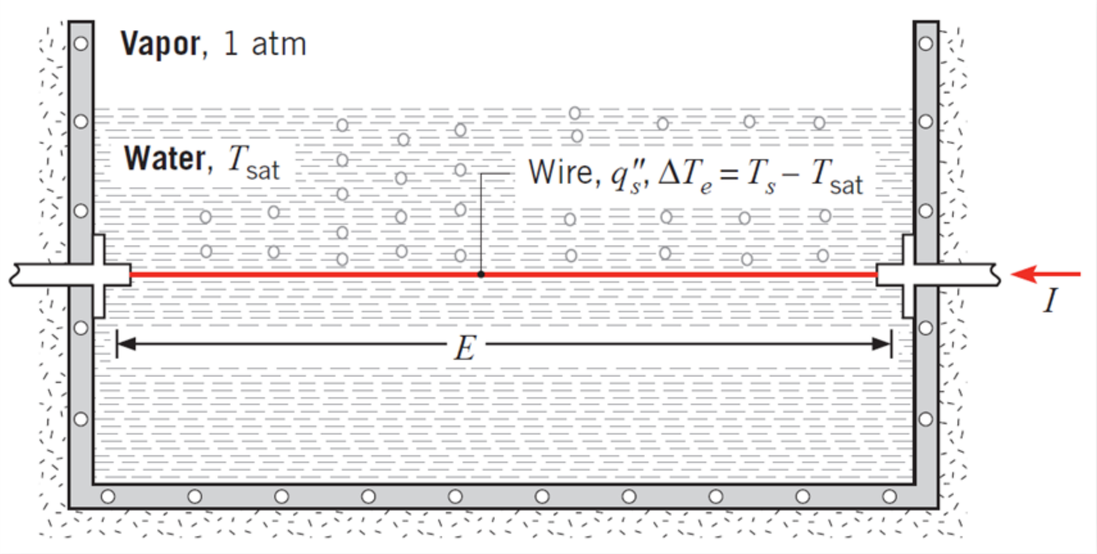


Fig. 8.2 Nukiyama's power controlled heating apparatus for demonstrating the boiling curve

A. Natural / Free Convection Boiling (up to point A on Boiling curve)

- The boiling takes place in a thin layer of liquid which adjoins the heated surface.
- The liquid in the immediate vicinity of the wall becomes superheated, i.e. temperature of the liquid exceeds the saturation temperature at the given pressure.
- The superheated liquid rises to the liquid-vapor interface where evaporation takes place.
- The fluid motion is by free convection effects.
- The heat transfer rate increases, but gradually, with growth in a temperature excess.

