

Chapter 6

BOILING AND CONDENSATION

Outline

- **Boiling heat transfer**
 - **Pool boiling**
 - **Heat transfer correlation in pool boiling**
 - **Enhancement of heat transfer in Pool Boiling**
 - **Flow boiling**
- **Condensation heat transfer**
 - **Film Condensation**
 - **Drop wise condensation**

BOILING HEAT TRANSFER

- **Evaporation** occurs at the *liquid–vapor interface* when the vapor pressure is less than the saturation pressure of the liquid at a given temperature.
- **Boiling** occurs at the *solid–liquid interface* when a liquid is brought into contact with a surface maintained at a temperature sufficiently above the saturation temperature of the liquid.

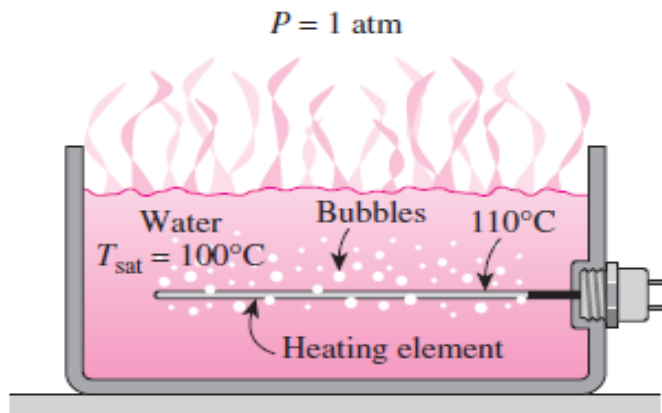


FIGURE 10–2

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



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.

Boiling heat flux from a solid surface to the fluid

$$\dot{q}_{\text{boiling}} = h(T_s - T_{\text{sat}}) = h\Delta T_{\text{excess}} \quad (\text{W/m}^2)$$

$$\Delta T_{\text{excess}} = T_s - T_{\text{sat}} \quad \text{excess temperature}$$

Classification of boiling

- Boiling is called **pool boiling** in the absence of 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.
- 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.

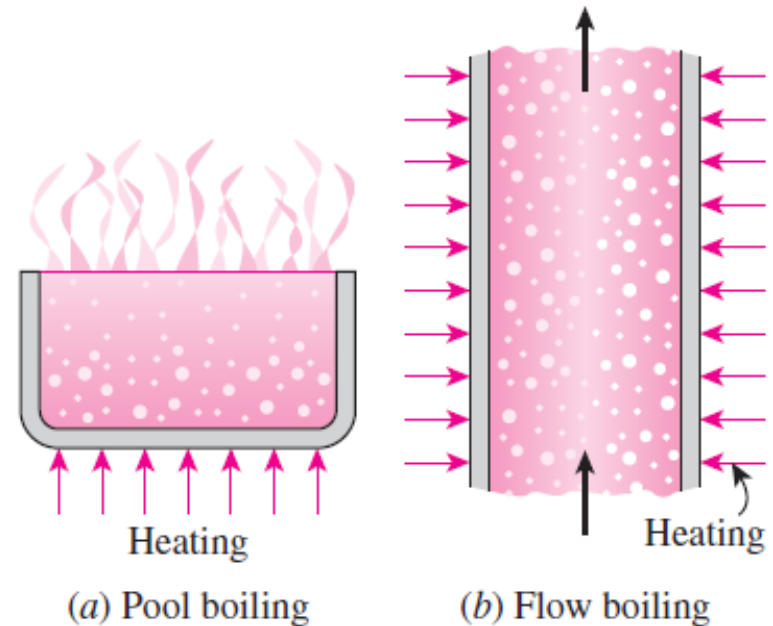


FIGURE 10–3

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

Subcooled Boiling

- When the temperature of the main body of the liquid is below the saturation temperature.

Saturated Boiling

- When the temperature of the liquid is equal to the saturation temperature.

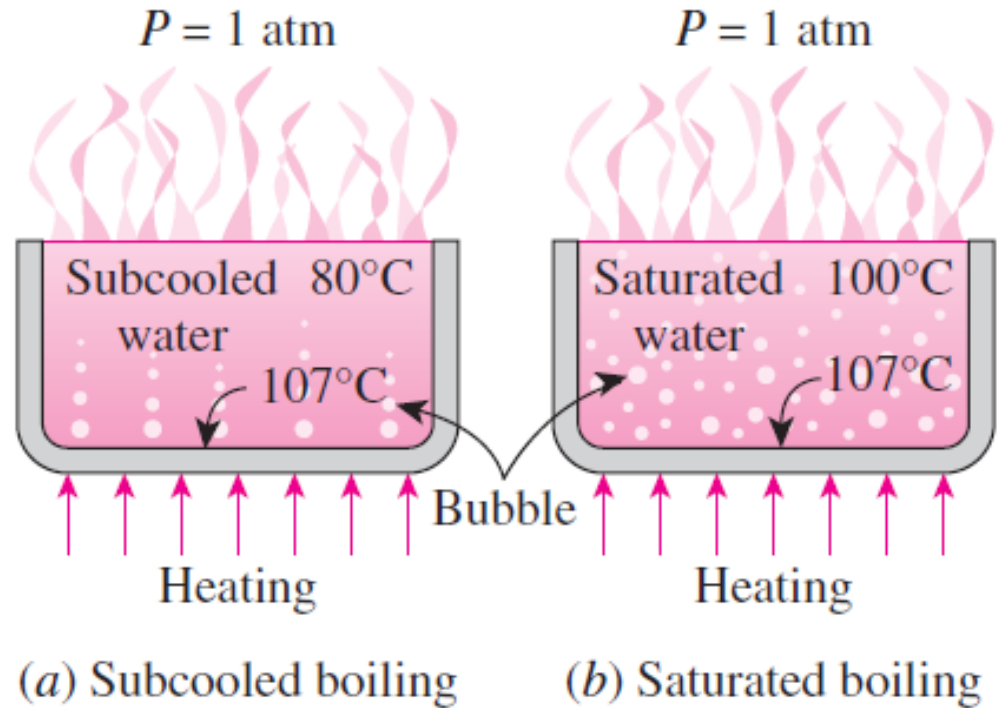


FIGURE 10-4

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

POOL BOILING

In pool boiling, the fluid is not forced to flow by a mover such as a pump.

Any motion of the fluid is due to natural convection currents and the motion of the bubbles under the influence of buoyancy.

Boiling Regimes and the Boiling Curve

$$\dot{q}_{\text{boiling}} = h(T_s - T_{\text{sat}}) = h\Delta T_{\text{excess}}$$

Boiling takes different forms, depending on the $\Delta T_{\text{excess}} = T_s - T_{\text{sat}}$

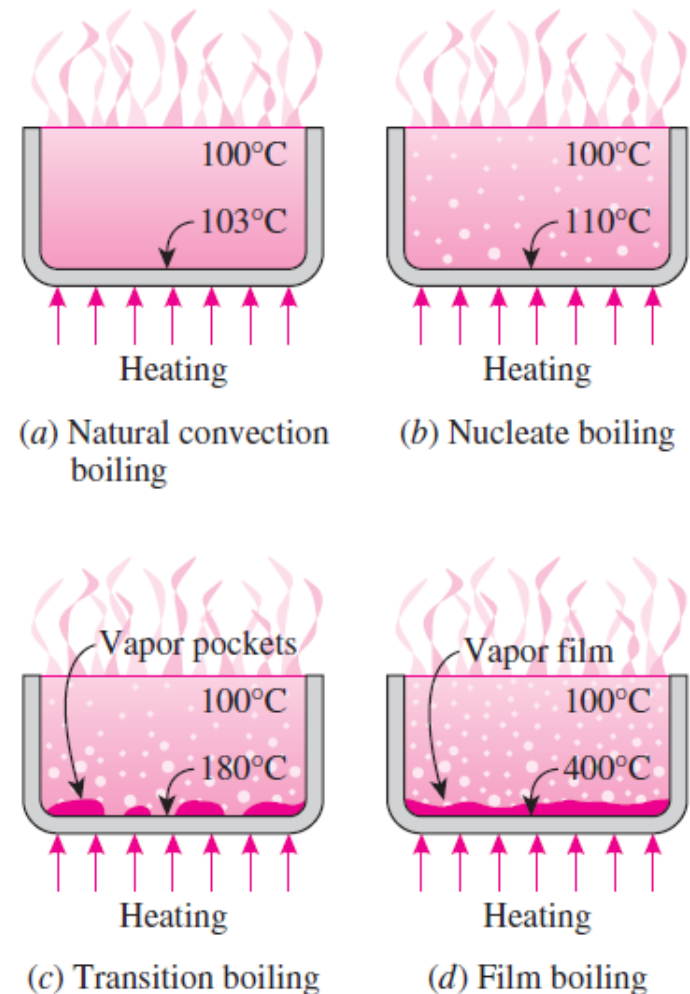


FIGURE 10-5

Different boiling regimes in pool boiling.

