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## UNIT –III

### Introduction to Convection

Thermal convection occurs when a temperature difference exists between a solid surface and a fluid flowing past it.

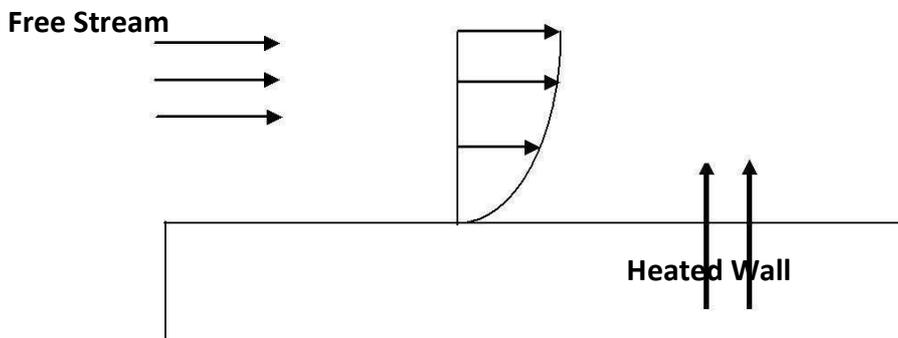


Fig. 1 Convection Phenomena

It is well known that a hot plate of metal will cool faster when placed in front of a fan than when exposed to still air.

For example, we know that the velocity at which the air blows over the hot plate obviously influences the heat transfer rate. But does it influence the cooling in a linear way? i.e. if the velocity is doubled, will the heat transfer rate doubled?

#### Relation with conduction:

As shown in Fig.1 the velocity of fluid layer at the wall will be zero, the heat must be transferred by **conduction** at that point.

Thus we might compute the heat transfer using Fourier's equation of conduction i.e. with the thermal conductivity of fluid and the fluid temperature gradient at wall.

Why then, if the heat flows by conduction in this layer, do we speak of "Convection" heat transfer and need to consider the velocity of the fluid?

The answer is that the temperature gradient is dependent on the rate at which the fluid carries the heat away; a high velocity produces a large temperature gradient, and so on.

It must be remembered that the physical mechanism of heat transfer at the wall is a conduction process.

## Newton-Rikhman Law or Newton's Law of Cooling OR

The value of film co-efficient is dependent upon:

1. Surface conditions: Roughness & Cleanliness
2. Geometry and orientation of surface: Plate, Tube and Cylinder placed horizontally or vertically.
3. Thermo-physical properties of the fluid: Density, Viscosity, Specific heat, Co-efficient of expansion and thermal conductivity.
4. Nature of fluid flow: Laminar or Turbulent
5. Boundary layer configuration
6. Existing thermal conditions.

The film co-efficient depends on viscosity of fluid because the viscosity influences the velocity profile and correspondingly the energy transfer rate in the region near the wall.

## Free and Forced Convection

With respect to the cause of fluid flow, two types of convection are distinguished:

1. Free Convection or Natural Convection and
2. Forced Convection.

### 1. Free Convection or Natural Convection

When a surface is maintained in still fluid at a temperature higher or lower than that of the fluid, a layer of fluid adjacent to the hot or cold surface gets heated or cooled by conduction.

A density difference is created between this adjacent layer and the still fluid surrounding it.

The density difference introduces a buoyant force causing flow of fluid near the surface.

Heat transfer under such conditions is known as Free or Natural Convection.

Thus, "Free or Natural convection is the process of heat transfer which occurs due to movement of the fluid particles by density changes associated with temperature differential in a fluid."

This mode of heat transfer occurs very commonly, some of the examples are:

House heating system, the cooling of transmission lines, electric transformers and rectifiers.

### 2. Forced Convection

Flow of fluid is caused by a pump, a fan or by the atmospheric winds.

These mechanical devices speeds up the heat transfer rate.

In free convection flow velocities encountered are lower compared to flow velocities in forced convection, consequently the value of convection co-efficient is lower, and for a given rate of heat transfer larger area could be required.

