

Boiling and Condensation



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9.1. INTRODUCTION

We have considered in the preceding chapter of convective heat transfer, homogeneous single phase systems only. However, there are specific convection processes as *boiling* and *condensation* which are associated with change of phase. Whereas *boiling* involves change from liquid to vapour phase of a fluid substance, *condensation* refers to a change from the vapour to a liquid phase.

The mode of heat transfer with change of phase (*i.e.* boiling and condensation processes) finds wide applications as mentioned below:

- (i) Cooling of nuclear reactors and rocket motors;
- (ii) Steam power plants (Boilers and condensers);
- (iii) Refrigerating and airconditioning systems (Evaporators and condensers);
- (iv) Melting of metal in furnaces;
- (v) Refineries and sugar mills (Heat exchangers);
- (vi) Process heating and cooling etc.

Boiling and condensation processes entail the following *unique features*:

- (i) As a consequence of phase change in these processes, the *heat transfer to or from the fluid can occur without influencing the fluid temperature*.
- (ii) The *heat transfer coefficient and rates*, due to latent heat associated with phase change, are generally *much higher* compared with the normal convection process (*i.e.*, without phase change).

(iii) High rate of heat transfer is achieved with small temperature difference.

The phenomena associated with boiling and condensation are much more complex (than the normal convection process) due to the following being very significant:

- (i) Latent heat effects;
- (ii) Surface tension;
- (iii) Surface characteristics and other properties of two phase systems.

9.2. BOILING HEAT TRANSFER

9.2.1. GENERAL ASPECTS

Boiling is the convective heat transfer process that involves a phase change from liquid to vapour state. Boiling is also defined as evaporation at a solid-liquid surface. This is possible only when the temperature of the surface (t_s) exceeds the saturation temperature corresponding to the liquid pressure (t_{sat}). Heat is transferred from the solid surface to the liquid according to the law

$$Q = h A_s (t_s - t_{sat}) = h A_s \Delta t_e \quad \dots(9.1)$$

where,

$$\Delta t_e = (t_s - t_{sat}) \text{ is known as excess temperature.}$$

The boiling process finds applications in the following cases:

- (i) Steam production (for generation of power and for industrial processes and space heating) in steam and nuclear power plants;
- (ii) Heat absorption in refrigeration and air conditioning systems;
- (iii) Distillation and refining of liquids;
- (iv) Concentration, dehydration and drying of foods and materials,
- (v) Cooling the machines like nuclear reactors and rocket motors where the large quantities of heat are released in relatively small volume (dissipation rates are as high as 10^8 W/m^2 ; the maximum heat transfer rate in modern boiler is about $2 \times 10^5 \text{ W/m}^2$).

The boiling heat transfer phenomenon may occur in the following forms:

1. 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.

The pool boiling occurs in steam boilers involving natural convection.

2. Forced convection boiling :

This refers to a situation where the fluid motion is induced by external means (and also by free convection and bubble induced mixing). The liquid is pumped and forced to flow. This type of boiling occurs in water tube boilers involving forced convection.

3. Sub-cooled or local boiling :

In this case the liquid temperature is below the saturation temperature and



The electrically heated copper disc is submerged into the water pool. Depending on the surface temperature of the disc and the water the heat is transferred by conduction and or convection and or radiation.

bubbles are formed in the vicinity of heat surface. These bubbles after travelling a short path get condensed in the liquid which has a temperature less than the boiling point.

4. *Saturated boiling* :

Here, the liquid temperature exceeds the saturation temperature. The vapour bubbles formed at the solid surface (liquid-solid interface) are then propelled through the liquid by buoyancy effects and eventually escape from a free surface (liquid-vapour interface).

9.2.2. BOILING REGIMES

The *process of boiling depends upon the nature of the surface, thermo-physical properties of the fluid and vapour bubble dynamics*. Due to involvement of large number of variables, general equations describing the boiling process are not available. Nonetheless, considerable progress has been made in arriving at a physical understanding of the boiling mechanism.

Figure 9.1 shows the temperature distribution in saturated pool boiling with a liquid-vapour interface. It is evident from the figure that although there is a sharp decline in the liquid temperature close to the solid surface, the temperature through most of the liquid remains slightly above saturation. Consequently bubbles generated at liquid-solid interface rise to and are transported across the liquid-vapour interface. Whether the boiling phenomenon corresponds to pool boiling or forced circulation boiling, there are three definite regimes of boiling (Interface evaporation, nucleate boiling and film boiling) associated with progressively increasing heat flux, as shown in Fig. 9.2. This specific curve has been obtained from an electrically heated platinum wire submerged in a pool of water (at saturation temperature) by varying its surface temperature and measuring the surface heat flux q_s .