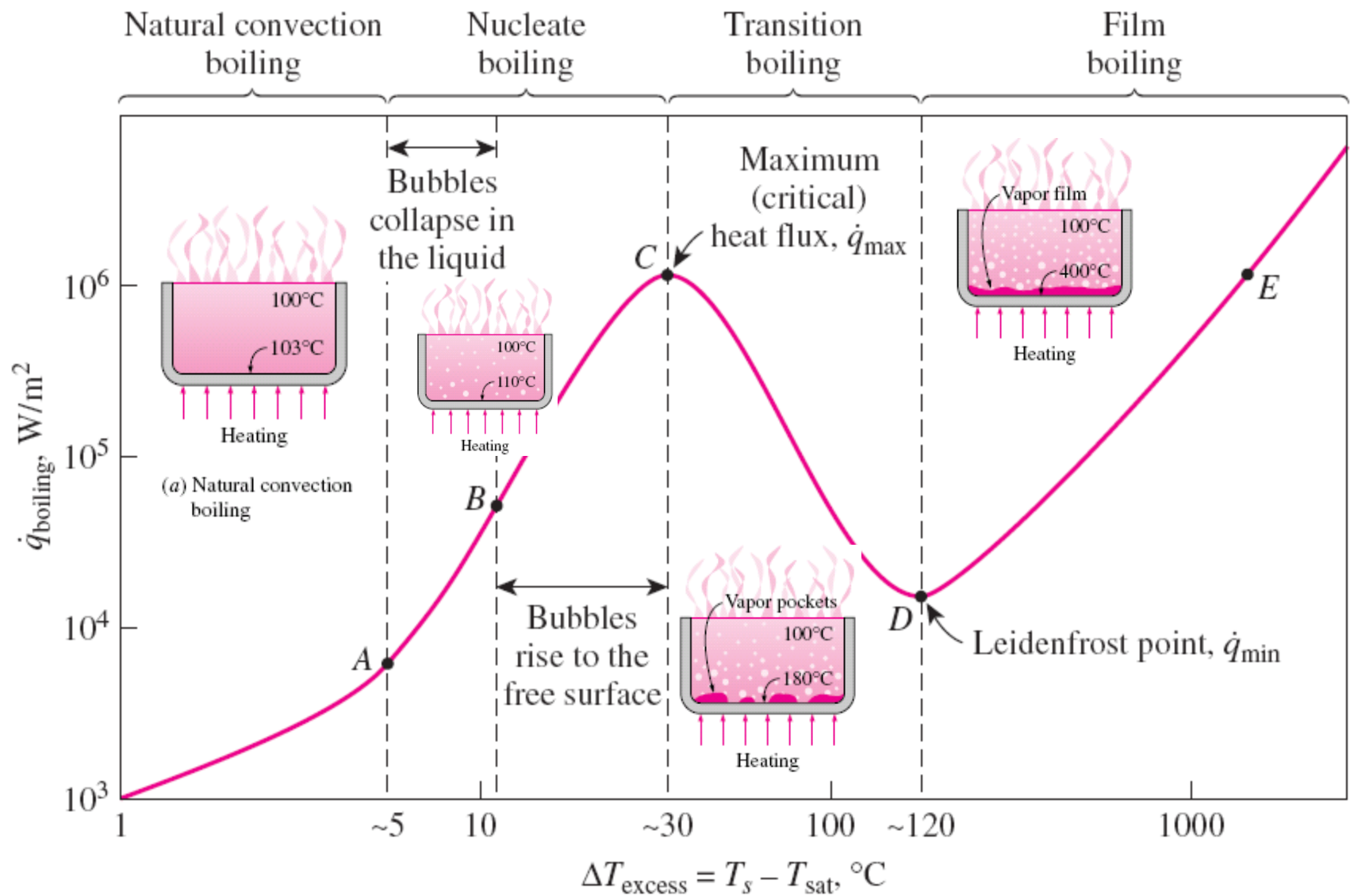
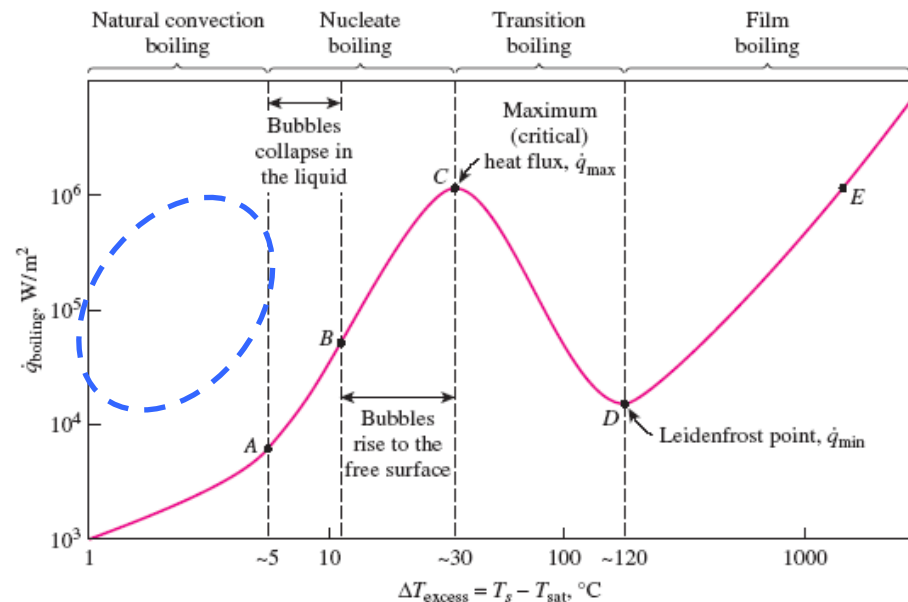


FIGURE 10–6
Typical boiling curve for water at 1 atm pressure.

Natural Convection Boiling (to Point A on the Boiling Curve)

- Bubbles do not form on the heating surface until the liquid is heated a few degrees above the saturation temperature (about 2 to 6°C for water)
- The liquid is slightly *superheated* in this case (*metastable* state).
- The fluid motion in this mode of boiling is governed by natural convection currents.

- Heat transfer from the heating surface to the fluid is by natural convection.
- For the conditions of Fig. 10–6, natural convection boiling ends at an excess temperature of about 5°C.



Nucleate Boiling (between Points A and C)

- The bubbles form at an **increasing rate** at an increasing number of nucleation sites as we move along the boiling curve **toward point C**.



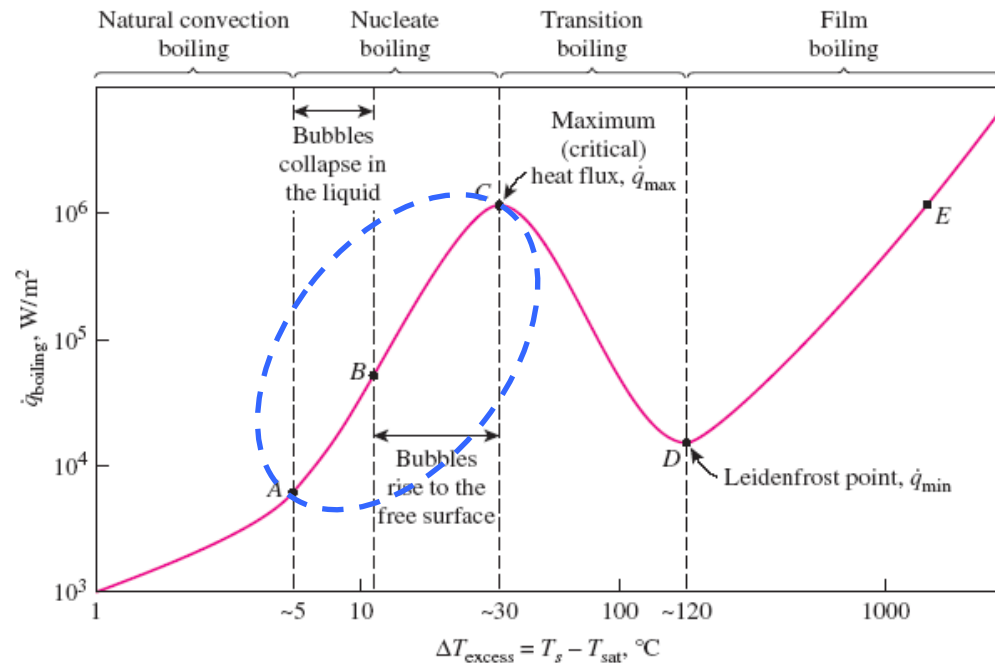
- Region A–B** — *isolated bubbles*.

$$(5^{\circ}\text{C} \leq \Delta T_{\text{excess}} \leq 10^{\circ}\text{C})$$

- Region B–C** — numerous *continuous columns of vapor* in the liquid.

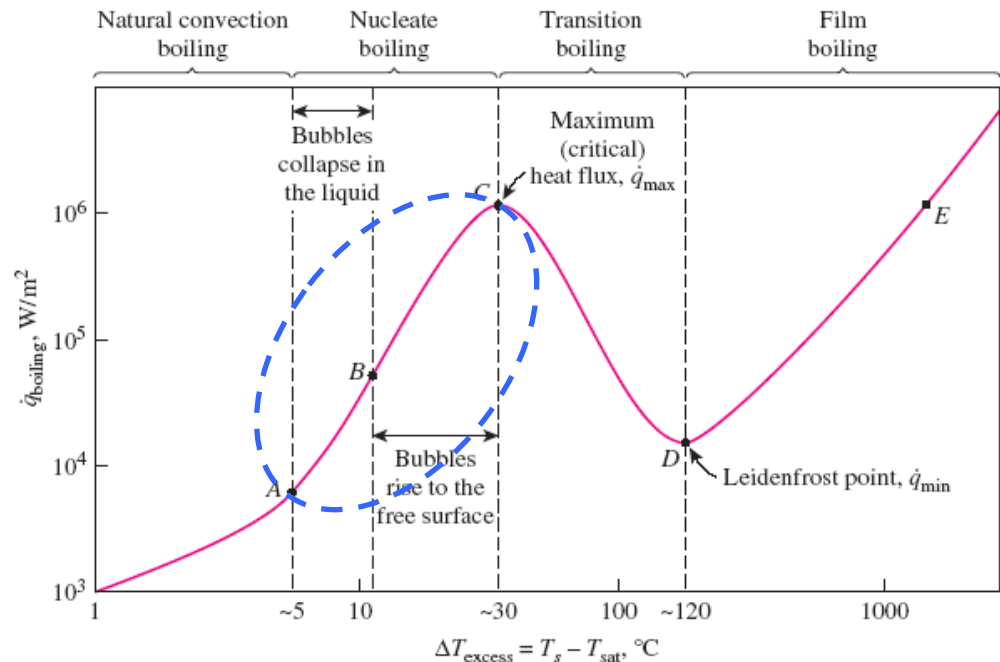
$$(10^{\circ}\text{C} \leq \Delta T_{\text{excess}} \leq 30^{\circ}\text{C})$$

Point A is referred to as the **onset of nucleate boiling (ONB)**.



