

E-Course on Heat Transfer-3151909

Chapter 5
TWO-PHASE HEAT TRANSFER

Topic : Boiling

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Learning Objectives

- Differentiate between evaporation and boiling
- Familiarity with different types of boiling
- Develop a good understanding of the boiling curve
- The different boiling regimes corresponding to different regions of the boiling curve
- Calculate the heat flux and its critical value associated with nucleate boiling

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.

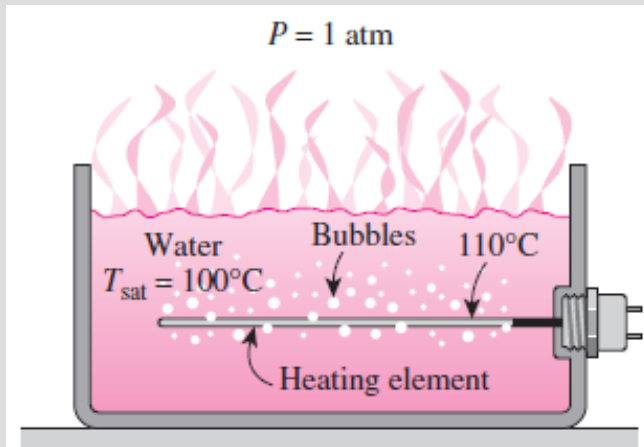


FIGURE 10-2

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.

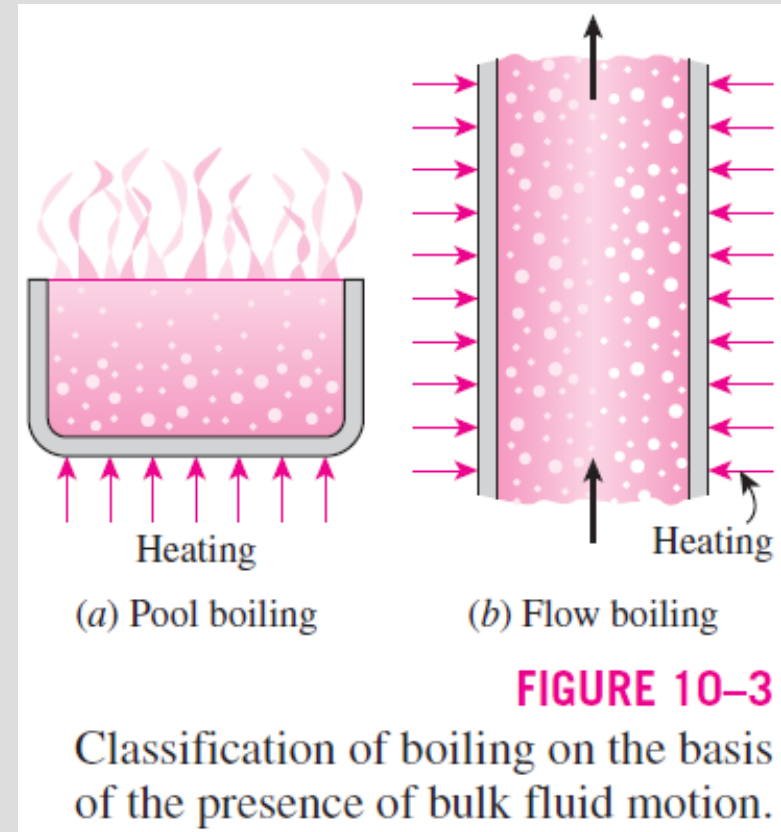
Boiling heat flux from a solid surface to the fluid

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

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

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.