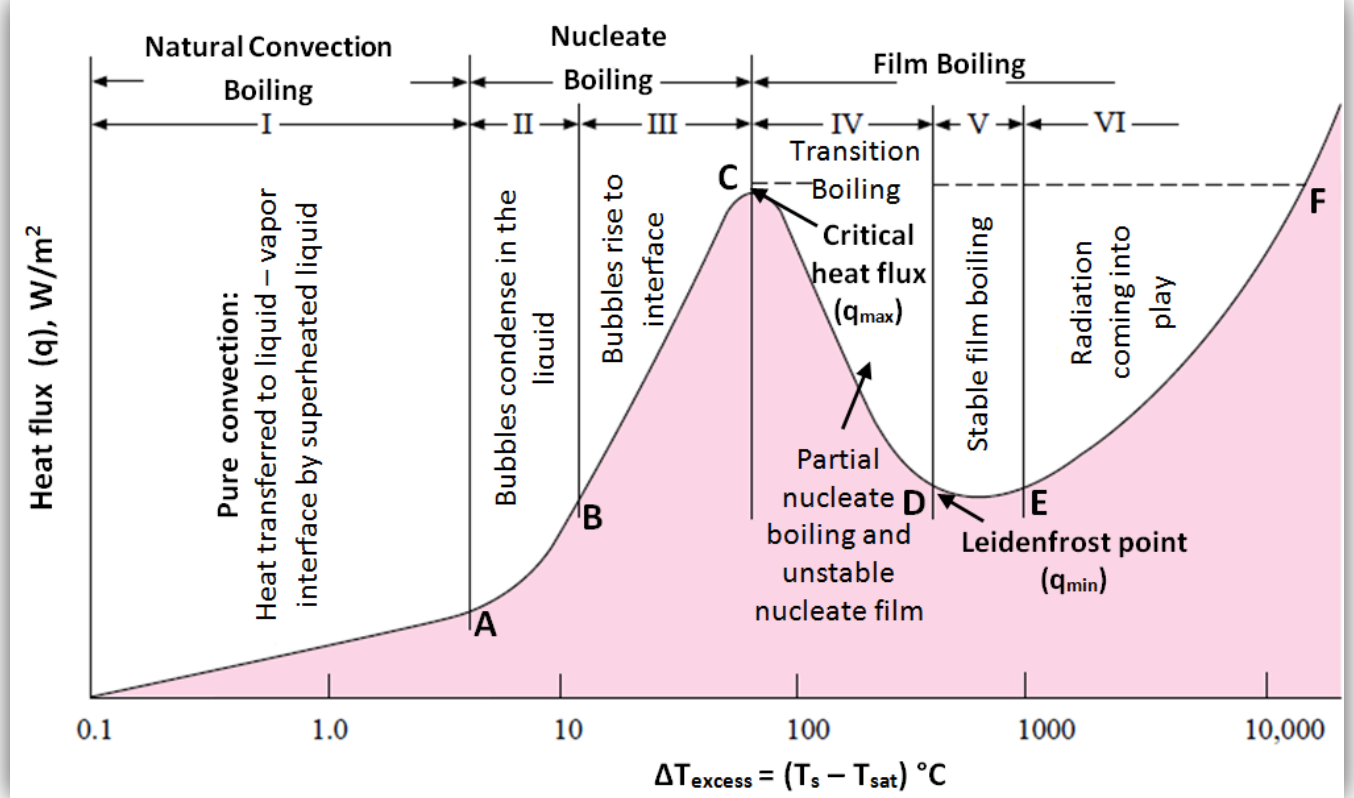


Fig. 8.3 Boiling curve for saturated water at atmospheric pressure

B. Nucleate Boiling (between point A & C on Boiling curve)

- When the liquid is overheated in relation to saturation temperature, vapor bubbles are formed at certain favorable spots called the ***Nucleation or Active sites***. Point **A** is referred as the ***onset of nucleate boiling, ONB***.
- The nucleate boiling regimes can be separated into two distinct regions:

A – B:-

- Isolated bubbles are formed at various nucleation sites, on the heated surface but these bubbles get condensed in the liquid after detaching from the surface.

B – C:-

- Heater temperature is further increased. Bubbles forms at very high rates and they form continuous columns of vapor in the liquid.
- The liquid is quite hot and the bubbles do not condense in it.
- These bubbles rise to the free surface, where they break-up and release its vapor content and that helps in rapid evaporation.

- The space vacated by the rising bubbles is filled by the liquid in the vicinity of the heated surface, and the process is repeated.
- The agitation or stirring caused by the entrainment of the liquid to the heated surface and rapid evaporation is responsible for the increased heat transfer co-efficient and heat flux in the nucleate boiling region.
- The heat flux hence reaches maximum at point C, which is called the ***critical /maximum heat flux, q_{max}***.
- Nucleate boiling is the most desirable boiling regime in practice because high heat transfer rates can be achieved in this regime with relatively small values of ΔT_{excess}.

C. Film Boiling (beyond point C on Boiling curve)

Transition Boiling (between point C & D)

- As the heater temperature and thus ΔT_{excess} is increased past point C, the heat flux decreases as shown in Fig. 8.3.
- This is because a bubble formation is very rapid; the bubbles blanket the heating surface and prevent the incoming fresh liquid from taking their place.
- A large fraction of the heating surface is covered by a vapor film, which acts as an insulation due to the low thermal conductivity of the vapor.
- In the transition boiling regime, both nucleate and film boiling partially occurs.
- Nucleate boiling at point C is completely replaced by film boiling at point D.
- Operation in the transition boiling regime, which is also called the unstable film boiling regime, is avoided in practice.