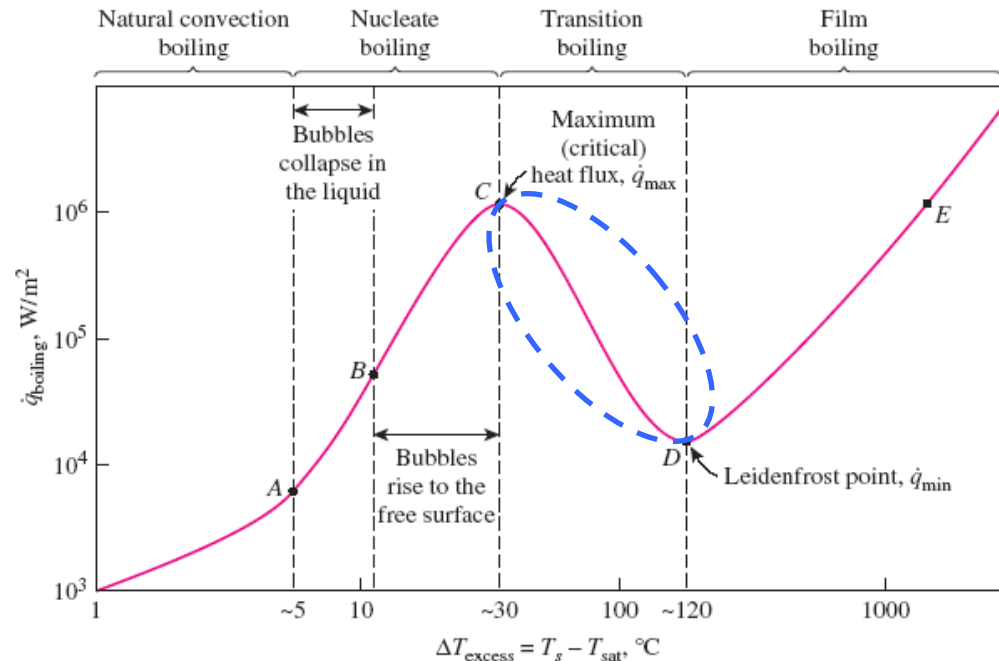
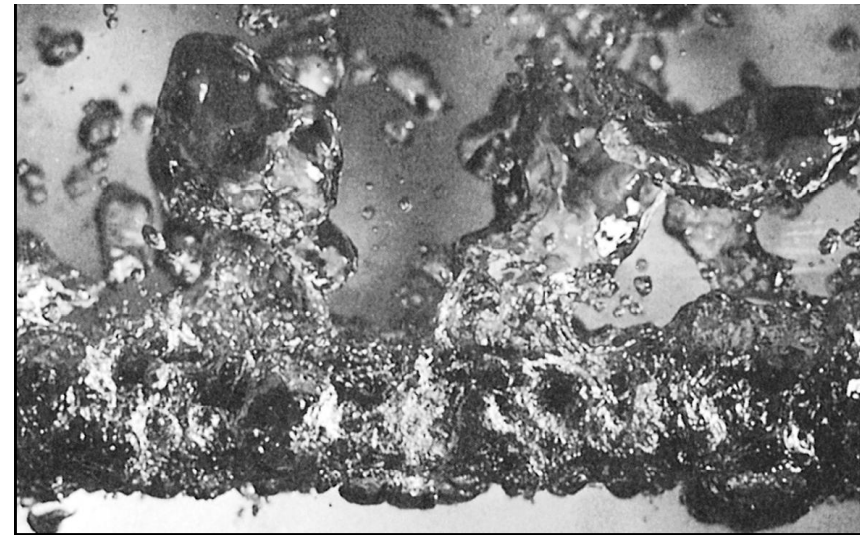
- In **region A–B** the stirring and agitation caused by the entrainment of the liquid to the heater surface is primarily responsible for the increased heat transfer coefficient.
- In **region A–B** the large heat fluxes obtainable in this region are caused by the combined effect of liquid entrainment and evaporation.
- For the entire nucleate boiling range, the heat transfer coefficient ranges from about 2000 to 30,000 W/m²·K.

- After point **B** the heat flux increases at a lower rate with increasing ΔT_{excess} , and reaches a maximum at **point C**.
- The heat flux at this point is called the **critical** (or **maximum**) **heat flux**, and is of prime engineering importance.



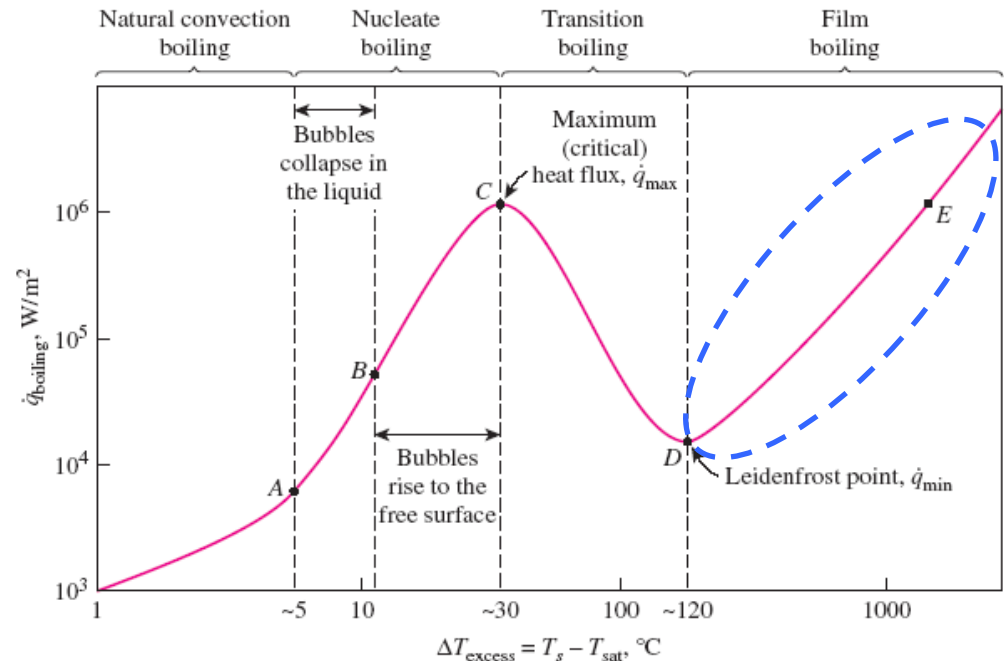
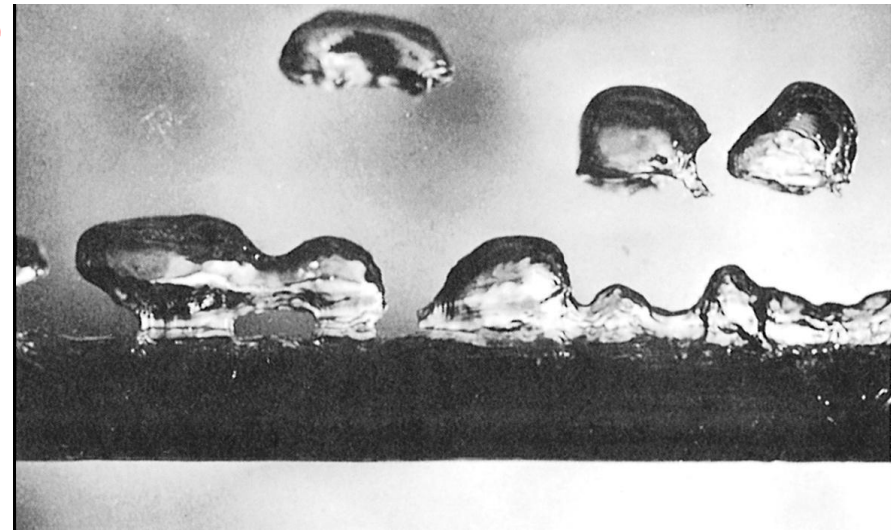
Transition Boiling (between Points C and D)

- When ΔT_{excess} is increased past point **C**, the heat flux decreases.
- This is because a large fraction of the **heater surface** is **covered by a vapor film**, which acts as an insulation.
- In the transition boiling regime, both nucleate and film boiling partially occur.
- Operation in the transition boiling regime, which is also called the **unstable film boiling regime**, is avoided in practice.
- For water, transition boiling occurs over the excess temperature range from about 30°C to about 120°C.



Film Boiling (beyond Point D)

- Beyond **point D** the heater surface is completely covered by a continuous stable vapor film.
- **Point D**, where the heat flux reaches a minimum is called the **Leidenfrost point**.
- The presence of a vapor film between the heater surface and the liquid is responsible for the low heat transfer rates in the film boiling region.
- The heat transfer rate increases with increasing excess temperature due to radiation to the liquid.



Burnout Phenomenon

- A typical boiling process does not follow the boiling curve beyond **point C**.
- When the power applied to the heated surface exceeded the value at **point C** even slightly, the surface temperature increased suddenly to **point E**.
- When the power is reduced gradually starting from **point E** the cooling curve follows Fig. 10–8 with a sudden drop in excess temperature when **point D** is reached.

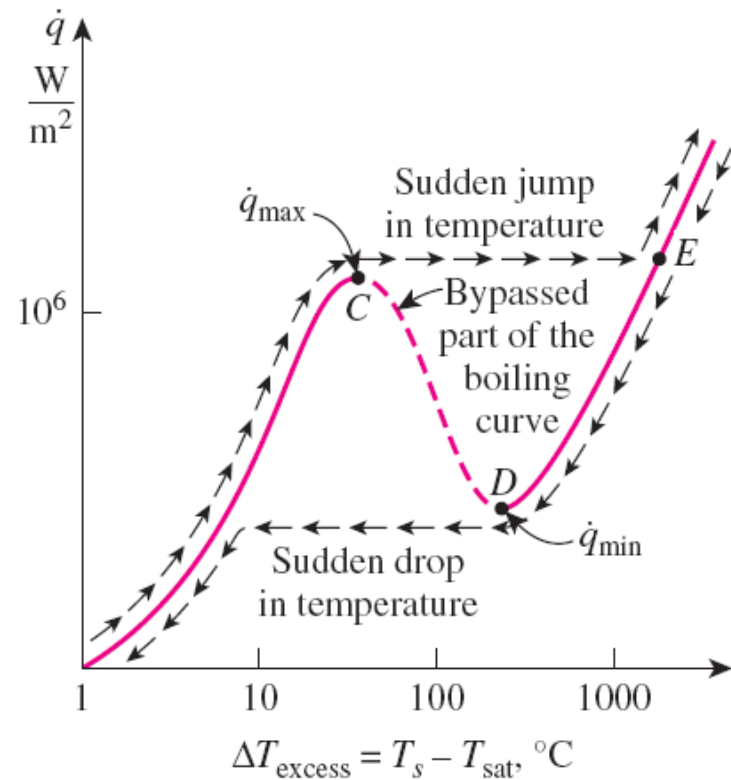


FIGURE 10–8

The actual boiling curve obtained with heated platinum wire in water as the heat flux is increased and then decreased.

- Any attempt to increase the heat flux beyond q_{\max} will cause the operation point on the boiling curve to jump suddenly from **point C** to **point E**.
- However, surface temperature that corresponds to point *E* is beyond the melting point of most heater materials, and **burnout** occurs.
- Therefore, **point C** on the boiling curve is also called the **burnout point**, and the heat flux at this point the **burnout heat flux**.
- Most boiling heat transfer equipment in practice operate **slightly below q_{\max}** to avoid any disastrous burnout.

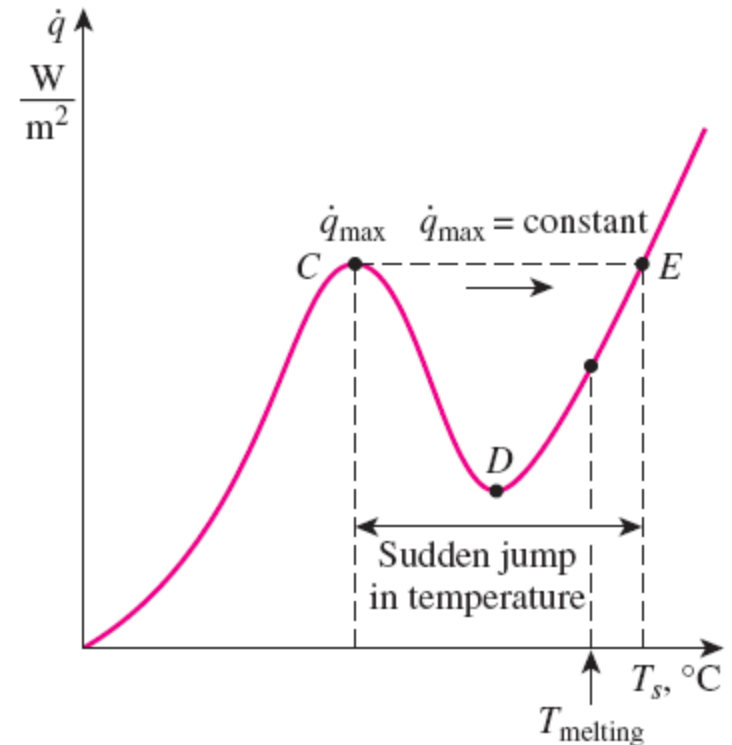


FIGURE 10–9

An attempt to increase the boiling heat flux beyond the critical value often causes the temperature of the heating element to jump suddenly to a value that is above the melting point, resulting in *burnout*.

