Heat transfer with phase change

Boiling heat transfer

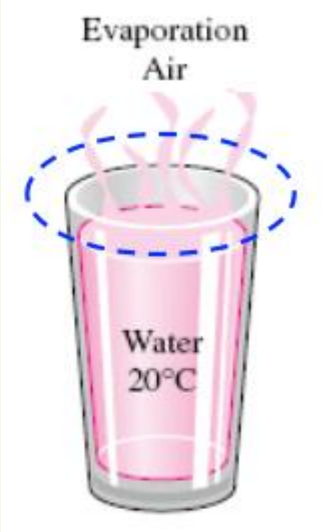
- Boiling heat transfer occurs when there is a ***change of phase from liquid to vapour***

- Boiling occurs at the *solid-liquid interface*, when a liquid is brought in contact with a surface maintained at T_s $(T_s > T_{sat})$

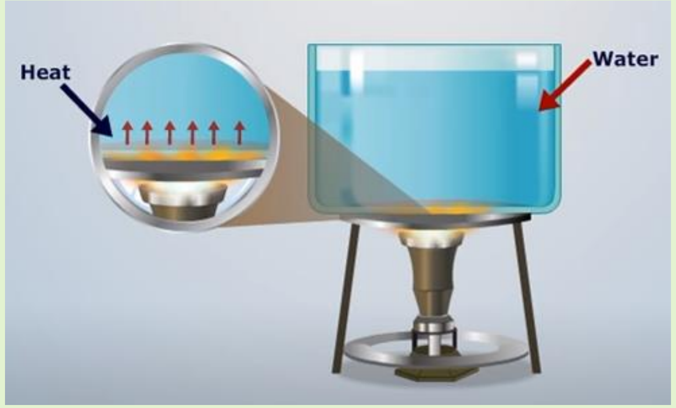
  Boiling is characterised by rapid formation of vapour bubbles at the solid-liquid interface

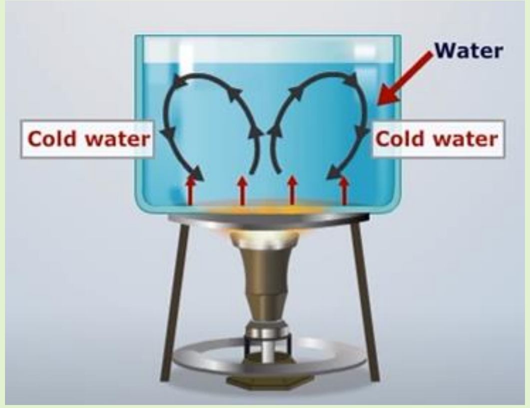
- Evaporation occurs at *liquid-vapour interface* when vapour pressure is less than saturation pressure of liquid at a given temperature

  Evaporation does not involve bubble formation or bubble motion



- When water contained in a beaker is heated, the heat transfer to the water from the hot bottom of the beaker occurs by free convection at the beginning
- When the water is considerably heated, the evaporation starts from the free surface
- As the heating proceeds, the water reaches boiling point and the formation of small vapour bubbles starts
- These small vapour bubbles are mostly formed at the bottom surface and they collapse before reaching the top. This means that although the water at the bottom is at the boiling point, the temperature of the upper layers is still below the boiling point
- As the heating continues, the whole liquid starts boiling. Vapour bubbles are generated at the bottom, grow in size and rise vigorously through the liquid





Classification of boiling

Pool Boiling

- Boiling is called pool boiling when the *fluid is stationary and there is no bulk fluid flow*
- Any *motion of the fluid is due to natural convection currents* and the motion of the bubbles under the influence of buoyancy

Flow Boiling

- Boiling is called flow boiling in the *presence of bulk fluid flow*
- In flow boiling, the *fluid is forced to move in a heated pipe or over a surface by external means* such as a pump

- In **pool boiling** the heated surface is submerged in liquid
- If the temperature of the liquid is below the saturation temperature, the process is called **subcooled** or **local boiling**