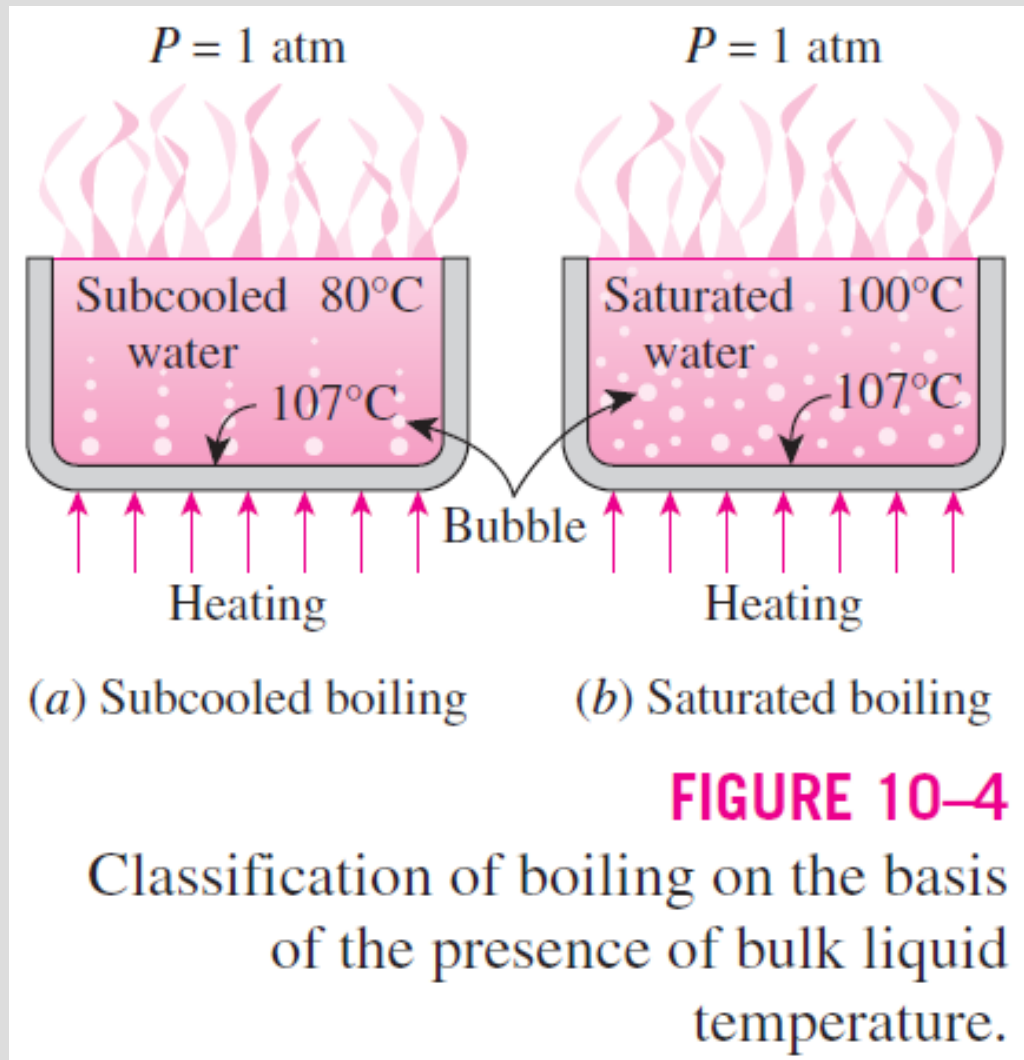


Subcooled Boiling

- 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.