Examples of forced convection are: cooling of I.C. Engines, Air conditioner, Heat exchangers, etc.

## Dimensional Analysis

"Dimensional analysis is a mathematical technique which makes use of the study of the dimensions for solving several engineering problems."

Dimensional analysis has become an important tool for analysing fluid flow problems. It is especially useful in presenting experimental results in a concise form.

There are two methods are used in dimensional analysis: Rayleigh's Method and Buckingham's -Theorem.

### Buckingham's $\pi$ -Theorem

"If there are variables (independent and dependent variables) in a physical phenomenon and if these variables contain fundamental dimensions, then the variables are arranged into dimensionless terms.

#### System of Dimensions:

In the area of heat transfer, two more dimensions namely the temperature difference and the heat are also taken as fundamental quantities.

Here heat can be expressed in terms of MLT. So the fundamental quantities are mass, length, time and temperature; designated by the M, L, T &  $\theta$  respectively.

Temperature is specially used in compressible flow and heat transfer phenomena.

### Dimensionless Numbers & Their Physical Significance

#### 1. Reynolds Number (Re)

It is defined as a ratio of inertia force to viscous force.

It indicates the relative importance of the inertial and viscous effects in a fluid motion.

At low Reynolds number, the viscous effect dominates and the fluid motion is laminar.

At high Reynolds number, the inertial effects lead to turbulent flow.

Reynolds number constitutes an important criterion of kinematic and dynamic similarity in forced convection heat transfer.

#### 2. Prandtl Number (Pr)

"It is the ratio of kinematic viscosity to thermal diffusivity of the fluid".

The kinematic viscosity represents the momentum transport by molecular friction and thermal diffusivity represents the heat energy transport through conduction.

Pr provides a measure of the relative effectiveness of **momentum** and **energy** transport by diffusion.

For highly viscous oils, Pr is quite large (100 to 10000) and that indicates rapid diffusion of momentum by viscous action compared to the diffusion of energy.

For gases, Pr is about 1, which indicates that both momentum and heat dissipate through the field at about the same rate.

The liquid (liquid sodium or liquid potassium) metals have Pr = 0.003 to 0.01 and that indicates more rapid diffusion of energy compared to the momentum diffusion rate.

The Prandtl number is connecting link between the velocity field and the temperature field, and its value strongly influences relative growth of velocity and thermal boundary layers.

#### 3. Nusselt Number (Nu)

Nu established the relation between convective film co-efficient ( ), thermal conductivity of the fluid ( ) and a significant length parameter ( ) of the physical system.

To understand the physical significance of the Nu, consider a fluid layer of thickness and temperature difference as shown in Fig. 2.



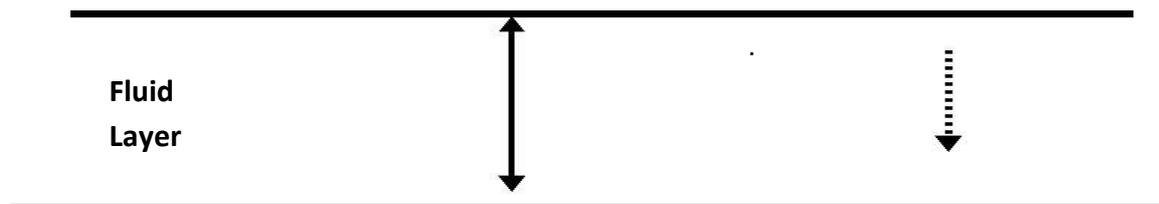


Fig. 2 Heat transfer through the fluid layer

Heat transfer through the fluid layer is by **convection** when the fluid involves some motion and by **conduction** when the fluid layer is motionless.

#### 4. Grashoff Number (Gr)

It indicates the relative strength of the buoyant to viscous forces.

Obviously the Grashoff number represents the ratio of buoyant force and Inertia force to the square of the viscous force.

Grashoff number has a role in free convection.