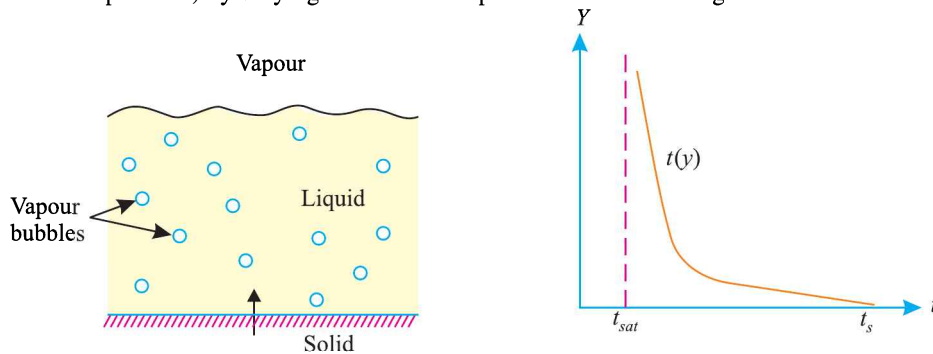


Fig. 9.1. Pool boiling with liquid-vapour interface.

1. Interface evaporation :

Interface evaporation (evaporation process with no bubble formation) exists in region *I*, called the *free convection zone*. Here the excess temperature, Δt_e , is very small and $\approx 5^\circ\text{C}$. In this region the *liquid near the surface is superheated slightly, the convection currents circulate the liquid and evaporation takes place at the liquid surface*.

2. Nucleate boiling :

This type of boiling exists in regions *II* and *III*. With the increase in Δt_e (excess temperature) the formation of bubbles on the surface of the wire at certain localised spots commences. The bubbles condense in the liquid without reaching the liquid surface. In fact, it is the region *II* where nucleate boiling starts. With further increase in Δt_e the bubbles are formed more rapidly and rise to the surface of the liquid resulting in rapid evaporation, as indicated in the region *III*. The *nucleate boiling* is thus characterised by *formation of bubbles at the nucleation sites and the resulting liquid agitation. The bubble agitation induces considerable fluid mixing and that promotes substantial increase in the heat flux and the boiling heat transfer coefficient* (The equipment used for boiling should be designed to operate in this region only).

Nucleate boiling exists upto $\Delta t_e \approx 50^\circ\text{C}$. The maximum heat flux, known as the *critical heat flux*, occurs at point A (see Fig. 9.2) and is of the order of 1MW/m^2 .

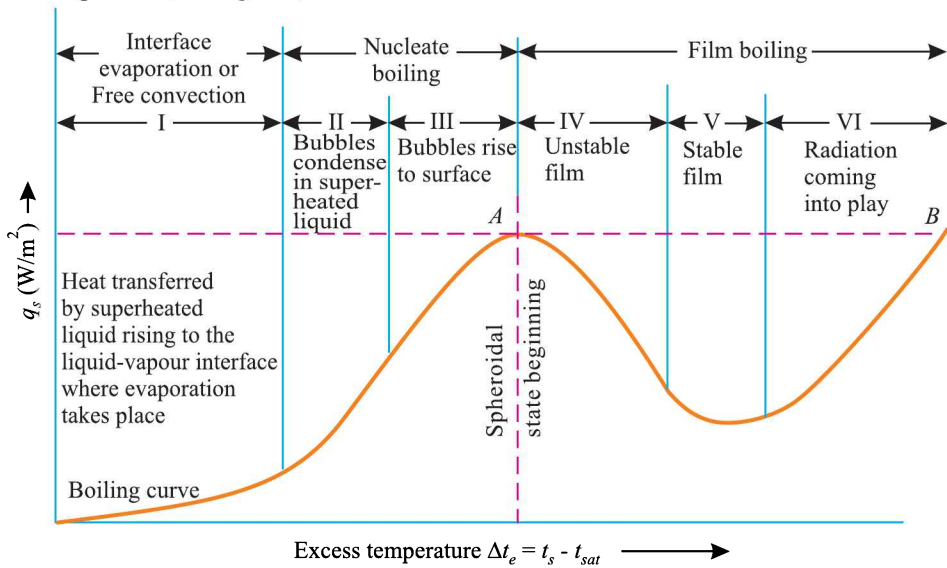


Fig. 9.2. The boiling curve for water.