Heat Transfer Correlations in Pool Boiling

- Boiling regimes differ considerably in their character.
- Different heat transfer relations need to be used for different boiling regimes.
- In the *natural convection boiling regime* heat transfer rates can be accurately determined using natural convection relations.

Nucleate Boiling

- No general theoretical relations for heat transfer in the *nucleate boiling regime* is available.
- Experimental based correlations are used.
- The rate of heat transfer strongly depends on the nature of nucleation and the type and the condition of the heated surface.

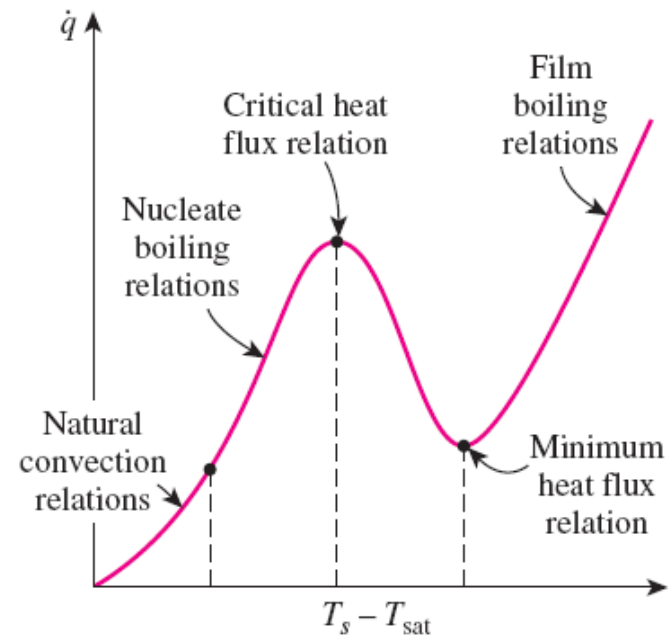


FIGURE 10-10

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

- For nucleate boiling a widely used correlation proposed in 1952 by Rohsenow:

$$\dot{q}_{\text{nucleate}} = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left[\frac{c_{pl}(T_s - T_{\text{sat}})}{C_{sf} h_{fg} \text{Pr}_l^n} \right]^3$$

$\dot{q}_{\text{nucleate}}$ = nucleate boiling heat flux, W/m²

μ_l = viscosity of the liquid, kg/m·s

h_{fg} = enthalpy of vaporization, J/kg

g = gravitational acceleration, m/s²

ρ_l = density of the liquid, kg/m³

ρ_v = density of the vapor, kg/m³

σ = surface tension of liquid–vapor interface, N/m

c_{pl} = specific heat of the liquid, J/kg·°C

T_s = surface temperature of the heater, °C

T_{sat} = saturation temperature of the fluid, °C

C_{sf} = experimental constant that depends on surface–fluid combination

Pr_l = Prandtl number of the liquid

n = experimental constant that depends on the fluid

$$\begin{aligned} \dot{q} &= \left(\frac{\text{kg}}{\text{m} \cdot \text{s}} \right) \left(\frac{\text{J}}{\text{kg}} \right) \\ &\times \left(\frac{\frac{\text{m}}{\text{s}^2} \frac{\text{kg}}{\text{m}^3}}{\frac{\text{N}}{\text{m}}} \right)^{1/2} \left(\frac{\frac{\text{J}}{\text{kg} \cdot ^\circ\text{C}} \cdot ^\circ\text{C}}{\frac{\text{J}}{\text{kg}}} \right)^3 \\ &= \frac{\text{W}}{\text{m}} \left(\frac{1}{\text{m}^2} \right)^{1/2} (1)^3 \\ &= \text{W/m}^2 \end{aligned}$$

FIGURE 10–11

Equation 10–2 gives the boiling heat flux in W/m² when the quantities are expressed in the units specified in their descriptions.

Peak Heat Flux

- The *maximum* (or *critical*) *heat flux* (CHF) in nucleate pool boiling:

$$\dot{q}_{\max} = C_{cr} h_{fg} [\sigma g \rho_v^2 (\rho_l - \rho_v)]^{1/4}$$

C_{cr} is a constant whose value depends on the heater geometry, but generally is about 0.15.

- The CHF is independent of the fluid–heating surface combination, as well as the viscosity, thermal conductivity, and the specific heat of the liquid.
- The CHF increases with pressure up to about one-third of the critical pressure, and then starts to decrease and becomes zero at the critical pressure.
- The CHF is proportional to h_{fg} , and large maximum heat fluxes can be obtained using fluids with a large enthalpy of vaporization, such as water.

TABLE 10–4

Values of the coefficient C_{cr} for use in Eq. 10–3 for maximum heat flux (dimensionless parameter $L^* = L[g(\rho_l - \rho_v)/\sigma]^{1/2}$)

Heater Geometry	C_{cr}	Charac. Dimension of Heater, L	Range of L^*
Large horizontal flat heater	0.149	Width or diameter	$L^* > 27$
Small horizontal flat heater ¹	$18.9K_1$	Width or diameter	$9 < L^* < 20$
Large horizontal cylinder	0.12	Radius	$L^* > 1.2$
Small horizontal cylinder	$0.12L^{*-0.25}$	Radius	$0.15 < L^* < 1.2$
Large sphere	0.11	Radius	$L^* > 4.26$
Small sphere	$0.227L^{*-0.5}$	Radius	$0.15 < L^* < 4.26$

¹ $K_1 = \sigma/[g(\rho_l - \rho_v)A_{\text{heater}}]$

Minimum Heat Flux

- Minimum heat flux, which occurs at the **Leidenfrost point**, is of practical interest since it represents the lower limit for the heat flux in the film boiling regime.
- Zuber derived the following expression for the minimum heat flux for a *large horizontal plate*

$$\dot{q}_{\min} = 0.09 \rho_v h_{fg} \left[\frac{\sigma g (\rho_l - \rho_v)}{(\rho_l + \rho_v)^2} \right]^{1/4} \quad \text{by 50\% or more.}$$

Transition boiling regime

Operation in the *transition boiling* regime ($30^\circ\text{C} \leq \Delta T_{\text{excess}} \leq 120^\circ\text{C}$) is normally avoided in the design of heat transfer equipment, and thus no major attempt has been made to develop general correlations for boiling heat transfer in this regime. However, the upper (*peak heat flux*, \dot{q}_{\max}) and the lower (*minimum heat flux*, \dot{q}_{\min}) limits of this region are of interest to heat transfer equipment designers.

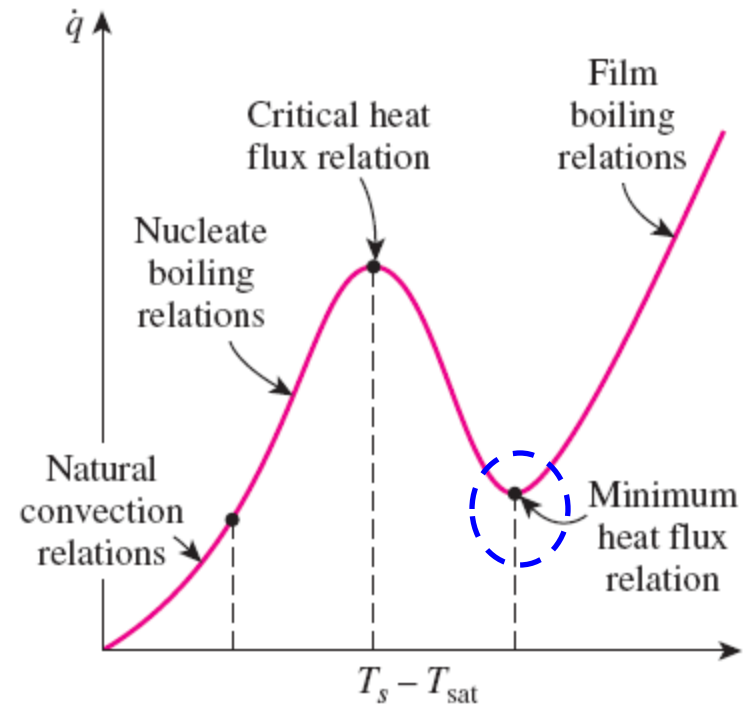


FIGURE 10–10

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

Film Boiling

The heat flux for film boiling on a *horizontal cylinder* or *sphere* of diameter D is given by

$$\dot{q}_{\text{film}} = C_{\text{film}} \left[\frac{g k_v^3 \rho_v (\rho_l - \rho_v) [h_{fg} + 0.4 c_{pv} (T_s - T_{\text{sat}})]}{\mu_v D (T_s - T_{\text{sat}})} \right]^{1/4} (T_s - T_{\text{sat}})$$

$$C_{\text{film}} = \begin{cases} 0.62 & \text{for horizontal cylinders} \\ 0.67 & \text{for spheres} \end{cases}$$

- At high surface temperatures (typically above 300°C), heat transfer across the vapor film by *radiation* becomes significant and needs to be considered.