Free convection is usually suppressed at sufficiently small Gr, begins at some critical value of Gr and then becomes more and more effective as Gr increases.

#### 5. Stanton Number (St)

“It is the ratio of heat transfer co-efficient to the flow of heat per unit temperature rise due to the velocity of fluid”.

It should be noted that Stanton number can be used only in co-relating forced convection data (since the expression contains velocity).

#### 6. Peclet Number (Pe)

“It is the ratio of mass heat flow rate by convection to the flow rate by conduction under an unit temperature gradient and through a thickness”.

The Peclet number is a function of Reynolds number and Prandtl number.

#### 7. Graetz Number (G)

“It is the ratio of heat capacity of fluid flowing through the pipe per unit length to the conductivity of pipe material.”

Graetz number is merely a product of a constant and the Peclet number.

## Dimensional Analysis Applied to Forced Convection & to Free Convection

### Key Notes:

In natural or free convection, the flow is produced by buoyant effects resulting from temperature difference. These effects are included in the Grashoff number.

Reynolds number is important in the case of forced convection and similarly the Grashoff number is important in the case of free convection.

### Empirical Co-relations for Free & Forced Convection

Mathematical analysis of convective heat problems is complicated due to the large number of variables involved.

Majority of the convective problems are, therefore, analysed through the technique of dimensional analysis supported by experimental investigations. The dimensional analysis helps to develop certain correlations for the convective coefficient.

The constants and exponents appearing in these correlations for a particular situation are worked out through experiments.

Use "Heat & Mass Transfer by Dr. D. S. Kumar" to see different empirical co-relations for free and forced convection for different cases. (Equations should be given in examination so no need to remember)

Some of the important terminology associated with this topic is explained below:

### Bulk Temperature & Mean Film Temperature

The physical properties ( $\mu$ ,  $\rho$ ,  $C_p$ ,  $k$ ) of a fluid are temperature dependent.

The accuracy of the results obtained by using theoretical relations and the dimensionless empirical co-relations would depend upon the temperature chosen for the evaluation of these properties.

No uniform procedure has been attained in the selection of this reference temperature.

However, it is customary to evaluate the fluid properties either on the basis of **bulk temperature** or the **mean film temperature**.

#### Mean Bulk Temperature:

The mean bulk temperature ( $t_b$ ) denotes the equilibrium temperature that would result if the fluid at a cross section was thoroughly mixed in an adiabatic container.

For internal flow (Heat exchangers), the fluid flowing through the tubes may be heated or cooled during its flow passage. The bulk temperature is then taken to be the arithmetic mean of the temperatures at inlet to and at exit from the heat exchanger tube; i.e.

#### Mean Film Temperature:

It is the arithmetic mean of the surface temperature of a solid and the undisturbed temperature of the fluid which flows over the surface.

## Thermal and Hydrodynamic Boundary Layer

The concept of boundary layer was first introduced by L. Prandtl in 1904 and since then it has been applied to several fluid flow problems.

### A. Hydrodynamic Boundary Layer: Flat Plate

“When a fluid flows around an object, there exist a thin layer of fluid close to the solid surface within which shear stresses significantly influence the velocity distribution. The fluid velocity varies from zero at the solid surface to the velocity of free stream flow at a certain distance away from the solid surface. This thin layer of changing velocity has been called the **hydrodynamic boundary layer**.”

Consider the parallel flow of a fluid over a flat plate as shown in Fig. 3.