Beyond point D

- In this region the heated surface is completely covered by a continuous stable vapor film.
- The temperature differences are so large that radiant heat flux becomes significant, and the heat flux curve begins to rise upward with increasing ΔT_{excess}. That marks the region of stable film boiling.
- The phenomenon of stable film boiling is referred as ***"Leidenfrost effect"*** and point D, where the heat flux reaches a minimum, is called the *Leidenfrost point.*

Burn out point (Point F)

- In order to move beyond point C, where q_{max} occurs, we must increase the heated surface temperature (Ts).

  - To increase Ts, however we must increase the heat flux. But the fluid can not receive this increased energy beyond point C, and the heated surface temperature (Ts) to rise even further.
  - If the surface temperature exceeds the temperature limit of the wall material, burn out (structural damage & failure) of the wall occurs.

8.5 Bubble Growth

- The bubble formation in nucleate boiling is greatly influenced by the nature and condition of the heating surface and surface tension at the solid-liquid interface (Shape, size and inclination of bubbles, however do not have much effect on the heat transfer rate).
- The surface tension signifies wetting capability of the surface with the liquid (i.e. low surface tension → Highly wetted surface) and that influences the angle of contact between the bubble and solid surface.
- Any contamination of the surface would affect its wetting characteristics and influence the size and shape of the vapor bubbles.
- If the surface tension of the liquid is low, it tends to wet the surface (fully wetted surface), so that the bubble is readily pushed by the liquid and rises. The vapor bubbles tend to become globular or oval in shape as shown in Fig. 8.4(a) (iii) and they are disengaged from the surface.

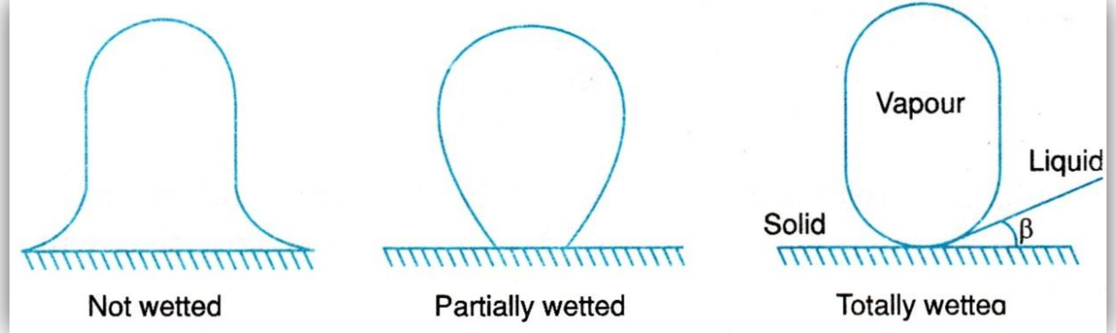


Fig. 8.4(a) Wetting characteristics for typical vapor bubbles

- In case of liquid having intermediate surface tension (partially wetted surface) a momentary balance may exist between the bubbles and solid surface so that it is necessary to form larger bubbles before the buoyant force can free them from the surface; the shape of the bubble is shown in Fig. 8.4(a) (ii).
- On the unwetted surface, the bubbles spread out as shown in Fig. 8.4(a) (i); forming a wedge between the water and heating surface, thereby allowing hydrostatic forces to resist the action of buoyancy.

- The formation of bubble with fully wetted surface as shown in Fig. 8.4(a) (iii) gives high heat transfer rate compared with the bubble shapes shown in Fig. 8.4(a) (i) and (ii); because the area covered by the insulating vapor film is the smallest.
- Experimental evidence does indicate that the vapor bubbles are not always in thermodynamic equilibrium with the surrounding liquid.