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

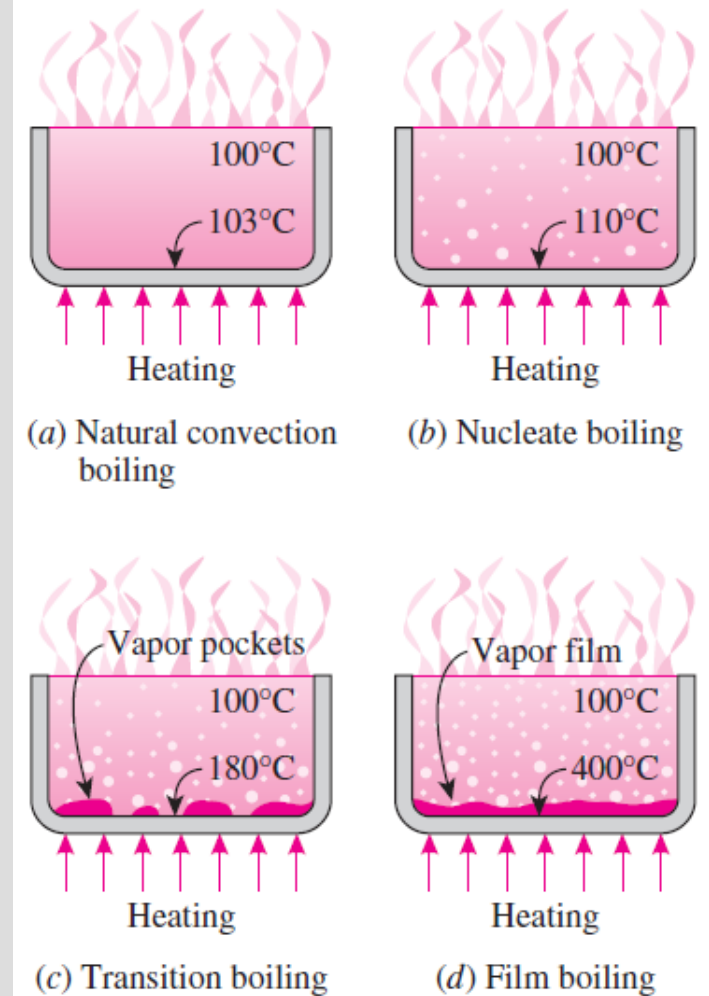


FIGURE 10-5

Different boiling regimes in pool boiling.

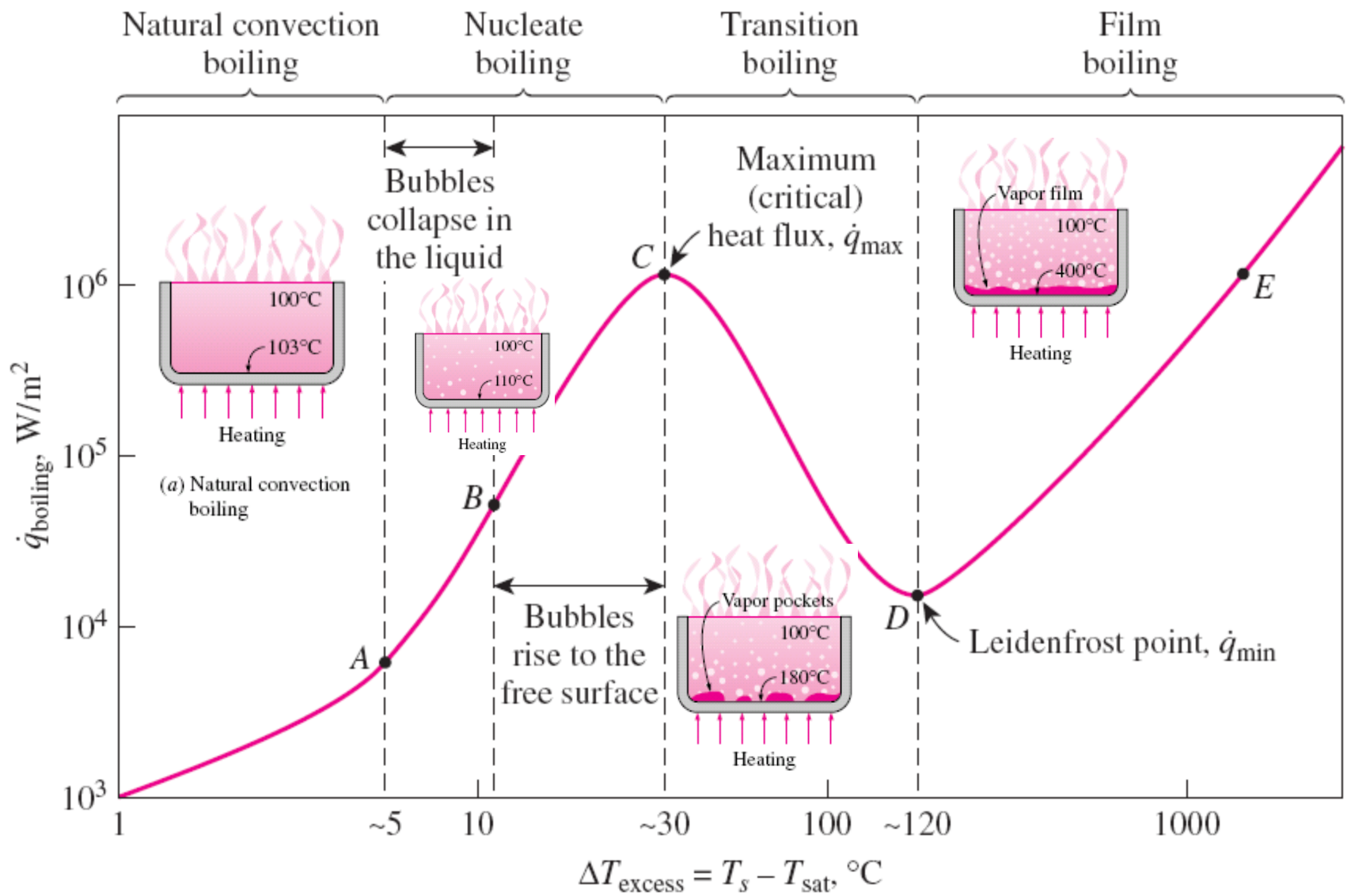
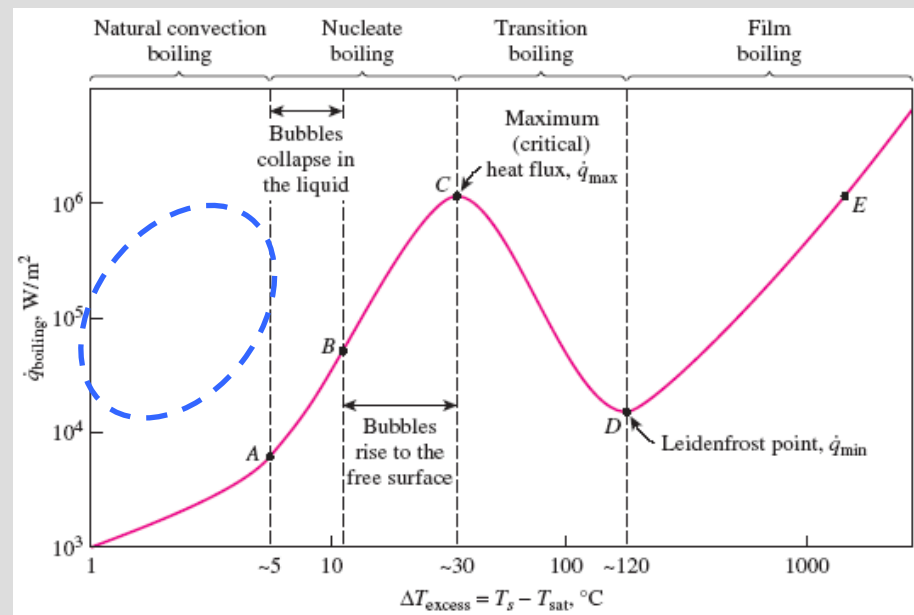