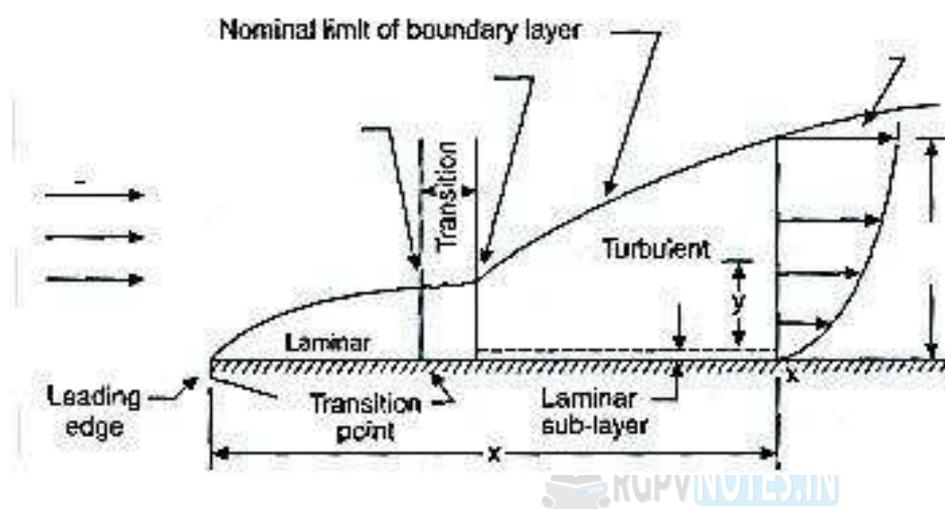


Fig. 3 Development of a boundary layer on a flat plate

The edge facing the direction of flow is called leading edge. The rear edge is called the trailing edge.

The velocity of the fluid particles in the first fluid layer adjacent to the plate becomes zero because of the no-slip condition.

This motionless layer slows down the particles of the neighbouring fluid layer as a result of friction between the particles of these two adjoining fluid layers at different velocities.

This fluid the thickness of boundary layer increases with distance from the leading edge; as more and more fluid is slowed down by the viscous effects, becomes unstable and breaks into turbulent boundary layer.

In turbulent boundary layer, a very thin layer near the smooth surface remains laminar, called **laminar sub-layer**.

For the flow over a flat surface, if Reynolds No. is less than  $5 \times 10^5$ , the flow is laminar and velocity distribution is parabolic.

#### The boundary layer thickness:

“It is arbitrarily defined as that distance from the plate surface in which the velocity reaches 99% of the velocity of the free stream.

The hypothetical line of divides the flow over a plate into two regions:

- (a) **The boundary layer region**, in which the viscous effects and the velocity changes are significant and (b) **The irrotational flow region**, in which the frictional effects are negligible and the velocity remains essentially constant.

## B. Thermal Boundary Layer

Whenever a flow of fluid takes place over a heated or cold surface, a temperature field is set-up in the field next to the surface. The zone or thin layer wherein the temperature field exists is called the **thermal boundary layer**.

The temperature gradient results due to heat exchange between the plate and the fluid.

Consider the flow of a fluid at a uniform temperature of over a hot flat plate at temperature as shown in Fig. 4.

The fluid particles in the layer adjacent to the surface will reach thermal equilibrium with the plate and assume the surface temperature. These fluid particles will then exchange energy with the particles in the adjoining fluid layer and so on. As a result, a temperature profile will develop in the flow field that ranges from at the surface to sufficiently far from the surface.

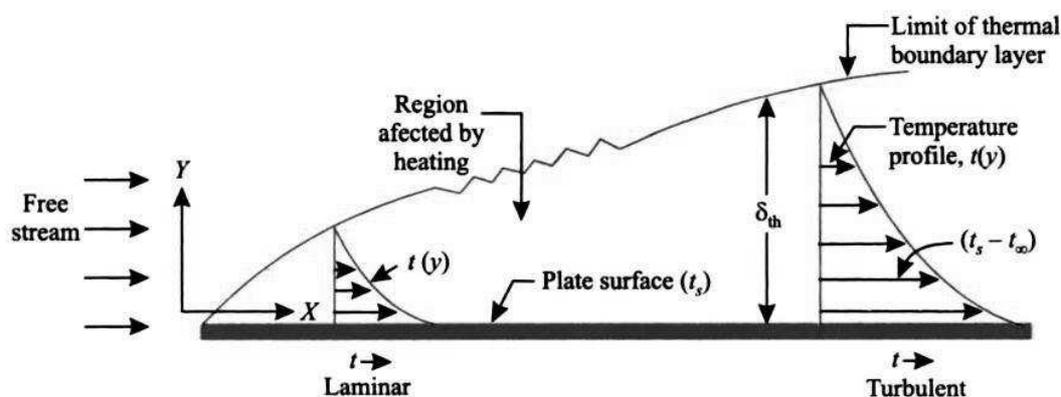


Fig. 4 Thermal boundary layer during flow of cold fluid over a warm plate

The flow region over the surface in which the temperature variation in the direction normal to the surface is significant is the **thermal boundary layer**.