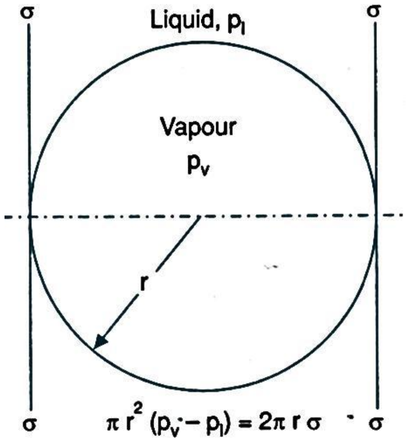


Fig. 8.4(b) Force balance for a spherical bubble

- The vapor inside the bubble is not necessarily at the same temperature as the liquid and the vapor pressure P_v inside the bubble exceeds the liquid pressure P_l acting from outside of the bubble. Fig. 8.4(b) indicates one such spherical bubble with various forces acting on it.
    i. The resultant pressure $(P_v - P_l)$ acts on area πr^2 and the pressure force equals $\pi r^2 (P_v - P_l)$.
    ii. The surface tension σ of the vapor-liquid interface acts on the interface length 2πr and the surface tension force equals 2πrσ.
  - Under equilibrium conditions, the pressure force is balanced by the surface tension force. Thus,

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

$$(P_v - P_l) = \frac{2\sigma}{r} - - - - - - - - - (8.1)$$

  - The vapor may be considered as a perfect gas for which the Clayperon equation may be used, which is given below:

$$\frac{dP}{P} = \frac{h_{fg}}{RT^2} dT - - - - - - - - - (8.2)$$

  - From equation (8.1) and (8.2) we can derive,

$$T_v - T_{sat} = \frac{2\sigma}{r} \left[\frac{R}{P} \frac{T_{sat}^2}{h_{fg}} \right] - - - - - - - - - (8.3)$$

  - Equation (8.3) is the equilibrium relationship between the bubble radius and the amount of superheat.

- A bubble of radius r will grow if $(T_l - T_{sat}) > (T_v - T_{sat})$; otherwise it will collapse. Here $T_l$is the temperature of the liquid surrounding the bubble.
- The bubble diameter D_b at the time of detachment from the surface can be worked out from the relation proposed by Fritz:

$$D_b = C_d \beta \sqrt{\frac{2\sigma}{g(\rho_l - \rho_v)}} ---------(8.4)$$

Where, β is the angle of contact and the empirical constant C_d has the value 0.0148 for water bubbles.

Factors affecting the nucleate pool boiling

1) **Material, shape and condition of the surface:**
Under identical conditions of pressure and temperature difference, the boiling heat transfer coefficient is different for different metals; copper has a high value compared to steel. Further a rough surface gives a better heat transmission then when the surface is either smooth or has been coated to weaken its tendency to get wetted.
2) **Pressure:**
The temperature difference between the heating surface and the bulk and hence the rate of bubble growth is affected by pressure. The maximum allowable heat flux for a boiling liquid increases with pressure until critical pressure is reached and thereafter it declines.
3) **Liquid properties:**
Experiments have shown that the bubble size increases with the dynamic viscosity of the liquid. With increase in bubble size, the frequency of bubble formation decreases and that result in reduced rate of heat transfer.

8.6 Condensation

- "Condensation occurs when the temperature of a vapor is reduced below its saturation temperature corresponding to the vapor pressure."
- This is usually done by bringing the vapor into contact with a solid surface whose temperature, Ts is below the saturation temperature T_{sat} of the vapor.
- The latent energy of the vapor is released, heat is transferred to the surface, and the condensate is formed.
- The 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 vapor is exposed is below T_{sat}.
- In this chapter we will consider surface condensation only.
- Depending upon the behavior of condensate upon the cooled surface, the condensation process has been categorized into two distinct modes: (A) Film wise condensation and (B) Drop wise condensation.