  Boiling in this case is confined in a region in the locality of the hot surface

- If the liquid is maintained at saturation temperature, the process is called **saturated** or **bulk boiling**

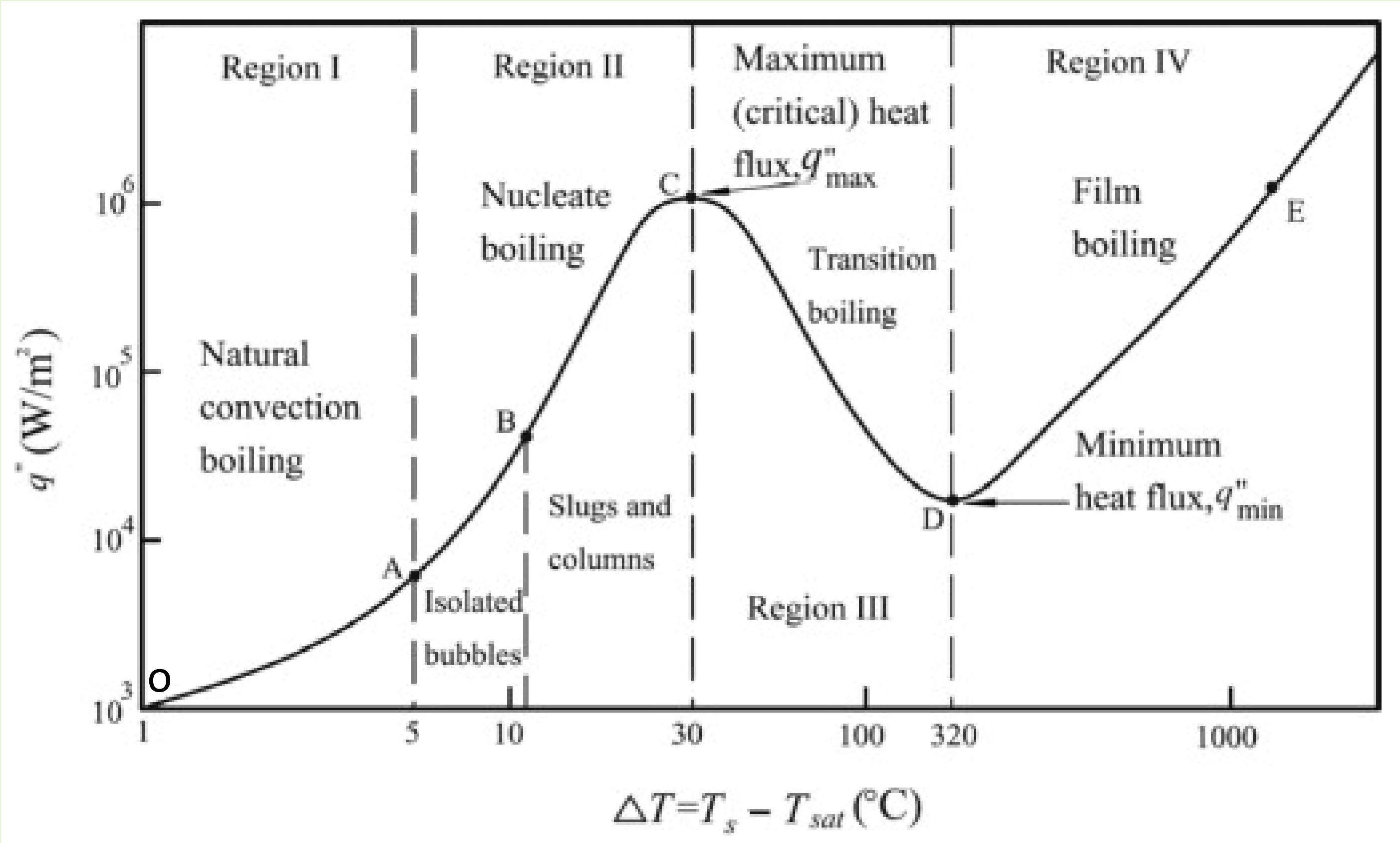
  In this case, we can see bubbles throughout the liquid