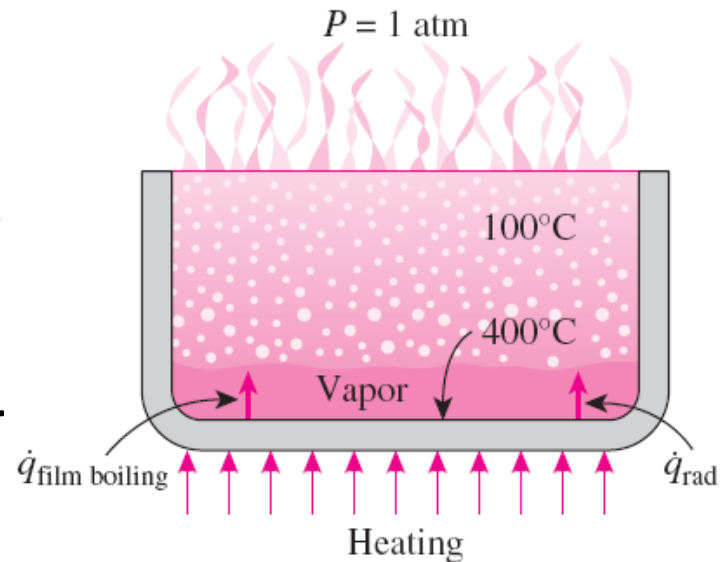


FIGURE 10–12

At high heater surface temperatures, radiation heat transfer becomes significant during film boiling.

$$\dot{q}_{\text{rad}} = \varepsilon \sigma (T_s^4 - T_{\text{sat}}^4) \quad \text{For } \dot{q}_{\text{rad}} < \dot{q}_{\text{film}},$$

$$\dot{q}_{\text{total}} = \dot{q}_{\text{film}} + \frac{3}{4} \dot{q}_{\text{rad}}$$

Enhancement of Heat Transfer in Pool Boiling

- The **rate of heat transfer** in the nucleate boiling regime strongly depends on the number of active **nucleation sites** on the surface, and the **rate of bubble formation** at each site.
- Therefore, modification that **enhances nucleation** on the heating surface will also **enhance heat transfer** in nucleate boiling.
- **Irregularities** on the heating surface, including roughness and dirt, serve as additional **nucleation sites** during boiling.
- The effect of **surface roughness** is observed to **decay with time**.

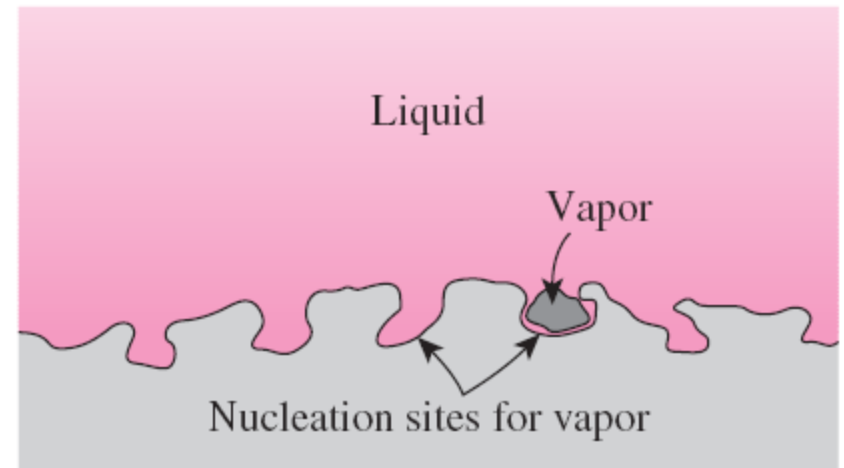


FIGURE 10–13

The cavities on a rough surface act as nucleation sites and enhance boiling heat transfer.

- Surfaces that provide enhanced heat transfer in nucleate boiling *permanently* are being manufactured and are available in the market.
- Heat transfer can be enhanced by a factor of up to 10 during *nucleate boiling*, and the *critical heat flux* by a factor of 3.
- The use of *finned surfaces* is also known to enhance nucleate boiling heat transfer and the maximum heat flux.
- Boiling heat transfer can also be enhanced by other techniques such as *mechanical agitation* and *surface vibration*.
- These techniques are not practical, however, because of the complications involved.

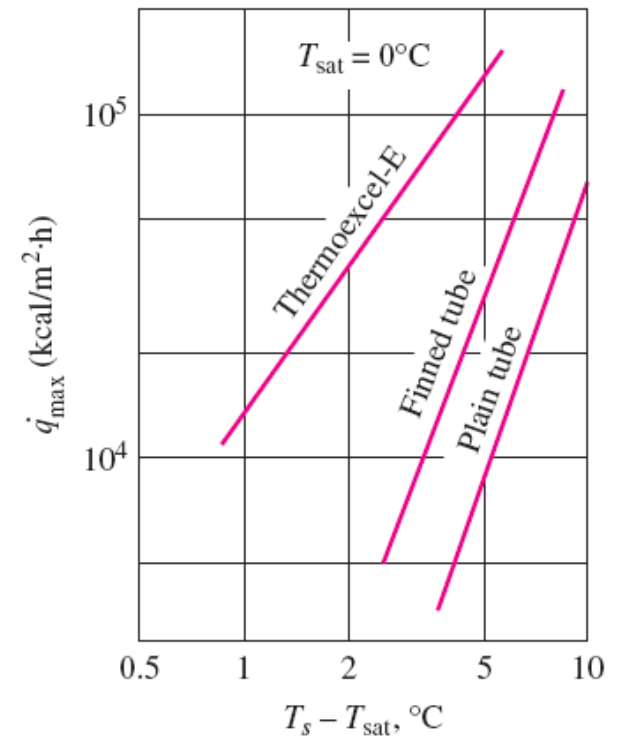
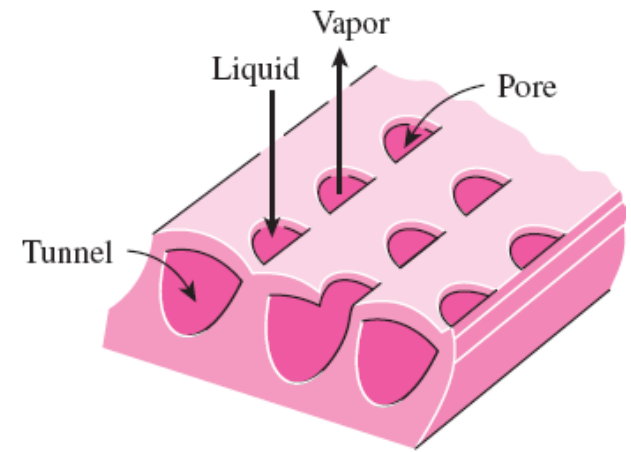


FIGURE 10-14

The enhancement of boiling heat transfer in Freon-12 by a mechanically roughened surface, thermoexcel-E.

FLOW BOILING

- In **flow boiling**, the fluid is forced to move by an external source such as a pump as it undergoes a phase-change process.
- It exhibits the combined effects of convection and pool boiling.
- **External flow boiling** over a plate or cylinder is similar to pool boiling, but the added motion increases both the nucleate boiling heat flux and the maximum heat flux considerably.
- The higher the velocity, the higher the nucleate boiling heat flux and the critical heat flux.
- **Internal flow boiling**, commonly referred to as **two-phase flow**, is much more complicated in nature because there is no free surface for the vapor to escape, and thus both the liquid and the vapor are forced to flow together.

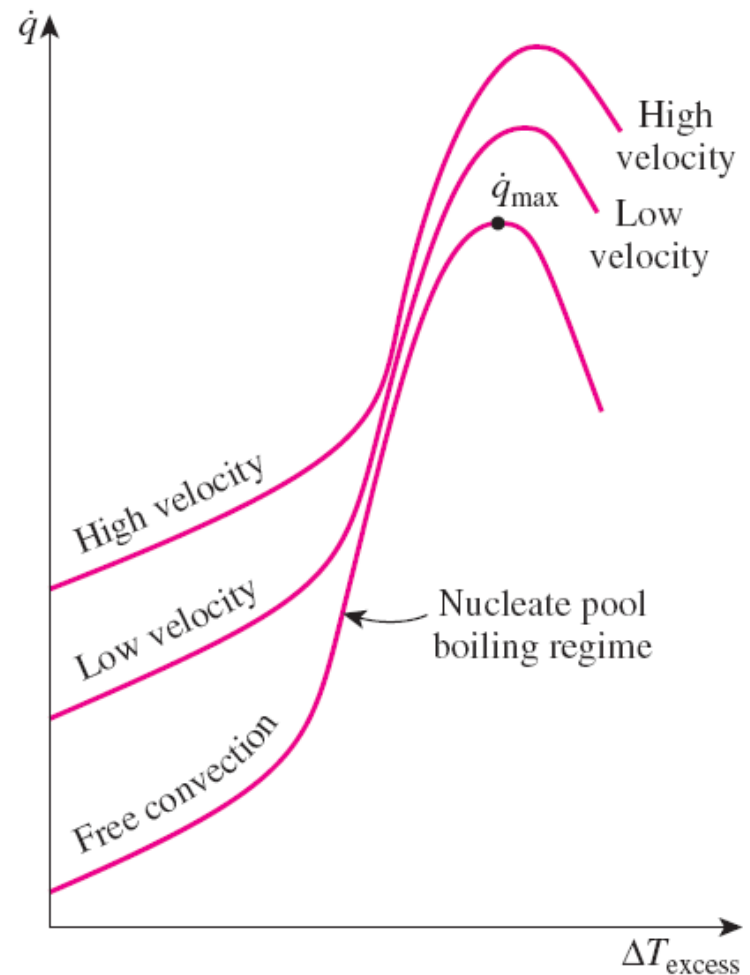


FIGURE 10–18

The effect of forced convection on external flow boiling for different flow velocities.

- The two-phase flow in a tube exhibits different flow boiling regimes, depending on the relative amounts of the liquid and the vapor phases.
- Note that the tube contains a liquid before the bubbly flow regime and a vapor after the mist-flow regime.
- Heat transfer in those two cases can be determined using the appropriate relations for single-phase convection heat transfer.