8.7 Drop wise and Film wise Condensation

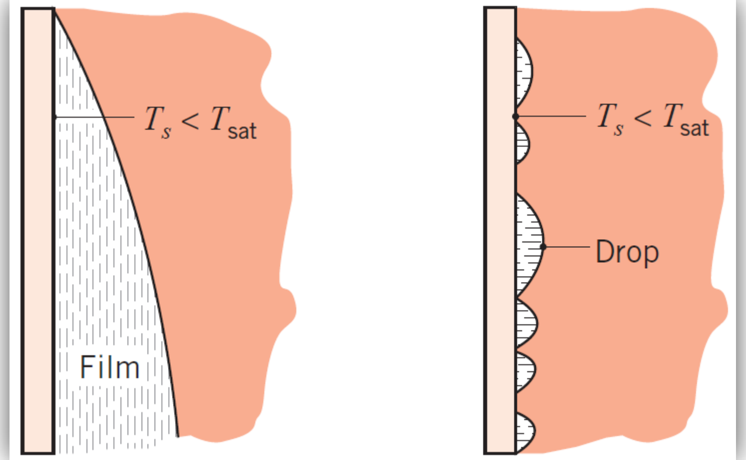


Fig. 8.5 Film wise and Drop wise Condensation

A. Film wise condensation

- The liquid condensate wets the solid surface, spread out and forms a continuous film over the entire surface.
- The liquid flows down the cooling surface under the action of gravity and the layer continuously grows in thickness because of newly condensing vapors.
- The continuous film offers resistance and restricts further transfer of heat between the vapor and the surface.

- Film condensation only occurs when a vapor relatively free from impurities, is allowed to condense on a clean surface.
- Film condensation is generally a characteristic of clean, uncontaminated surfaces.

B. Drop wise condensation

- The liquid condensate collects in droplets and does not wet the solid cooling surface.
- The droplets develop in cracks, pits and cavities on the surface, grow in size, break away from the surface, knock-off other droplets and eventually run-off the surface without forming a film.
- A part of the condensation surface is directly exposed to the vapor without an insulating film of condensate liquid.
- Evidently there is no film barrier to heat flow and higher heat transfer rates are experienced.
- Drop wise condensation has been observed to occur either on highly polished surfaces, or on surfaces contaminated with impurities like fatty acids and organic compounds.
- Drop wise condensation gives co-efficient of heat transfer generally 5 to 10 times larger than with film condensation.
- It is therefore common practice to use surface coatings that inhibit wetting, and hence simulate drop wise condensation.
- Silicon, Teflon and an assortment of waxes and fatty acids are often used for this purpose.
- However such coatings gradually lose their effectiveness due to oxidation, fouling or outright removal and film condensation eventually occurs.
- Although it is desirable to achieve drop wise condensation in industrial applications, it is often difficult to maintain this condition.
- Condenser design calculations are often based on the assumption of film condensation.

☞ Influence of the presence of non-condensable gases

- The presence of non-condensable gas such as air in a condensing vapor produces a detrimental (negative) effect on the heat transfer coefficient.
- It has been observed that even with a few percent by volume of air in steam the condensation heat transfer coefficient is reduced by more than 50%.
- This is owing to the fact that when a vapor (containing non-condensable gas) condenses, the non-condensable gas is left at the surface.
- Any further condensation at the surface will occur only after incoming vapor has diffused through this non-condensable gas collected in the vicinity of the surface.
- *The non-condensable gas adjacent to the surface acts as a thermal resistance to the condensation process. The rate of condensation decreases greatly when the condensable vapor is contaminated with even very small amounts of non-condensable gases.*
- As the presence of non-condensable gas in a condensing vapor is undesirable, the general practice in the design of a condenser should be to vent the non-condensable gas to the maximum extent possible.

8.8 References

[1] Heat and Mass Transfer by D. S. Kumar, S K Kataria and Sons Publications.

[2] Heat and Mass Transfer by R. K. Rajput, S. Chand Publications.

[3] Fundamentals of Heat and Mass Transfer by Frank P. Incropera, John Wiley & Sons Publication.

[4] Heat Transfer – A Practical Approach by Yunus Cengel & Boles, McGraw-Hill Publication.