Pool boiling curve

- When a surface is exposed to a liquid and is maintained at a temperature above the saturation temperature of the liquid, boiling may occur
- The temperature of the hot surface (T_s) is higher then the boiling point of the liquid (T_{sat}) and the difference is the excess temperature

$$T_e = T_s - T_{sat}$$

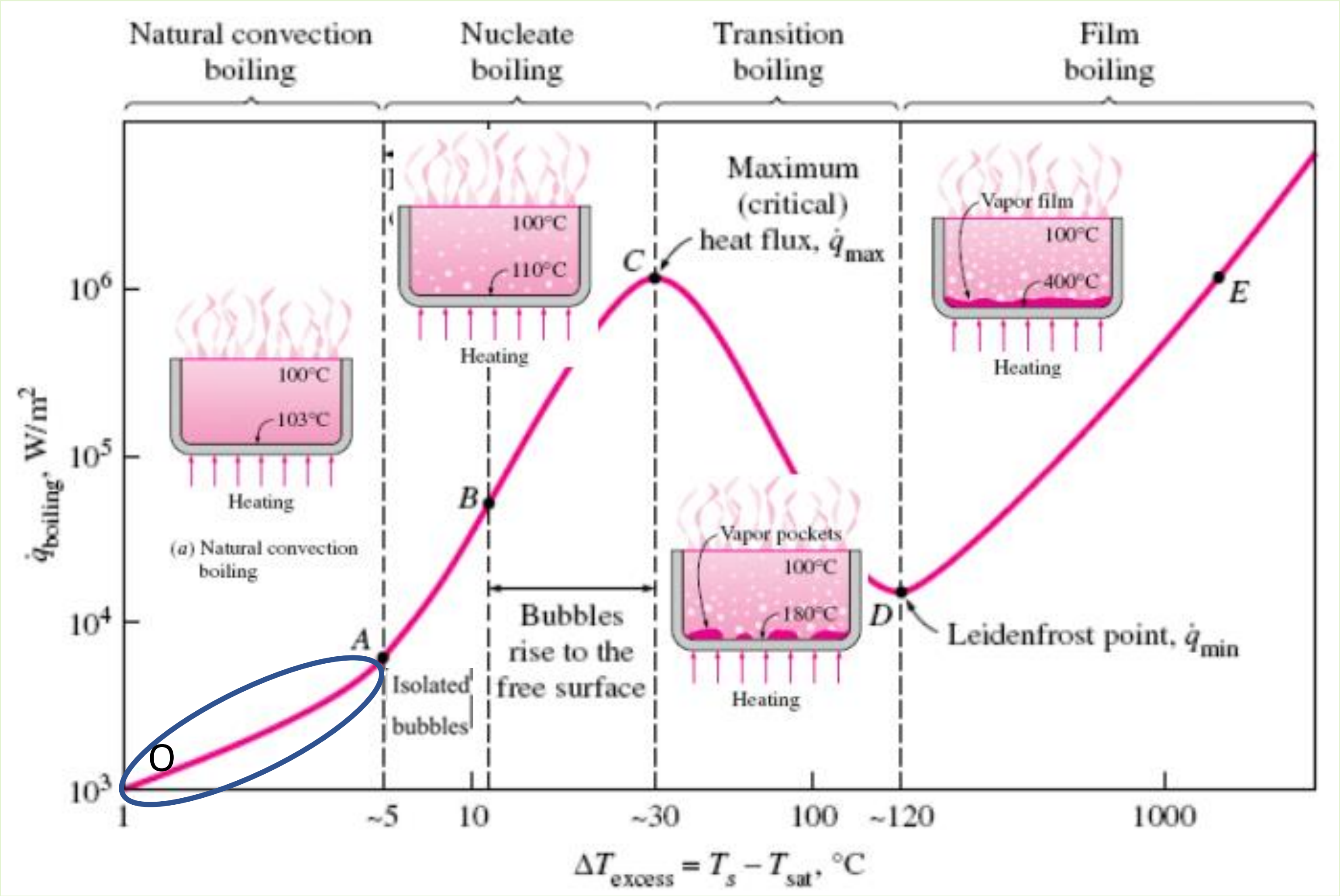
- The heat flux is dependent on this excess temperature, T_e
- When the heated surface is submerged below a free surface of liquid, the process is known as pool boiling
- The heat flux data ($\dot{q}$) is collected from an electrically heated platinum wire submerged in water and is plotted alongside to show the different regimes of boiling