3. Film boiling :

Film boiling comprises of regions IV, V and VI. The trend of increase of heat flux with increase in excess temperature observed upto region III is reversed in region IV (called *film boiling region*). 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. Eventually the bubbles coalesce and form a vapour film which covers the surface completely. Since the thermal conductivity of vapour film is *much less* than that of the liquid the heat flux *drops* with growth in Δt_e . Within the temperature range $50^\circ\text{C} < \Delta t_e < 150^\circ\text{C}$, conditions oscillate between nucleate and film boiling and the phase is referred to as *transition boiling*, *unstable film boiling* or *partial film boiling* (region IV). With further increase in Δt_e the vapour film is stabilised and the heating surface is completely covered by a vapour blanket and the *heat flux* is the lowest as shown in region V. The surface temperatures required to maintain a stable film are high and under these conditions a sizeable amount of heat is lost by the surface *due to radiation*, as indicated in the region VI. The phenomenon of stable film boiling can be observed when a drop of water falls on a red hot stove. The drop does not evaporate immediately but dances a few times on the stove; this is *due to the formation of a stable steam film at the interface between the hot surface and the liquid droplet*.

Critical heat flux or burnout point: The critical heat flux or burnout point (Point A in Fig. 9.2) is the point of maximum heat flux on the boiling curve at which transition from nucleate to film boiling initiates. This point is also called the *boiling crisis* because the boiling process beyond that point is unstable unless of course, point B is reached. The temperature at point B is extremely high and normally above the melting of the solid. So if the heating of the metallic surface is not limited to point A, it is possible that the metal may get damaged or it may even melt (For this reason, point A is often termed as *boiling crisis* or *burnout point*). Thus we may be interested to operate the equipment close to this value and not beyond it.

9.2.3. BUBBLE SHAPE AND SIZE CONSIDERATION

The heat transfer rate 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 or 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 the solid surface. If the surface is contaminated, its wetting characteristics are affected which eventually influence the size and shape of the vapour bubbles.

If the surface tension of the liquid is *low*, it tends to wet the surface, so that the bubble is readily pushed by the liquid and rises. The liquid shear-off the bubbles causing them to become globular or oval as shown in Fig. 9.3 (i) (for totally wetted surface). In case of liquids 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. 9.3 (ii).

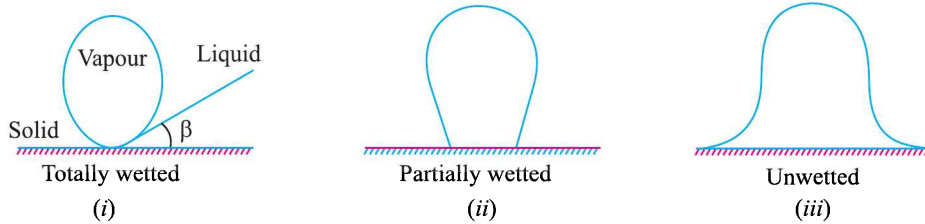


Fig. 9.3. Typical shapes of steam bubbles.

On the unwetted surface [Fig. 9.3 (iii)], the bubbles spread out; forming a wedge between the water and heating surface, thereby allowing hydrostatic forces to resist the action of buoyancy.

The formation of bubble as shown in Fig. 9.3 (i) gives high heat transfer rate compared with the bubble shapes shown in Fig. 9.3 (ii) and (iii).

Addition of agents for reducing the surface tension was found to have the same effect as providing of wettable surface and to give increased rates of heat transfer.

9.2.4. BUBBLE GROWTH AND COLLAPSE

From Experiments it has been observed that the bubbles are not always in thermodynamic equilibrium with surrounding liquid. The vapour inside the bubble is not necessarily at the same temperature as the liquid. Consider the forces acting on a spherical vapour bubble as shown in Fig. 9.4; the pressure forces on the bubble must be balanced by the surface tension at vapour-liquid interface. Thus

$$\pi r^2 (p_v - p_l) = 2\pi r \cdot \sigma$$

or,
$$P_v - P_l = \frac{2\sigma}{r} \quad \dots(9.2)$$

- where, p_v = Vapour pressure inside the bubble,
- p_l = Liquid pressure over the surface of bubble, and
- σ = Surface tension of vapour-liquid interface.

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

$$\frac{dp}{p} = \frac{h_{fg}}{RT^2} dT \quad \dots(9.3)$$

where, h_{fg} = Latent heat of vaporisation.