**The thickness of the thermal boundary layer** defined as the distance from the surface at equal at any location along the surface is which the temperature difference.

The thickness of the thermal boundary layer increases in the flow direction, since the effects of heat transfer are felt at greater distances from the surface further downstream.

If the approaching free stream temperature is above the plate surface temperature, the thermal boundary layer will have the shape as depicted in Fig. 5.

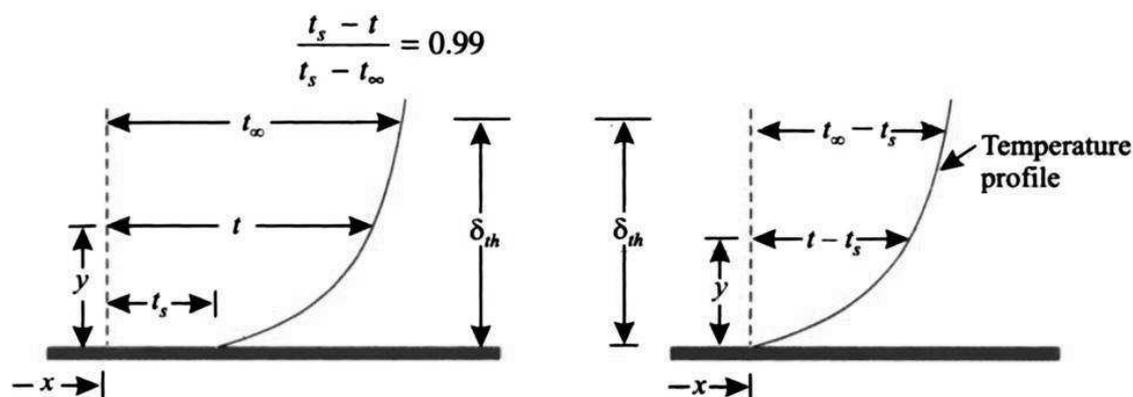


Fig. 5 Temperature profile in T.B.L. when warm fluid flows over a cold plate

The temperature of the fluid changes from a minimum at the plate surface to the temperature of the main stream at a certain distance from the surface.

At point A, the temperature of the fluid is the same as the surface temperature .

The fluid temperature increases gradually until it acquires the free stream temperature.

The distance measured perpendicularly to thickness of thermal boundary layer at a distance plate.

### **Relation between Thermal & Velocity Boundary Layer**

The velocity profile of the velocity boundary layer is dependent primarily upon the viscosity of the fluid.

The temperature profile of the thermal boundary layer is depends upon the flow velocity, specific heat, viscosity and thermal conductivity of the fluid.



## Boiling and Condensation

### Introduction

When the temperature of a liquid at a specified pressure is raised to the saturation temperature ( $T_{\text{sat}}$ ), at that pressure **Boiling** occurs.

Likewise, when the temperature of a vapour is lowered to saturation temperature ( $T_{\text{sat}}$ ), **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 ( $h_{\text{fg}}$ ) of the fluid and the surface tension ( $\sigma$ ) at the liquid vapour 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.

### Boiling

Boiling is the convective heat transfer process that involves a phase change from liquid to vapor state.

Boiling is a liquid to vapour phase change process just like evaporation, but there are significant differences between the two. **Evaporation** occurs at the liquid–vapour 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  $T_{\text{sat}}$  of the liquid. At 1 atm, for example, liquid water in contact with a solid surface at  $110^\circ\text{C}$  will boil since the saturation temperature of water at 1 atm is  $100^\circ\text{C}$ .