FIGURE 10-6
 Typical boiling curve for water at 1 atm pressure.

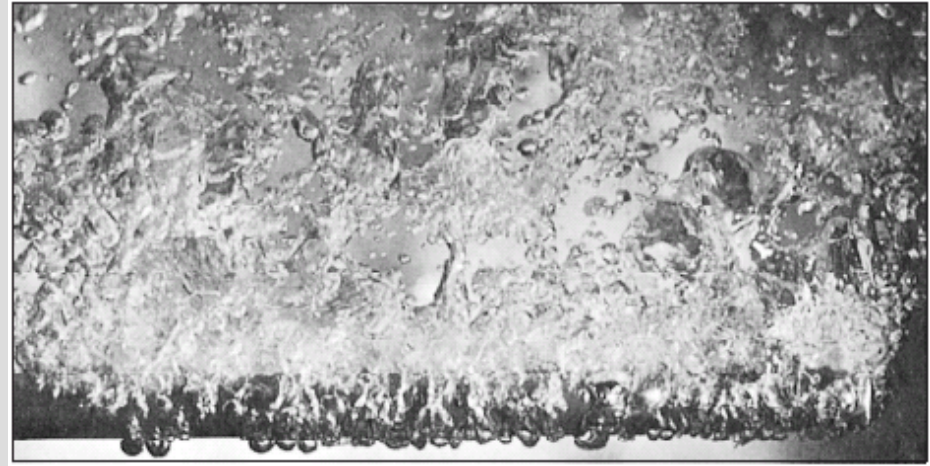
Natural Convection Boiling (to Point A on the Boiling Curve)

- 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**.