From perfect gas law:
$$\frac{p}{RT} = \rho_v$$

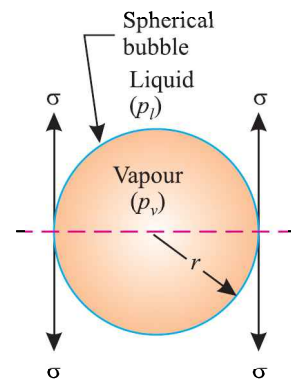


Fig. 9.4. Force balance on a spherical vapour bubble.

[where, R = Gas or vapour constant; ρ_v = Density of vapour formed]

Substituting the above equation in eqn. (9.3) and rearranging, we get

$$\frac{dp}{dT} = \frac{h_{fg} \cdot \rho_v}{T}$$

or,
$$\frac{p_v - p_l}{T_v - T_{sat}} = \frac{h_{fg} \cdot \rho_v}{T_{sat}} = \frac{p \cdot h_{fg}}{R T_{sat}^2} \quad \dots(9.4)$$

where, T_v = Vapour temperature inside the bubble, and

T_{sat} = Saturation temperature of vapour inside the bubble at p_v .

From eqns. (9.2) and (9.4), we get

$$T_v - T_{sat} = \frac{2\sigma}{r} \left[\frac{R}{p} \cdot \frac{T_{sat}^2}{h_{fg}} \right] \quad \dots(9.5)$$

The above equation suggests that if $(T_l - T_{sat}) > (T_v - T_{sat})$, the bubble of radius r will grow otherwise it will collapse. Here T_l is the temperature surrounding the bubble.

9.2.5. CRITICAL DIAMETER OF BUBBLE

Refer figure 9.5, the maximum diameter of the bubble formed on the heating surface depends on the following parameters:

- σ_{lv} = Tension between liquid and vapour
- σ_{ls} = Tension between liquid and solid surface
- σ_{vs} = Tension between vapour and solid surface
- β = Angle formed by the bubble as shown in Fig. 9.5
- d_c = Maximum or critical diameter of bubble.

$g(\rho_l - \rho_v)$ = Buoyancy force.

Thus
$$d_c = f \left[\beta, \sigma_{lv}, g(\rho_l - \rho_v), \frac{\sigma_{lv}}{\sigma_{ls}} \right]$$

By the use of the dimensional analysis technique, we get

$$d_c = C \cdot \beta \left(\frac{\sigma_{lv}}{\sigma_{ls}} \right) \sqrt{\frac{\sigma_{lv}}{g(\rho_l - \rho_v)}} \quad \dots(9.6)$$

where C is constant which is generally calculated by experimental results.

The value of $C = 0.0148$ for water bubbles.

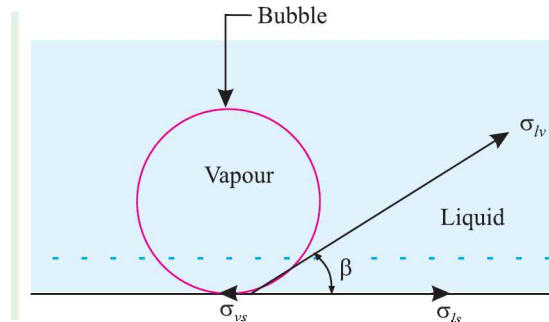


Fig. 9.5. Critical diameter of bubble.

...suggested by Fritz.

9.2.6. FACTORS AFFECTING NUCLEATE BOILING

The nucleate boiling is affected by the following factors:

1. *Material, shape and condition of the heating surface* :

The boiling heat transfer coefficient depends greatly on the material of the heating surface; under identical conditions of pressure and temperature difference, it is different for different metals (*viz.* copper has high value than steel, zinc and chromium).

The heat transfer rates are also influenced by the *condition of heating surface*. A rough surface gives a better heat transmission than when the surface is either smooth or has been coated (smoothness weakens the metal tendency to get wetted).

The shape of the heating surface also affects transmission of heat.

2. *Liquid properties :*

Through experiments it has been observed that the size of the bubble increases with the dynamic viscosity of the liquid. With increase in bubble size, frequency of bubble formation decreases which results in reduced heat transfer.

Further, high thermal conductivity of the liquid improves the rate of heat transfer.

3. *Pressure :*

The pressure influences the rate of bubble growth and in turn also affects the temperature difference ($t_s - t_{\infty}$) causing heat flow. For a boiling liquid, the maximum allowable heat flux first increases with pressure until critical pressure is reached and thereafter it declines.

