

Lecture Six

Heat Transfer in Boiling

In the previous chapter we have discussed about the convective heat transfer in which the homogeneous single phase system was considered. The heat transfer processes associated with the change of fluid phase have great importance in chemical process industries. In this chapter, we will focus our attention towards the phase change from liquid to vapor and vice-versa. We know from thermodynamics 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 vapor is lowered to T_{sat} , *condensation* occurs. In this chapter we study the rates of heat transfer during such liquid-to-vapor and vapor-to-liquid phase transformations. 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.

1- Introduction.

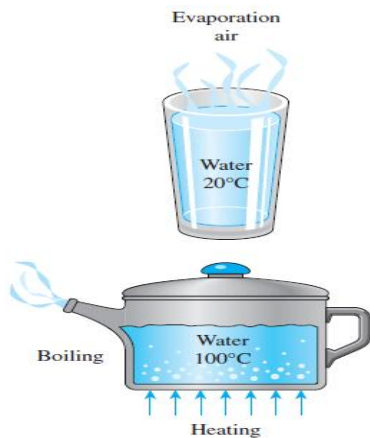


FIGURE 10-1

A liquid-to-vapor phase change process is called *evaporation* if it originates at a liquid-vapor interface and *boiling* if it occurs at a solid-liquid interface.

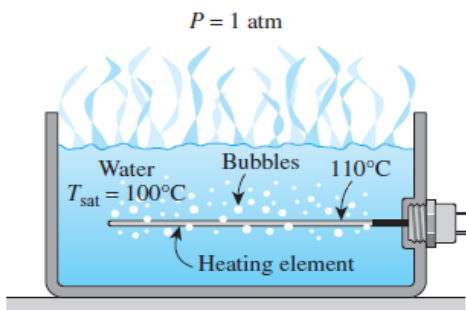


FIGURE 10-2

Boiling occurs when a liquid is brought into contact with a surface at a temperature above the saturation temperature of the liquid.

Evaporation occurs at the *liquid-vapor interface* when the vapor pressure is less than the saturation pressure of the liquid at a given temperature. Water in a lake at 20°C, for example, evaporates to air at 20°C and 60 percent relative humidity since the saturation pressure of water at 20°C is 2.3 kPa and the vapor pressure of air at 20°C and 60 percent relative humidity is 1.4 kPa

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 (Fig. 10-2). At 1 atm, for example, liquid water in contact with a solid surface at 110°C boils since the saturation temperature of water at 1 atm is 100°C. 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.

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.

2- Boiling Heat Transfer.

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

$$Q = h A_s (t_s - t_{sat}) = h A_s \Delta t_e \quad \text{-----(1)}$$

where,

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

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 may be in general of two types. The one in which the heating surface is submerged in a quiescent part of liquid, and the heat transfer occur by free convection and bubble agitation. The process is known as pool boiling. The pool boiling may further be divided into sub-cooled or local boiling and saturated or bulk boiling. If the temperature of the liquid is below the saturation temperature, the process is known as sub-cooled, or local, boiling. If the liquid is maintained at saturation temperature, the process is known as saturated or bulk boiling.

The other form of the boiling is known as forced convective boiling in which the boiling occurs simultaneously with fluid motion induced by externally imposed pressure difference. In this chapter, we will mostly consider the pool boiling.

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

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).

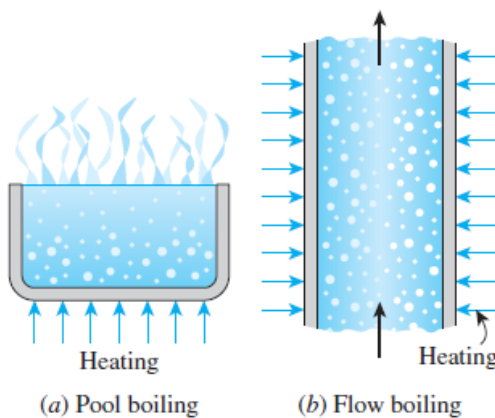


FIGURE 10-3

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

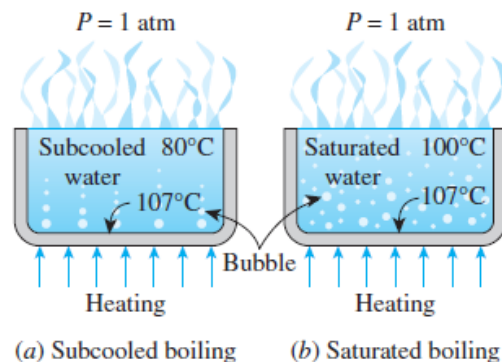


FIGURE 10-4

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

3- Boiling Regime.

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.

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. 1 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 .

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.