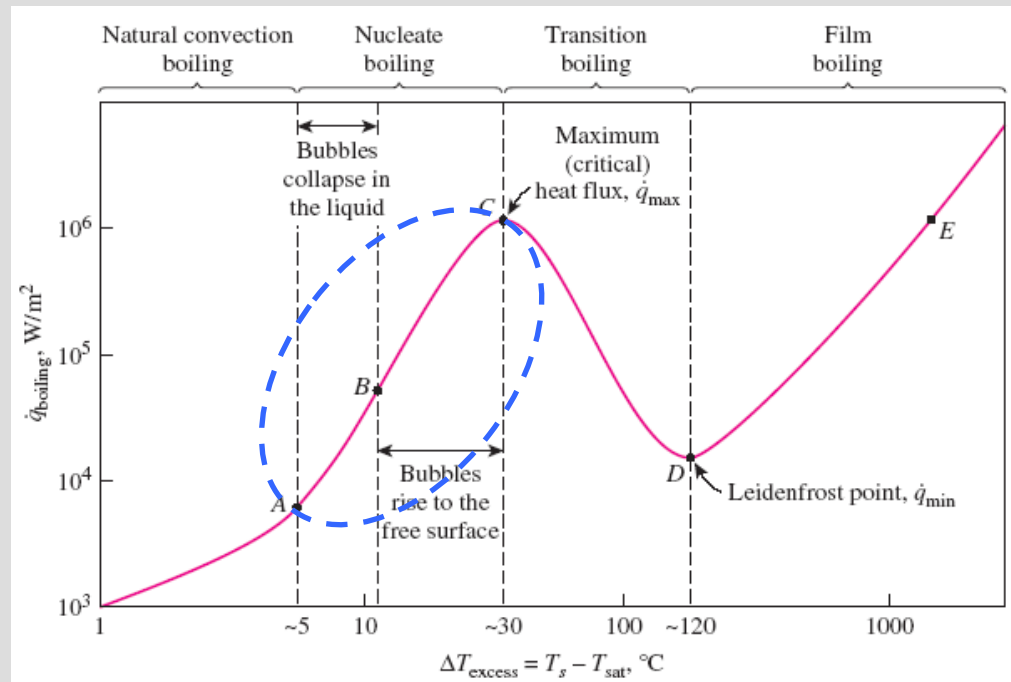
- Region A–B** — *isolated bubbles*.

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

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

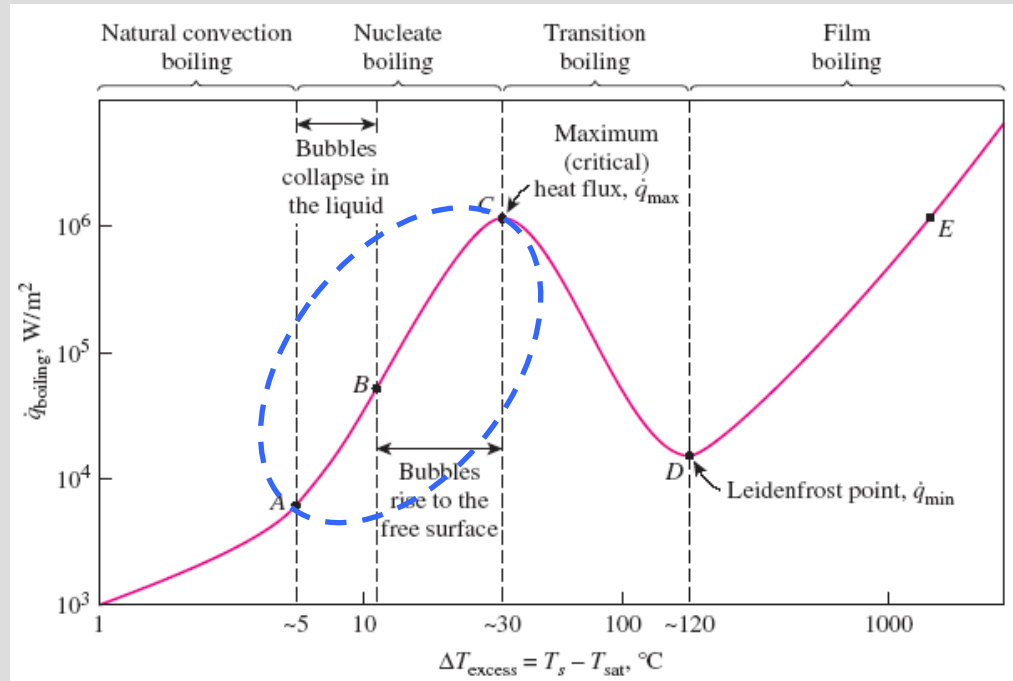
$$(10^{\circ}\text{C} \leq \Delta T_{\text{excess}} \leq 30^{\circ}\text{C})$$