4. *Mechanical agitation :*

Experiments have shown that the heat transfer rate increases with the increase in degree of agitation.

9.2.7. BOILING CORRELATIONS

In boiling heat transfer, a *driving force is the excess temperature*, which is given by:

$$\Delta t_e = t_s - t_{sat} \quad \dots(9.7)$$

For the boiling process the governing equation is

$$Q = hA \Delta t_e$$

where h is the *boiling film coefficient*.

Since no analytical solution is available for boiling heat transfer due to difficult fluid behaviour, empirical relations are used for engineering calculations. some of them are given in following subsections.

9.2.7.1. Nucleate pool boiling

(i) For nucleate pool boiling, Rosenhow has recommended the following correlation:

$$q_s = \mu_l \cdot h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{0.5} \left[\frac{c_{pl} \cdot \Delta t_e}{C_{sl} \cdot h_{fg} \cdot Pr_l^n} \right]^3 \quad \dots(9.8)$$

where,

q_s = Surface heat flux, W/m²;

μ_l = Liquid viscosity, kg/ms;

h_{fg} = Enthalpy of vaporisation, J/kg;

ρ_l = Density of saturated liquid, kg/m³;

ρ_v = Density of the saturated vapour, kg/m³;

σ = Surface tension of the liquid-vapour interface, N/m;

c_{pl} = Specific heat of saturated liquid, J/kg K;

$\Delta t_e = (t_s - t_{sat})$ = excess temperature;

C_{sl} = Surface fluid constant (determined from experimental data);

n = Another constant which depends upon the liquid and the surface; for water $n = 1$, while for other liquids $n = 1.7$.

The value of C_{sl} are given in Table 9.1.

Table 9.1. Values of C_{sl} for pool boiling

S.No.	Liquid-surface	C_{sl}
1.	Water - copper	0.013
2.	Water - brass	0.060
3.	Water - platinum	0.013
4.	Water - ground and polished stainless steel	0.008
5.	Water - mechanically polished stainless steel	0.013
6.	Benzene - chromium	0.010
7.	Ethanol - chromium	0.0027
8.	n-pentane - chromium	0.0150
9.	n-butanol - copper	0.003
10.	Isopropyl alcohol - copper	0.00225

(ii) Jacob has proposed the following correlation for nucleate boiling at atmospheric pressure on a flat plate and with low heat fluxes :

$$Nu = 0.16 (Gr \cdot Pr)^{0.33} \quad \dots(9.9)$$

(iii) For the nucleate boiling on a vertical flat plate, Jacob correlation is of the form:

$$Nu = 0.61 (Gr \cdot Pr)^{0.25} \quad \dots(9.10)$$

9.2.7.2. Critical heat flux for nucleate pool boiling

On the boiling curve the critical heat flux is an important point. It is always desirable to operate a boiling process close to this point. Zuber (1958) predicted the following expression, for such a case:

$$q_{sc} = 0.18 (\rho_v)^{1/2} h_{fg} [g\sigma (\rho_l - \rho_v)]^{1/4} \quad \dots(9.11)$$

The expression given above is independent of fluid viscosity, conductivity and specific heat.

9.2.7.3. Film pool boiling

In *stable film boiling*, the heat transfer is due to both convection and radiation. Bromley (1950) has suggested the following correlation for film boiling from the outer surface of horizontal tubes:

$$(h)^{4/3} = (h_{conv.})^{4/3} + h_{rad.} (h)^{1/3} \quad \dots(9.12)$$

The equation (9.12) being tedious to solve, could be written within $\pm 5\%$ of error as

$$h = h_{conv.} + \frac{3}{4} h_{rad.} \quad \dots(9.13)$$

The convective coefficient, $h_{conv.}$ (in the absence of radiation), is given by

$$h_{conv.} = 0.62 \left[\frac{k_v^3 \rho_v (\rho_l - \rho_v) g (h_{fg} + 0.4 c_{pv} \Delta t_e)}{\mu_v D \Delta t_e} \right]^{1/4} \quad \dots(9.14)$$

where, D is the outer diameter of the tube. The vapour properties in the above equation are evaluated at the arithmetic mean of the surface and saturation temperatures.

Radiative heat transfer coefficient

$$h_{rad} = \frac{5.67 \times 10^{-8} \epsilon (T_s^4 - T_{sat}^4)}{(T_s - T_{sat})} \quad \dots(9.15)$$

where ϵ is the emissivity of solid.