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.

### 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.

## 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.



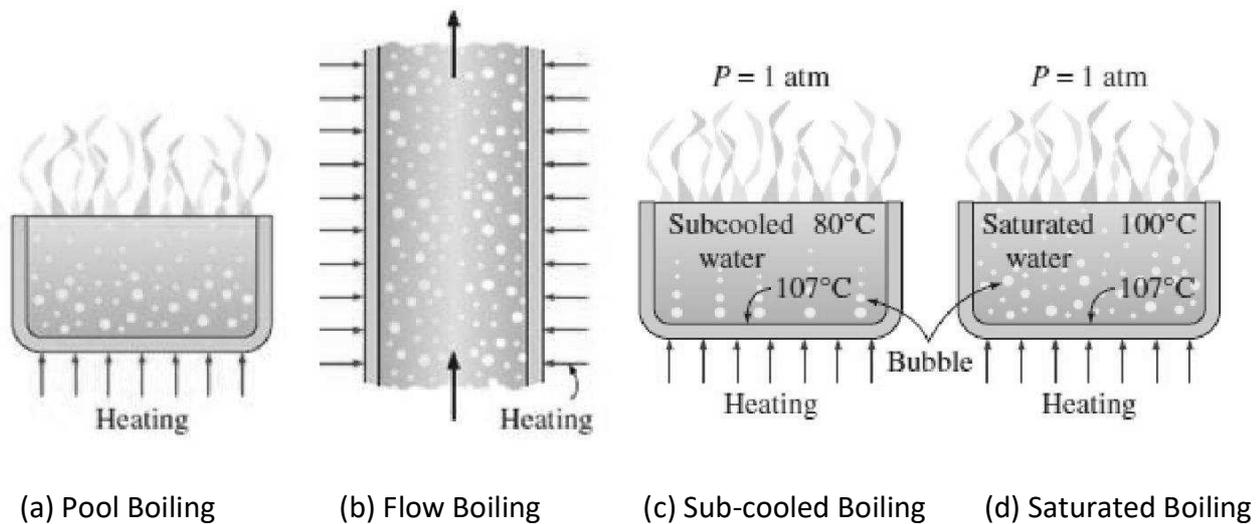


Fig. 1 Classification of boiling

## 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.

### 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. 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. 2 shows the relationship between heat flux and the temperature excess ( $T_s - T_{sat}$ ); Where,