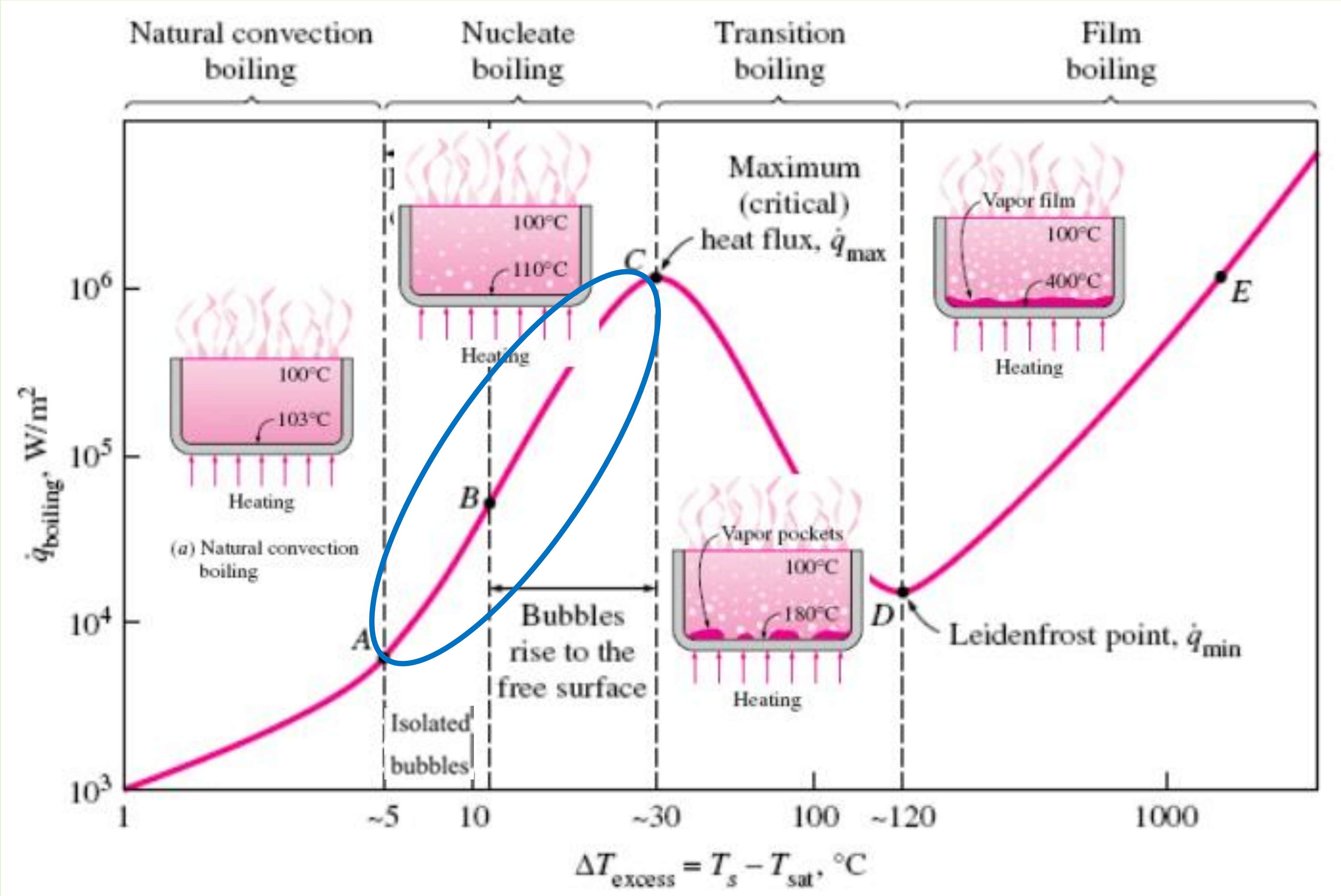
Understanding the pool boiling curve

https://www.youtube.com/watch?v=N1yZwRcQSZw

- In the **section O-A**, the wire temperature is slightly above the saturation temperature of the liquid ($T_e \leq 5°\mathrm{C}$)
- The motion of the liquid is primarily caused by natural convection
- The hot liquid vaporizes at the top surface
- The heat transfer in this region can be calculated using the equations for free or natural convection
- This region is called the ***interfacial evaporation regime*** or ***natural convection boiling regime***