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



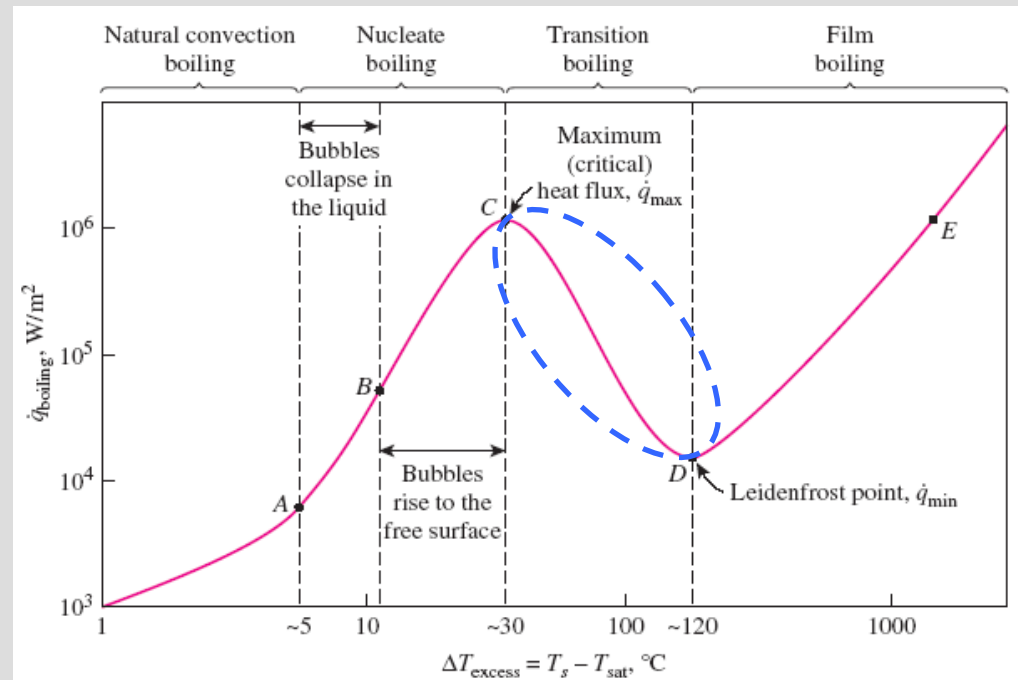
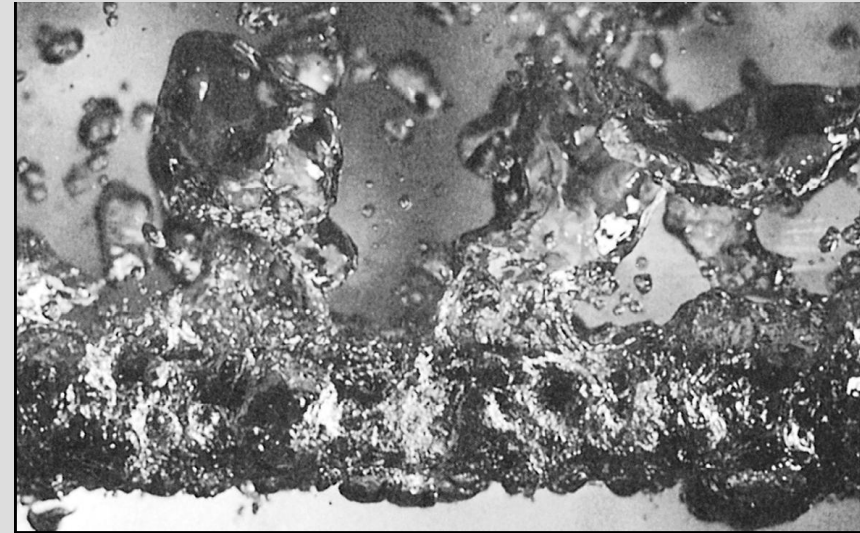
- In **region A–B** the stirring and agitation caused by the entrainment of the liquid to the heater surface is primarily responsible for the increased heat transfer coefficient.
- In **region A–B** the large heat fluxes obtainable in this region are caused by the combined effect of liquid entrainment 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.