### Different boiling regimes are:

- A. Natural Convection Boiling
- B. Nucleate Boiling
- C. Film Boiling

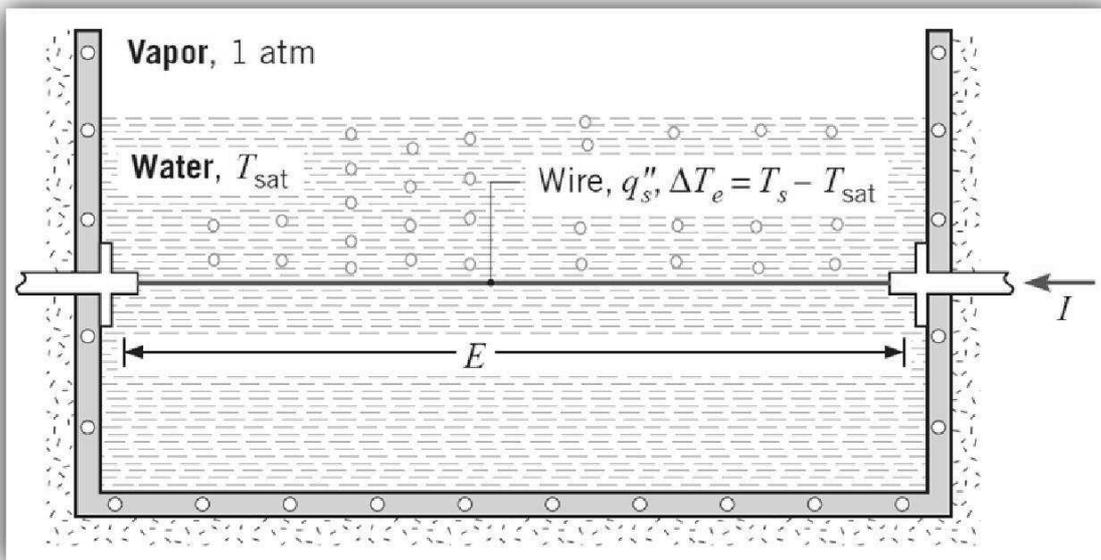


Fig. 2 Nukiyama's power controlled heating apparatus for demonstrating the boiling curve

#### 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.

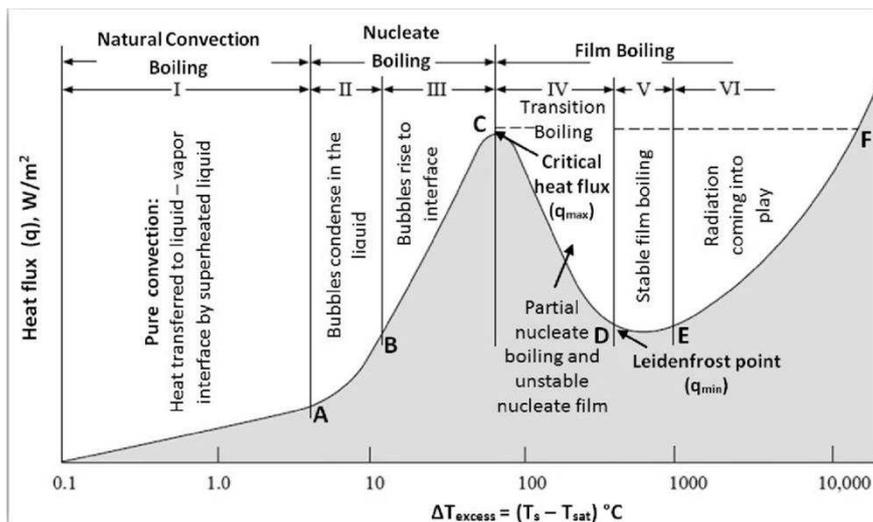


Fig. 3 boiling curve for saturated water at atmospheric pressure

## 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 favourable 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  $\Delta T_{\text{excess}}$ .

### C. Film Boiling (beyond point C on Boiling curve) Transition Boiling (between point C & D)

As the heater temperature and thus  $\Delta T_{\text{excess}}$  is increased past point C, the heat flux decreases as shown in Fig. 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  $\Delta T_{\text{excess}}$ . 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  $q_{\text{max}}$  occurs, we must increase the heated surface temperature ( $T_s$ ).

To increase  $T_s$ , however we must increase the heat flux. But the fluid cannot receive this increased energy beyond point C, and the heated surface temperature ( $T_s$ ) 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.

## 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  $\rightarrow$  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. 4(a) (iii) and they are disengaged from the surface.

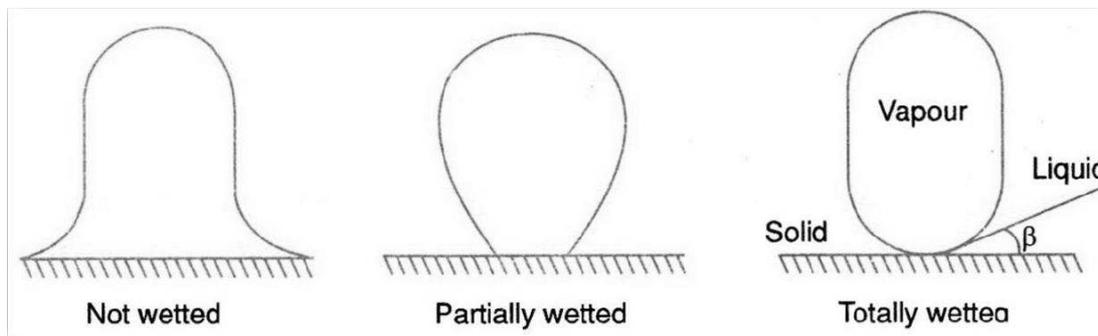


Fig. 4(a) Wetting characteristics for typical vapor bubbles

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. 4(a) (ii).