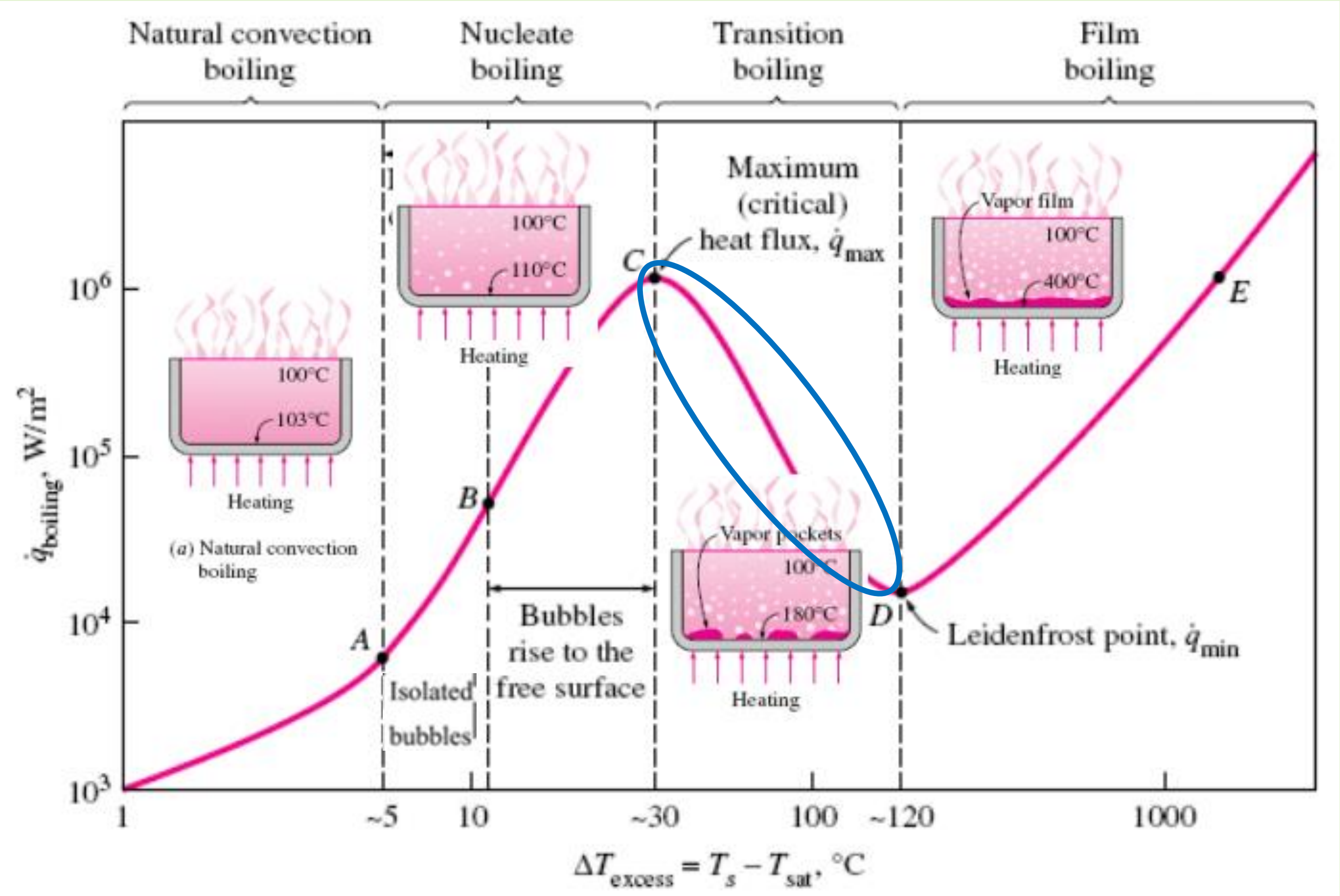


- The section A-B-C is characterized by bubbles forming at an increasing rate at an increasing number of nucleation sites as one moves along the boiling curve toward point C – this region is known as ***nucleate boiling***
- Here the excess temperature varies between $\sim 5^\circ\mathrm{C}$ (at A) to $\sim 30^\circ\mathrm{C}$ (at C) – this regime is subdivided into two regimes
- In the first regime (A-B), bubbles begin to form on the surface of the wire, but most of them collapse before reaching the free surface of the liquid
- As the excess temperature increases (seen from B-C), bubbles form more rapidly and rise to the surface of the liquid and escape at the free surface