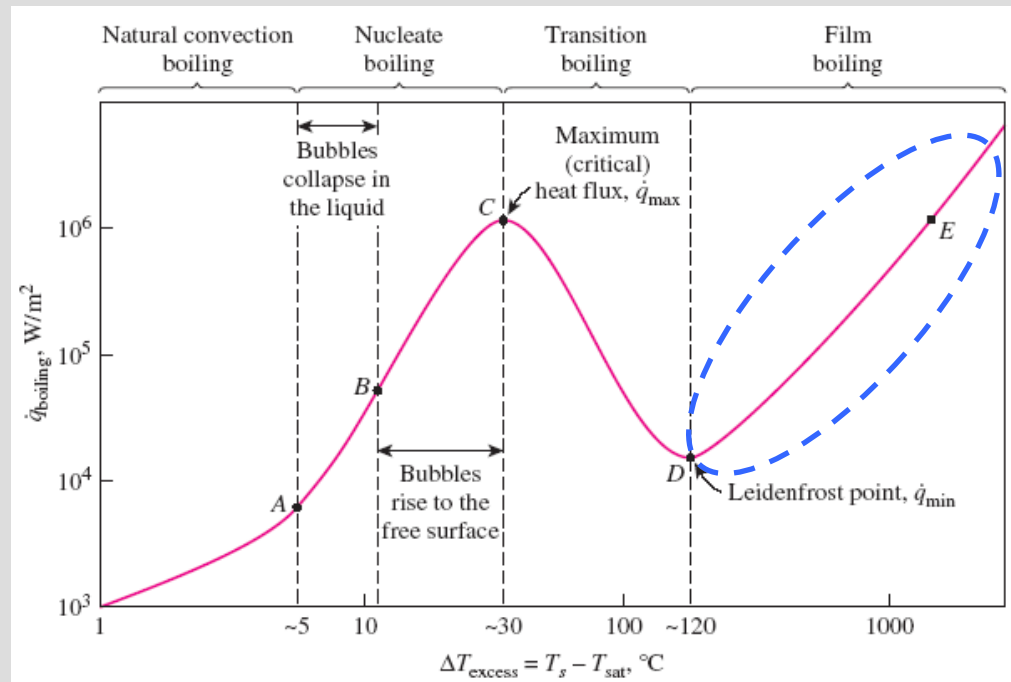
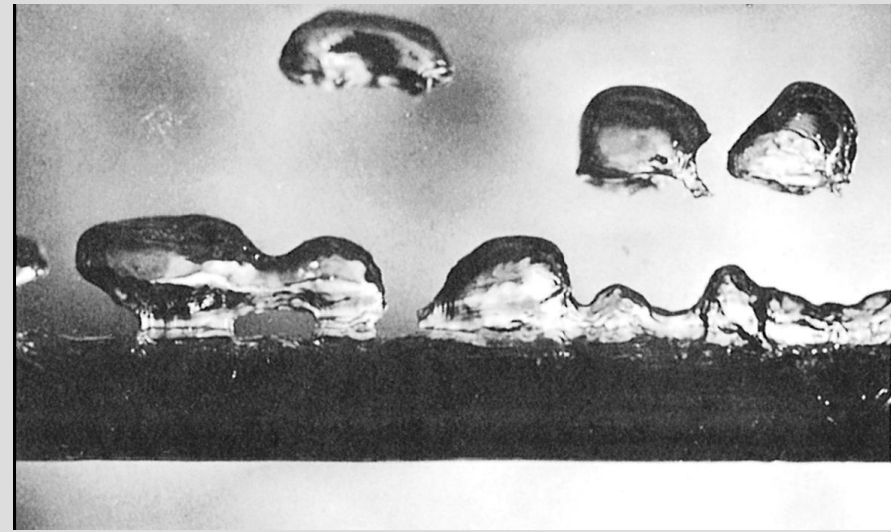
Transition Boiling (between Points C and D)

- 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.