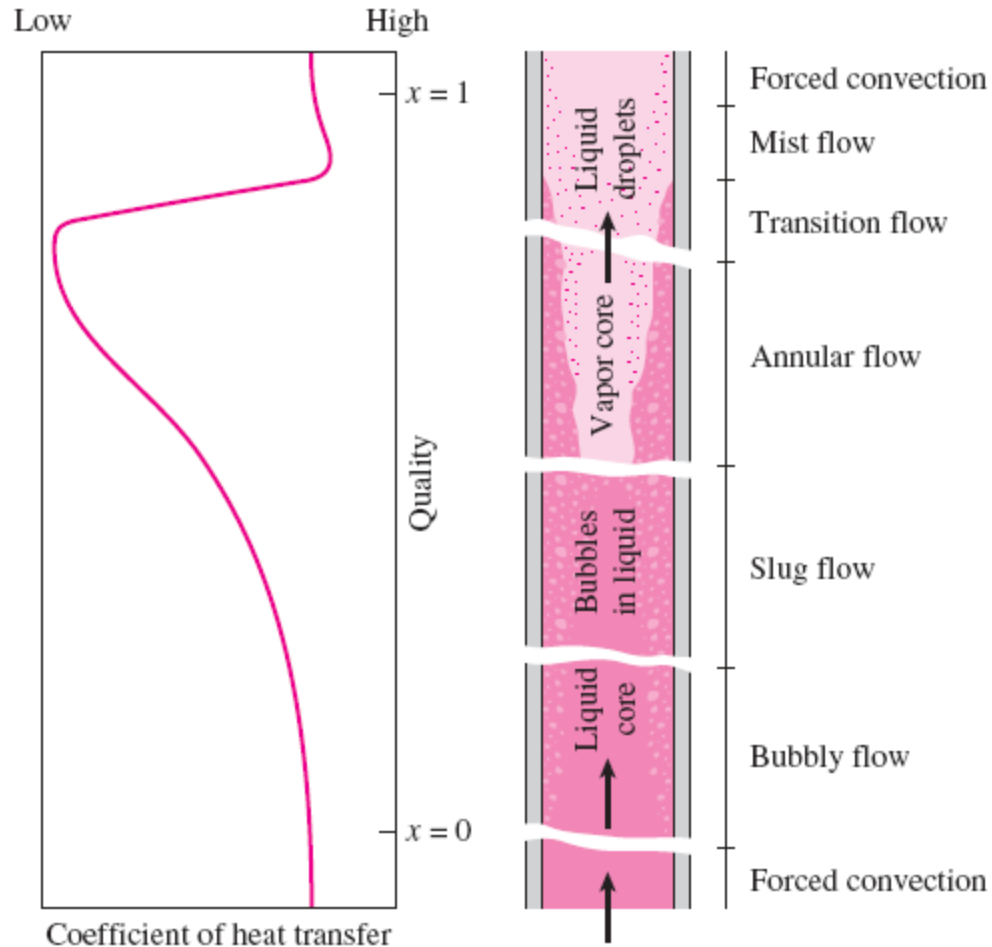
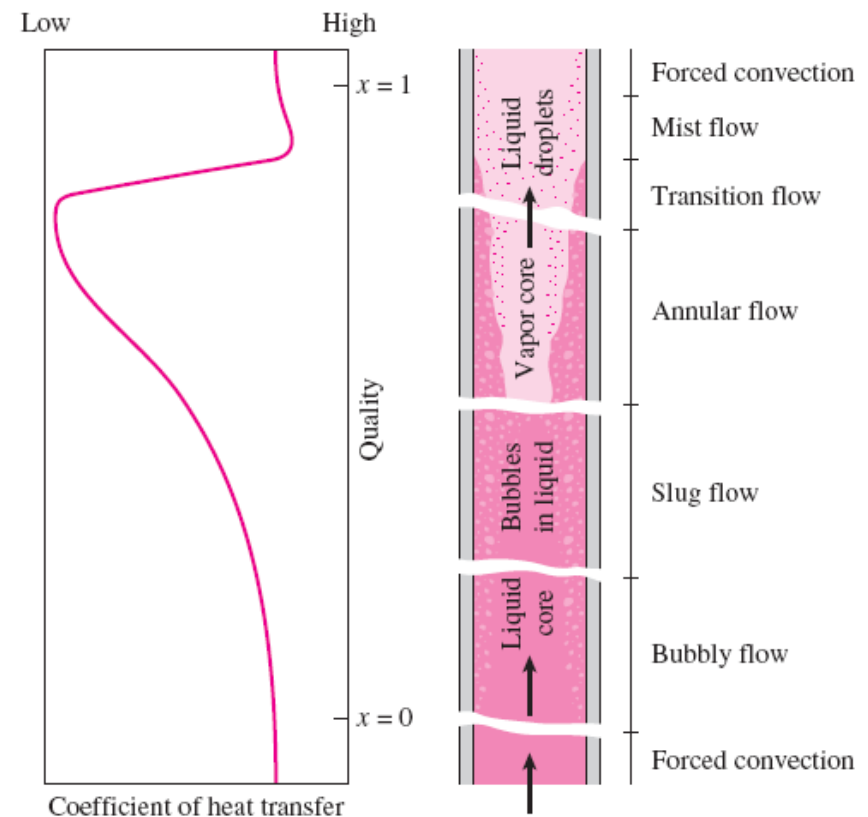


FIGURE 10-19
Different flow regimes encountered in
flow boiling in a tube under forced
convection.

- **Liquid single-phase flow**
 - ✓ In the inlet region the liquid is subcooled and heat transfer to the liquid is by *forced convection* (assuming no subcooled boiling).
- **Bubbly flow**
 - ✓ Individual bubbles
 - ✓ Low mass qualities
- **Slug flow**
 - Bubbles coalesce into slugs of vapor.
 - Moderate mass qualities
- **Annular flow**
 - Core of the flow consists of vapor only, and liquid adjacent to the walls.
 - Very high heat transfer coefficients
- **Mist flow**
 - A sharp decrease in the heat transfer coefficient
- **Vapor single-phase flow**
 - The liquid phase is completely evaporated and vapor is superheated.



CONDENSATION HEAT TRANSFER

Condensation occurs when the temperature of a vapor is reduced *below* its saturation temperature.

Film condensation

- The condensate wets the surface and forms a liquid film.
- The surface is blanketed by a liquid film which serves as a *resistance* to heat transfer.

Dropwise condensation

- The condensed vapor forms droplets on the surface.
- The droplets slide down when they reach a certain size.
- No liquid film to resist heat transfer.
- As a result, heat transfer rates that are more than 10 times larger than with film condensation can be achieved.

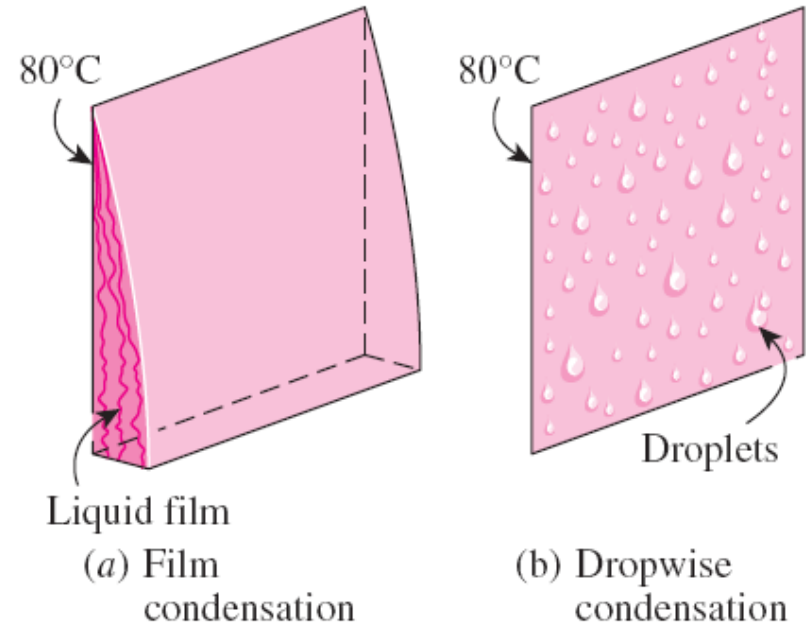


FIGURE 10–20

When a vapor is exposed to a surface at a temperature below T_{sat} , condensation in the form of a liquid film or individual droplets occurs on the surface.

FILM CONDENSATION

- Liquid film starts forming at the top of the plate and flows downward **under the influence of gravity**.
- δ **increases** in the flow direction x
- Heat in the amount h_{fg} is released during condensation and is *transferred* through the film to the plate surface.
- T_s must be below the saturation temperature for condensation.
- The *temperature* of the condensate is T_{sat} at the interface and decreases gradually to T_s at the wall.

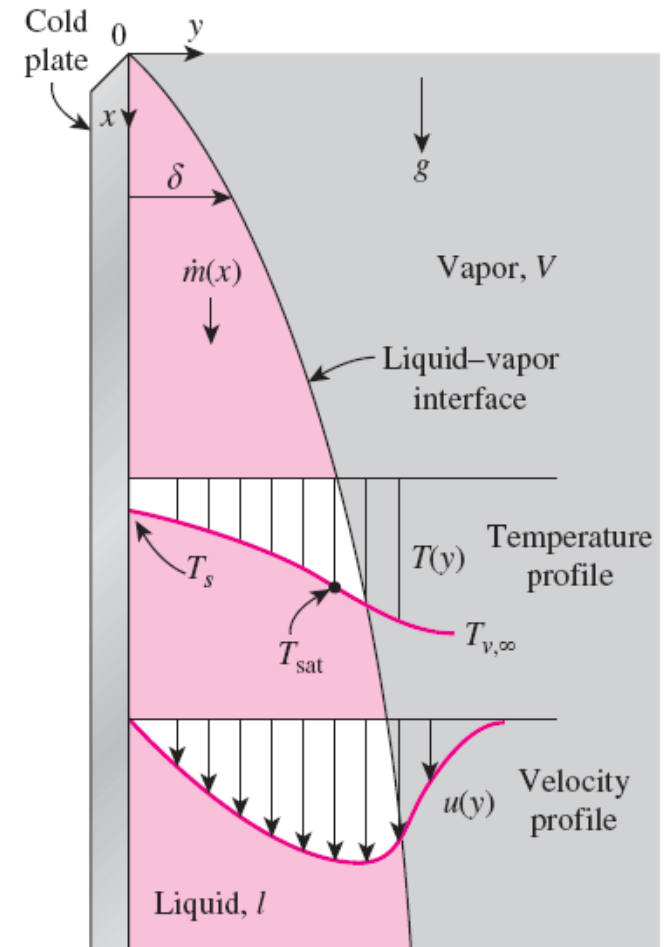


FIGURE 10-21

Film condensation on a vertical plate.

$$\text{Re} = \frac{D_h \rho_l V_l}{\mu_l} = \frac{4 A_c \rho_l V_l}{p \mu_l} = \frac{4 \rho_l V_l \delta}{\mu_l} = \frac{4 \dot{m}}{p \mu_l}$$

$D_h = 4A_c/p = 4\delta$ = hydraulic diameter of the condensate flow, m

p = wetted perimeter of the condensate, m

$A_c = -p\delta$ = wetted perimeter \times film thickness, m^2 , cross-sectional area of the condensate flow at the lowest part of the flow

ρ_l = density of the liquid, kg/m^3

μ_l = viscosity of the liquid, $\text{kg}/\text{m}\cdot\text{s}$

V_l = average velocity of the condensate at the lowest part of the flow, m/s

$\dot{m} = \rho_l V_l A_c$ = mass flow rate of the condensate at the lowest part, kg/s

Heat transfer in condensation depends on whether the condensate flow is *laminar* or *turbulent*. The criterion for the flow regime is provided by the Reynolds number.