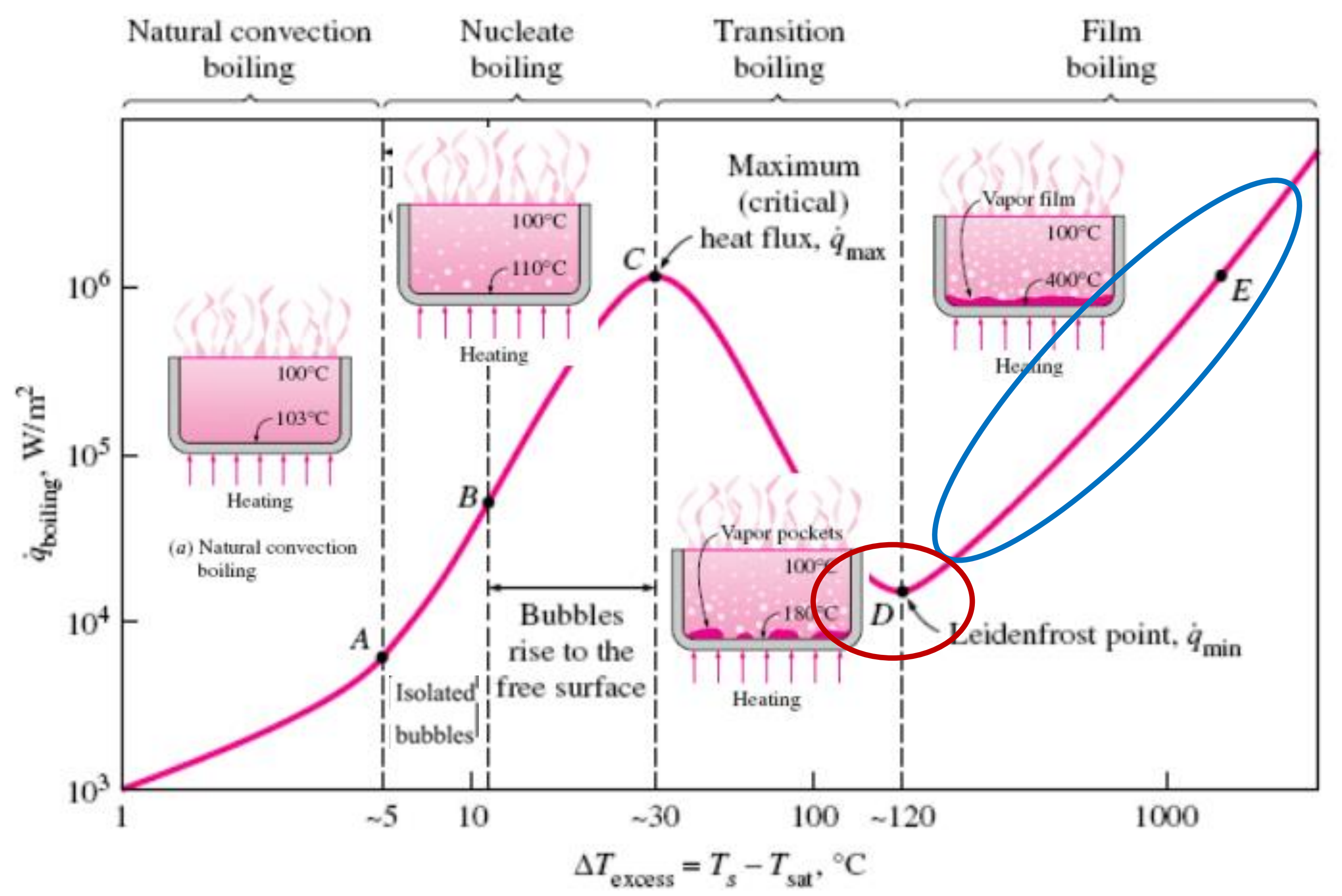


The heat flux at point C is called the ***critical (or maximum) heat flux***

- When is increased beyond point C, the heat flux decreases
- At around point C, the bubbles are formed so rapidly and they are so large in number that they coalesce right on the heating surface to form a film of vapour
- The heat from the wire must be conducted through this film before it can reach the liquid
- The thermal resistance of this film causes a reduction in heat flux from C to D
- In the regime C-D, the formation of the vapour film on the surface is not continuous
- This portion represents a transition from nucleate boiling to film boiling and is called ***partial nucleate boiling*** or ***transition boiling***



- The portion beyond the transition boiling is known as ***film boiling***
- The section around D is characterized by a continuous stable vapour film which blankets the heating surface and has very low heat transfer rates – this region is called ***stable film boiling***
- The lowest heat flux at point D is called the **Leidenfrost point**
- After ***stable film boiling*** regime, as the wire temperature becomes very high, radiative heat transfer comes into play
- Heat flux curve increases and this is seen in the region D-E
- If the excess temperature is too high, the wire might even melt – the meltdown or burnout of the heat transfer surface is called ***boiling crisis***



Formation of bubbles

- In nucleate boiling, the *bubbles are created by expansion of entrapped gas or vapour at small cavities on the surface*
- The *bubbles grow to a certain size*, depending on the surface tension at the liquid-vapour interface and the temperature and pressure