On the unwetted surface, the bubbles spread out as shown in Fig. 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. 4(a) (iii) gives high heat transfer rate compared with the bubble shapes shown in Fig. 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.

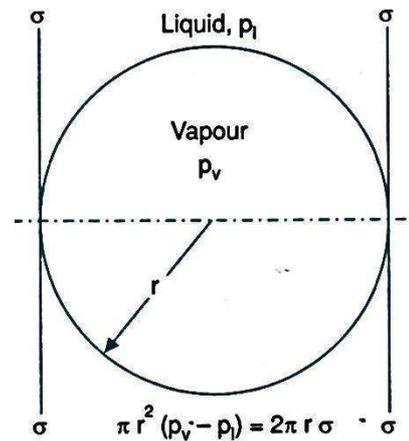


Fig. 4(b) Force balance for a spherical bubble

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. 4(b) indicates one such spherical bubble with various forces acting on it.

- i. The resultant pressure  $(P_v - P_l)$  acts on area  $\pi r^2$  and the pressure force equals  $\pi r^2 (P_v - P_l)$ .
- ii. The surface tension  $\sigma$  of the vapor-liquid interface acts on the interface length  $2\pi r$  and the surface tension force equals  $2\pi r \sigma$ .

### 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 than 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.

## 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,  $T_s$  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 behaviour 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.

### Drop wise and Film wise Condensation

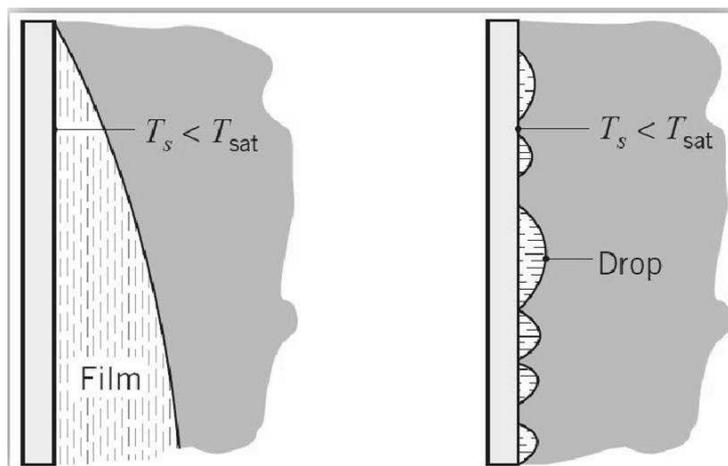


Fig. 5 Film wise and Drop wise Condensation

#### 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 vapor.

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.

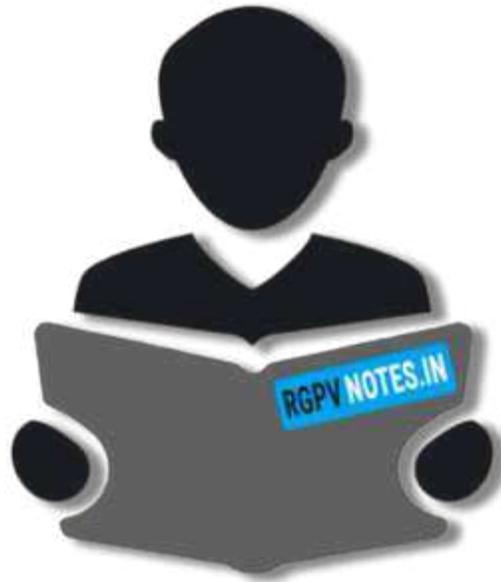
It has been observed that even with a few percent by volume of air in steam the condensation heat transfer coefficient is reduced by more than 50%.

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.



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