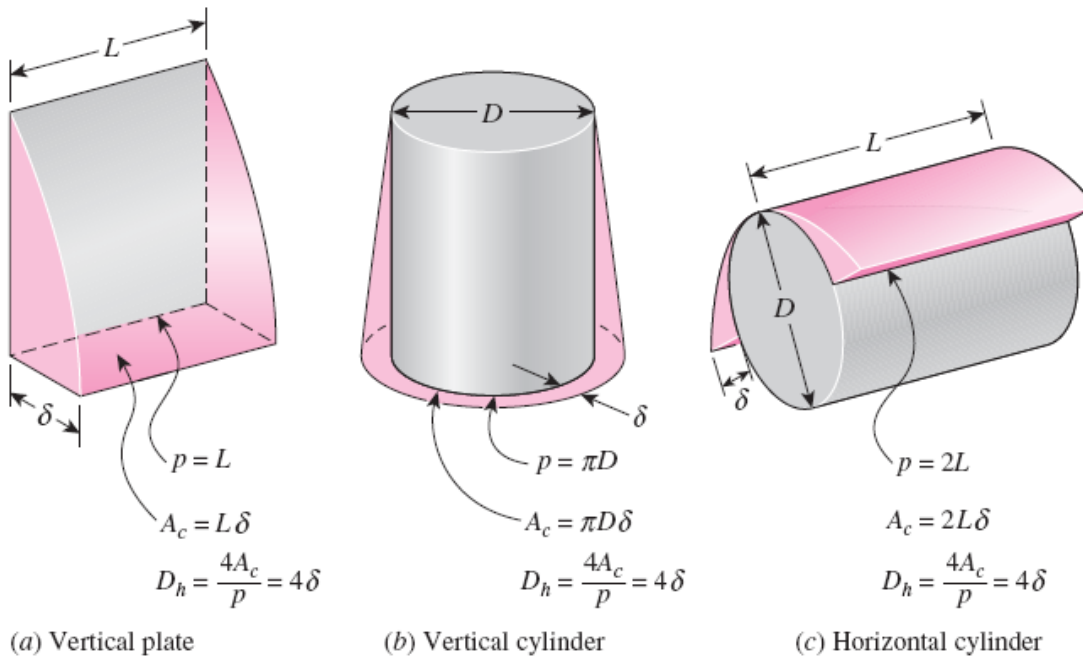


FIGURE 10-22

The wetted perimeter p , the condensate cross-sectional area A_c , and the hydraulic diameter D_h for some common geometries.

When the final state is subcooled liquid instead of saturated liquid:

$$h_{fg}^* = h_{fg} + 0.68c_{pl}(T_{\text{sat}} - T_s) \quad \text{Modified latent heat of vaporization}$$

For vapor that enters the condenser as **superheated vapor** at a temperature T_v instead of as saturated vapor:

$$h_{fg}^* = h_{fg} + 0.68c_{pl}(T_{\text{sat}} - T_s) + c_{pv}(T_v - T_{\text{sat}})$$

$$\dot{Q}_{\text{conden}} = hA_s(T_{\text{sat}} - T_s) = \dot{m}h_{fg}^* \quad \text{Rate of heat transfer}$$

$$\text{Re} = \frac{4\dot{Q}_{\text{conden}}}{p\mu_l h_{fg}^*} = \frac{4A_s h(T_{\text{sat}} - T_s)}{p\mu_l h_{fg}^*}$$

This relation is convenient to use to determine the Reynolds number when the condensation heat transfer coefficient or the rate of heat transfer is known.

$$T_f = (T_{\text{sat}} + T_s)/2 \quad \text{The properties of the liquid should be evaluated at the } \textit{film temperature}$$

The h_{fg} should be evaluated at T_{sat}

Flow Regimes

- The dimensionless parameter controlling the transition between regimes is the **Reynolds number** defined as:
- $$Re = \frac{D_h \rho_l V_l}{\mu_l} = \frac{4 A_c \rho_l V_l}{p \mu_l} = \frac{4 \rho_l V_l \delta}{\mu_l} = \frac{4 \dot{m}}{p \mu_l}$$
 - $Re < 30$ – Laminar (wave-free)
 - $30 < Re < 1800$ – Laminar (wavy)
 - $Re > 1800$ – Turbulent
- The Reynolds number increases in the flow direction.

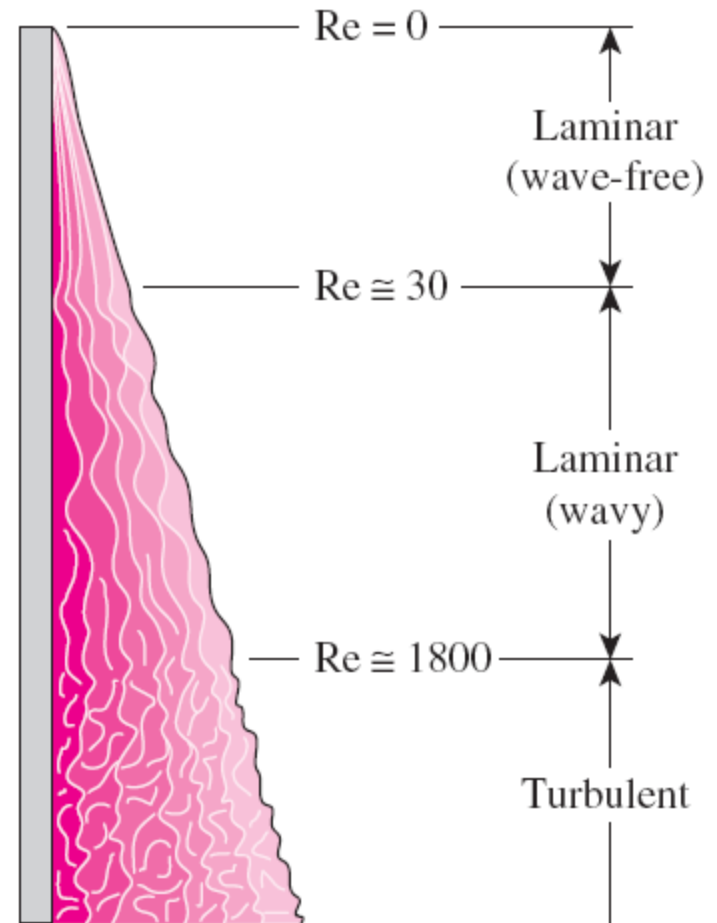


FIGURE 10-23

Flow regimes during film condensation on a vertical plate.

Heat Transfer Correlations for Film Condensation (Vertical Plates)

Vertical Plates

Assumptions:

1. Both the plate and the vapor are maintained at *constant temperatures* of T_s and T_{sat} , respectively, and the temperature across the liquid film varies *linearly*.
2. Heat transfer across the liquid film is by pure *conduction*.
3. The velocity of the vapor is low (or zero) so that it exerts *no drag* on the condensate (no viscous shear on the liquid–vapor interface).
4. The flow of the condensate is *laminar* ($Re < 30$) and the properties of the liquid are constant.
5. The acceleration of the condensate layer is negligible.

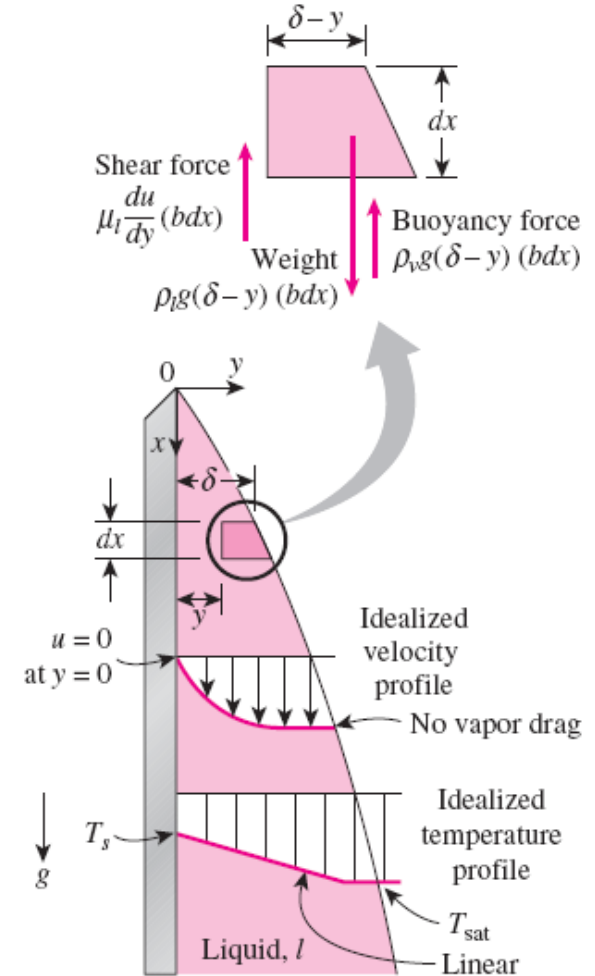


FIGURE 10–24

The volume element of condensate on a vertical plate considered in Nusselt's analysis.

Laminar Flow on Vertical Plates

The *average heat transfer coefficient* for laminar film condensation over a vertical flat plate of height L is

$$h_{\text{vert}} = 0.943 \left[\frac{g \rho_l (\rho_l - \rho_v) h_{fg}^* k_l^3}{\mu_l (T_{\text{sat}} - T_s) L} \right]^{1/4} \quad (\text{W/m}^2 \cdot \text{K}), \quad 0 < \text{Re} < 30 \quad (10-22)$$

g = gravitational acceleration, m/s^2

ρ_l, ρ_v = densities of the liquid and vapor, respectively, kg/m^3

μ_l = viscosity of the liquid, $\text{kg/m} \cdot \text{s}$

$h_{fg}^* = h_{fg} + 0.68 c_{pl} (T_{\text{sat}} - T_s)$ = modified latent heat of vaporization, J/kg

k_l = thermal conductivity of the liquid, $\text{W/m} \cdot \text{K}$

L = height of the vertical plate, m

T_s = surface temperature of the plate, $^{\circ}\text{C}$

T_{sat} = saturation temperature of the condensing fluid, $^{\circ}\text{C}$

$$\text{Re} \cong \frac{4g \rho_l (\rho_l - \rho_v) \delta^3}{3\mu_l^2} = \frac{4g \rho_l^2}{3\mu_l^2} \left(\frac{k_l}{h_{x=L}} \right)^3 = \frac{4g}{3\nu_l^2} \left(\frac{k_l}{3h_{\text{vert}}/4} \right)^3$$

$$h_{\text{vert}} \cong 1.47 k_l \text{Re}^{-1/3} \left(\frac{g}{\nu_l^2} \right)^{1/3}, \quad 0 < \text{Re} < 30$$

$\rho_v \ll \rho_l$

$T_f = (T_{\text{sat}} + T_s)/2$ All properties of the liquid are to be evaluated at the film temperature. The h_{fg} and ρ_v are to be evaluated at the saturation temperature T_{sat} .