- Depending on the temperature excess, (i) the *bubbles may collapse on the surface*, (ii) may *expand and detach from the surface to be dissipated in the body of the liquid*, or (iii) at sufficiently high temperature, *may rise to the surface of the liquid before being dissipated*

- During *subcooled boiling*, the main mechanism of heat transfer is thought to be the *intense agitation at the heat transfer surface*, which creates high heat transfer rates
- In *saturated boiling*, bubbles may *break away from the surface because of the buoyancy action and move into the liquid*

In this case, heat transfer rate is influenced by both the agitation caused by the bubbles and the vapour transport of energy into the body of the liquid

Formation of bubbles

- In a bubble, the pressure forces of the liquid and vapour must be balanced by the surface tension force at the vapour-liquid interface
- The pressure forces $[(p_v - p_l)\pi r^2]$ acts on an area πr^2, and the surface tension, σ acts on the interface length of $2\pi r$
- The force balance is

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

$$\boxed{(p_v - p_l) = \frac{2\sigma}{r}}$$

- The pressure difference between the inside and outside of the bubble is related to liquid superheat by a Clausius-Clapyron equation (assuming vapour phase behaves like an ideal gas)

$$\frac{dlnp}{dT} = \frac{\lambda}{RT^2}$$

$$\int_{p_l}^{p_v} dlnp = \frac{\lambda}{R}\int_{T_{sat}}^{T_l} \frac{dT}{T^2}$$

$T_l = temperature\ of\ superheated\ liquid = vapour\ temp\ as\ vapour\ is\ in\ thermal\ equilibrium\ with\ liquid$