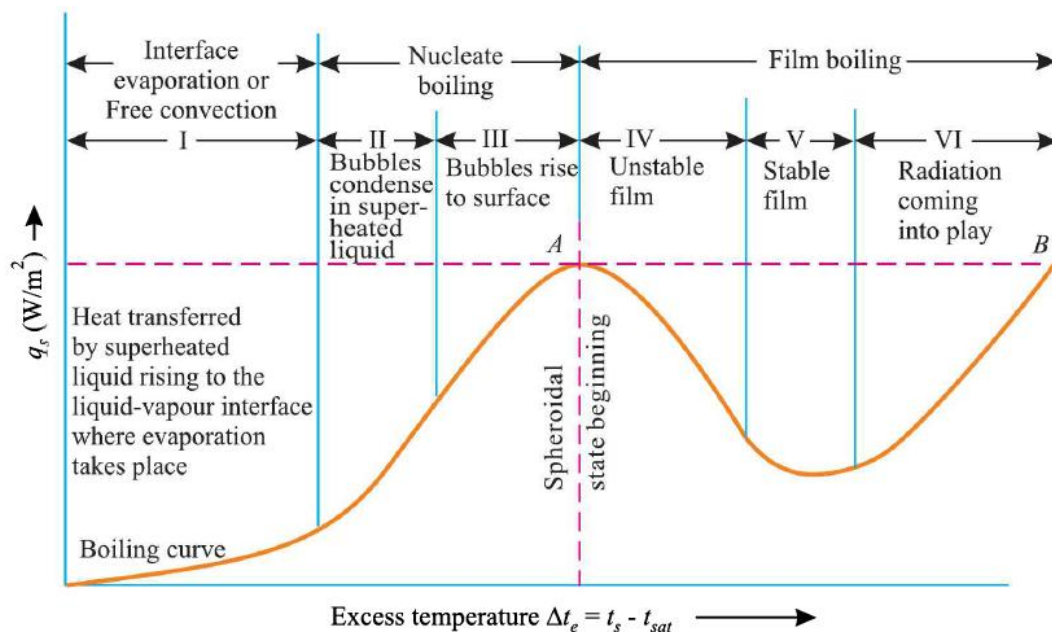


Fig.(1) The boiling curve for water.



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. 1) and is of the order of 1MW/m^2 .

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*).

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*.

4- Heat Transfer Correlations in Pool Boiling.

A- Free Convection Relations.

Boiling regimes discussed above differ considerably in their character, and thus different heat transfer relations need to be used for different boiling regimes (Fig. 2). In the *natural convection boiling* regime ($\Delta T_e \leq 5^\circ\text{C}$), boiling is governed by natural convection currents, and heat transfer rates in this case can be determined accurately using natural convection relations presented in previous lectures.

B- Nucleate Pool Boiling.

In the *nucleate boiling* regime ($5^\circ\text{C} \leq \Delta T_e \leq 30^\circ\text{C}$), the rate of heat transfer strongly depends on the nature of nucleation (the number of active nucleation sites on the surface, the rate of bubble formation at each site, etc.), which is difficult to predict. The type and the condition of the heated surface also affect the heat transfer. These complications made it difficult to develop theoretical relations for heat transfer in the nucleate boiling regime, and we had to rely on relations based on experimental data. The most widely used correlation for the rate of heat transfer in the nucleate boiling regime was proposed in 1952 by Rohsenow, and expressed as

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

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

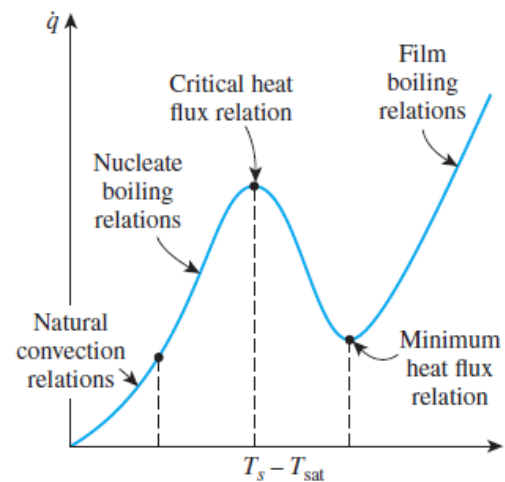


Figure 2

Different relations are used to determine the heat flux in different boiling regimes.

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

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

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

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

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

C- Peak Heat Flux.

In the design of boiling heat transfer equipment, it is extremely important for the designer to have a knowledge of the maximum heat flux in order to avoid the danger of burnout. The *maximum* (or *critical*) *heat flux* in nucleate pool boiling was determined theoretically by S. S. Kutateladze in Russia in 1948 and N. Zuber in the United States in 1958 using quite different approaches, and is expressed as

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

D- 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:

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

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

$$h = h_{conv.} + \frac{3}{4} h_{rad}.$$

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

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

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

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

where ϵ is the emissivity of solid.