Wavy Laminar Flow on Vertical Plates

The average heat transfer coefficient in wavy laminar condensate flow for

$$\rho_v \ll \rho_l \text{ and } 30 < \text{Re} < 1800$$

$$h_{\text{vert, wavy}} = \frac{\text{Re } k_l}{1.08 \text{ Re}^{1.22} - 5.2} \left(\frac{g}{v_l^2} \right)^{1/3}, \quad \begin{matrix} 30 < \text{Re} < 1800 \\ \rho_v \ll \rho_l \end{matrix}$$

$$h_{\text{vert, wavy}} = 0.8 \text{ Re}^{0.11} h_{\text{vert (smooth)}} \quad \text{A simpler alternative to the relation above}$$

$$\text{Re}_{\text{vert, wavy}} = \left[4.81 + \frac{3.70 L k_l (T_{\text{sat}} - T_s)}{\mu_l h_{fg}^*} \left(\frac{g}{v_l^2} \right)^{1/3} \right]^{0.820}, \quad \rho_v \ll \rho_l$$

Turbulent Flow on Vertical Plates

Turbulent flow of condensate on *vertical plates*:

$$h_{\text{vert, turbulent}} = \frac{\text{Re } k_l}{8750 + 58 \text{Pr}^{-0.5} (\text{Re}^{0.75} - 253)} \left(\frac{g}{v_l^2} \right)^{1/3}, \quad \text{Re} > 1800, \quad \rho_v \ll \rho_l$$

The physical properties of the condensate are again to be evaluated at the film temperature $T_f = (T_{\text{sat}} + T_s)/2$.

$$\text{Re}_{\text{vert, turbulent}} = \left[\frac{0.0690 L k_l \text{Pr}^{0.5} (T_{\text{sat}} - T_s)}{\mu_l h_{fg}^*} \left(\frac{g}{v_l^2} \right)^{1/3} - 151 \text{Pr}^{0.5} + 253 \right]^{4/3}$$

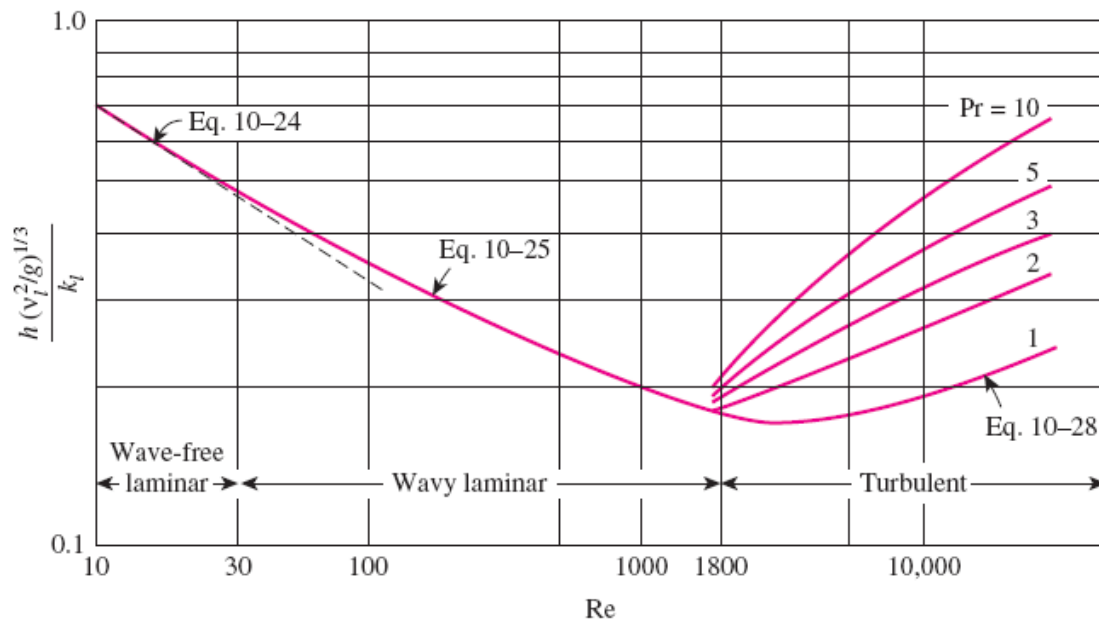


FIGURE 10-26

Nondimensionalized heat transfer coefficients for the wave-free laminar, wavy laminar, and turbulent flow of condensate on vertical plates.

Effect of Vapor Velocity

- In the analysis above we assumed the vapor velocity to be small and thus the vapor drag exerted on the liquid film to be negligible, which is usually the case.
- However, when the vapor velocity is high, the vapor will “pull” the liquid at the interface along since the vapor velocity at the interface must drop to the value of the liquid velocity.
- If the vapor flows downward (i.e., in the same direction as the liquid), this additional force will increase the average velocity of the liquid and thus decrease the film thickness.
- This, in turn, will decrease the thermal resistance of the liquid film and thus increase heat transfer.
- Upward vapor flow has the opposite effects: the vapor exerts a force on the liquid in the opposite direction to flow, thickens the liquid film, and thus decreases heat transfer.

The Presence of Noncondensable Gases in Condensers

- Experimental studies show that the presence of noncondensable gases in the vapor has a detrimental effect on condensation heat transfer.
- Even small amounts of a noncondensable gas in the vapor cause significant drops in heat transfer coefficient during condensation.
- It is common practice to periodically vent out the noncondensable gases that accumulate in the condensers to ensure proper operation.
- Heat transfer in the presence of a noncondensable gas strongly depends on the nature of the vapor flow and the flow velocity.
- A *high flow velocity* is more likely to remove the stagnant noncondensable gas from the vicinity of the surface, and thus *improve* heat transfer.

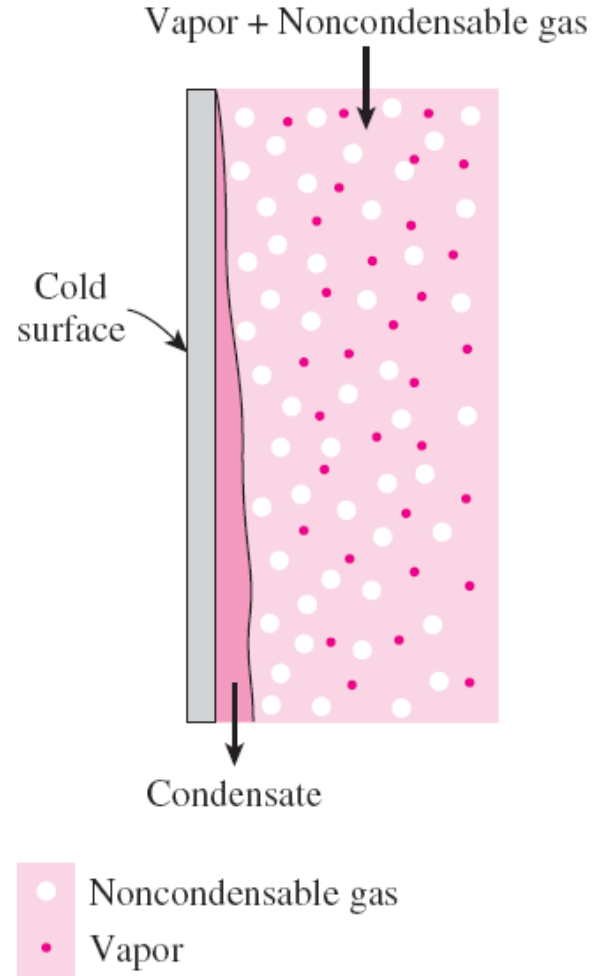


FIGURE 10–29

The presence of a noncondensable gas in a vapor prevents the vapor molecules from reaching the cold surface easily, and thus impedes condensation heat transfer.

DROPWISE CONDENSATION

Dropwise condensation, characterized by countless droplets of varying diameters on the condensing surface instead of a continuous liquid film and extremely large heat transfer coefficients can be achieved with this mechanism.

The small droplets that form at the nucleation sites on the surface grow as a result of continued condensation, coalesce into large droplets, and slide down when they reach a certain size, clearing the surface and exposing it to vapor. There is no liquid film in this case to resist heat transfer.

As a result, with dropwise condensation, heat transfer coefficients can be achieved that are more than 10 times larger than those associated with film condensation.

The challenge in dropwise condensation is not to achieve it, but rather, to *sustain* it for prolonged periods of time.

$$h_{\text{dropwise}} = \begin{cases} 51,104 + 2044T_{\text{sat}}, \\ 255,310 \end{cases}$$

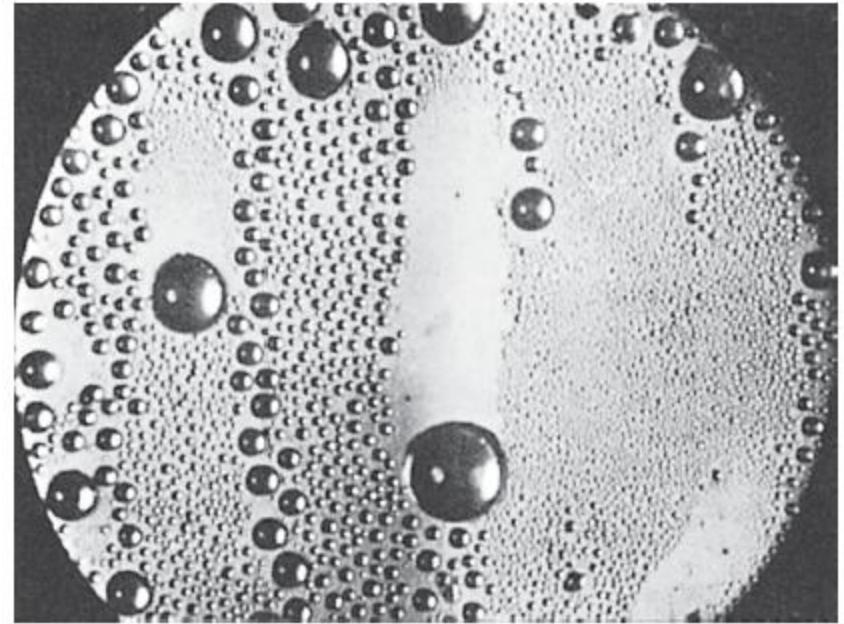


FIGURE 10–35

Dropwise condensation of steam on a vertical surface.

Dropwise condensation of steam on copper surfaces:

$$\begin{aligned} 22^{\circ}\text{C} < T_{\text{sat}}, 100^{\circ}\text{C} \\ T_{\text{sat}} > 100^{\circ}\text{C} \end{aligned}$$

Summary – Boiling

- **Boiling heat transfer**
 - Difference between Boiling and Evaporation
 - Classification : Pool/Flow & Subcooled/Saturated
- **Pool boiling**
 - Boiling Regimes
 - Natural Convection
 - Nucleate
 - Transition
 - Film
 - Burnout
- **Heat transfer correlation in pool boiling**
 - Nucleate
 - Critical (Peak) Heat flux (CHF)
 - Minimum Heat flux (Leidenfrost Point)
 - Film
- **Enhancement of heat transfer in Pool Boiling**
 - Irregularities/ Surface Roughness
 - Mechanical Agitation/ Vibration
- **Flow boiling**
 - Classified: External/Internal
 - Regimes: Force Convection (Liquid)-Bubbly-Slug-Annular-Mist-Force Convection (Vapour)

Summary – Condensation

- Condensation heat transfer
- Film Condensation
 - Vertical Plate (Laminar, Wavy, Turbulent)
 - Heat transfer correlation
 - Effect of Vapor Velocity
 - The presence of Non-condensable gases in condenser
- Drop wise condensation