$p_l = pressure\ in\ superheated\ liquid$

$T_{sat} = boiling\ point\ of\ liquid$

$$\int_{p_l}^{p_v} d\ln p = \frac{\lambda}{R}\int_{T_{sat}}^{T_l}\frac{dT}{T^2}$$

$$\ln\frac{p_v}{p_l} = \frac{\lambda}{R}\left[\frac{1}{T_{sat}} - \frac{1}{T_l}\right]$$

$$\ln\frac{p_v}{p_l} = \ln\left[1 + \frac{p_v - p_l}{p_l}\right] \approx \frac{p_v - p_l}{p_l}$$

$$\therefore \qquad \frac{p_v - p_l}{p_l} = \frac{\lambda}{R}\left[\frac{1}{T_{sat}} - \frac{1}{T_l}\right]$$

Substituting for $(p_v - p_l)$ = $(\frac{2\sigma}{r})$

$$\frac{2\sigma}{r}.\frac{1}{p_l} = \frac{\lambda}{R}\left[\frac{T_l - T_{sat}}{T_{sat}T_l}\right]$$

$$T_l - T_{sat} = \frac{2\sigma}{rp_l}.\frac{RT_{sat}T_l}{\lambda} \approx \frac{2\sigma RT_{sat}^2}{rp_l\lambda}$$

$$\boxed{\therefore \qquad r = \frac{2\sigma RT_{sat}^2}{p_l\lambda(T_l - T_{sat})}}$$

⇒ Radius of vapour bubble in mechanical equilibrium in superheated liquid

At a certain degree of super heat if the bubble is generated which has a radius smaller than the above value, the bubble will not be in mechanical equilibrium and is going to collapse

Correlations for pool boiling heat transfer

Boiling regimes differ considerably in their character - different heat transfer relations need to be used for different boiling regimes

- The first region (**natural convection boiling regime**) is characterized by motion due to natural convection and equations corresponding to natural convection can be used to accurately determine heat transfer rates
- The second region corresponds to **nucleate boiling regime** – the heat flux can be estimated by means of the **Rohsenow equation**

$$\boxed{q_s = \mu_l \lambda \left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2} \left[\frac{C_{pl}(T_s - T_{sat})}{C_{sf}\lambda (Pr_l)^n}\right]^3}$$

where μ_l = liquid viscosity (Pa.s) λ = enthalpy of vaporization (J/kg)

ρ_l, ρ_v = density of liquid, vapour (kg/m^3) σ = surface tension (N/m)

C_{pl} = specific heat of saturated liquid (J/kg^{o}C) T_s, T_{sat} = temp of boiling surface and saturated liquid (K)

Pr_l = Liquid Prandtl No C_{sf} = constant (available in tables) n = 1.0 for water, 1.7 for other liquids

- The **Rohsenow equation** can be used for any geometry and any orientation of the heated surface

- The **critical heat flux or maximum heat flux** (heat flux at C) can be estimated from

$$\boxed{q_{max} = 0.149\rho_v\lambda\left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v}\right]^{1/4}}$$

This is the **Lienhard equation**

- In the section around point D (minimum heat flux) representing the stable film boiling, the boiling heat transfer can be estimated using the **Bromley correlation**

$$\boxed{q_{sb} = h_b\,(T_s - T_{sat})} \qquad and \qquad \boxed{h_b = 0.62\left[\frac{k_v^3\rho_v(\rho_l - \rho_v)g\left(+0.4C_{pv}T_e\right)}{d\mu'_v T_e}\right]^{1/4}}$$

where $T_e = T_s - T_{sat}$ d = tube diameter

- In the section where radiative heat transfer becomes important (**film boiling regime**), the total heat transfer coefficient is calculated as,

$$\boxed{h = h_b\left(\frac{h_b}{h}\right)^{1/3} + h_r}$$

where $h_b = given\ as\ above$ h_r= radiation heat transfer coefficient

$$\boxed{h_r = \frac{\sigma\epsilon(T_s^4 - T_{sat}^4)}{(T_s - T_{sat})}}$$

where
ϵ = emissivity
σ = Stefan Boltzman constant