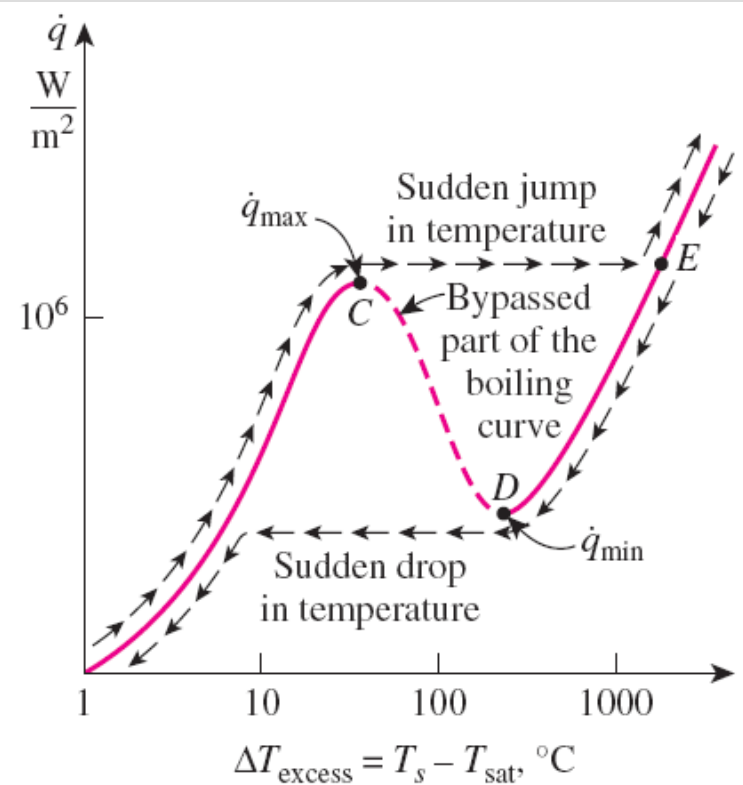


FIGURE 10–8

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.

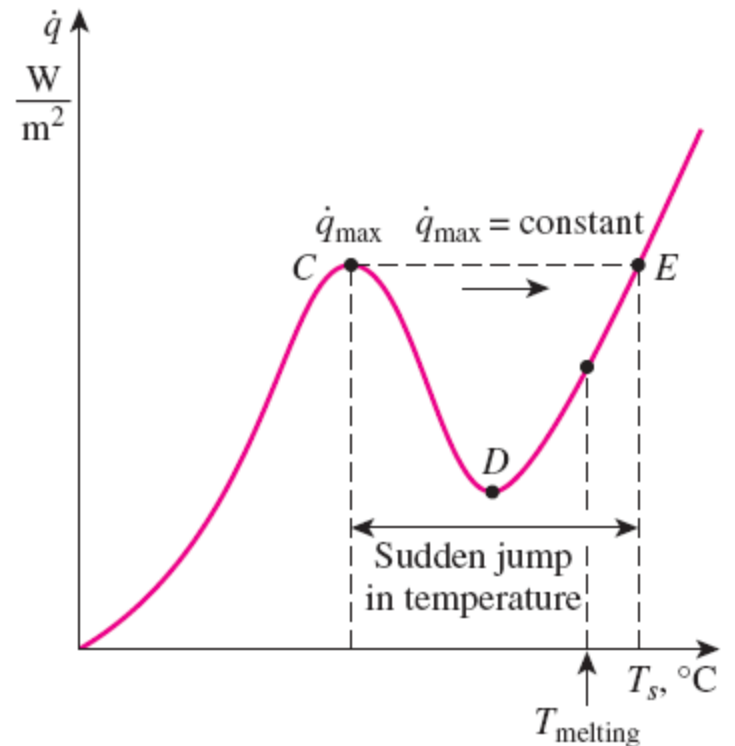


FIGURE 10–9

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.

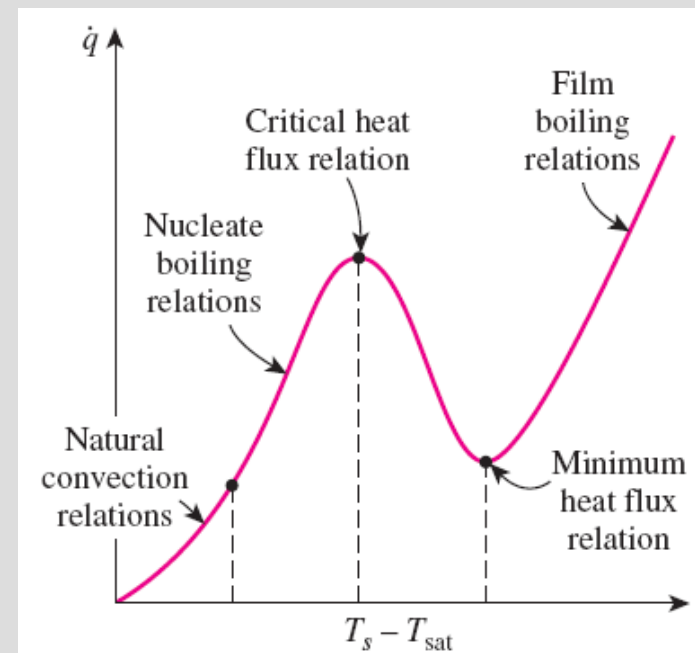


FIGURE 10-10

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

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

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.

TABLE 10-1

Surface tension of liquid–vapor interface for water

$T, ^\circ\text{C}$	$\sigma, \text{N/m}^*$
0	0.0757
20	0.0727
40	0.0696
60	0.0662
80	0.0627
100	0.0589
120	0.0550
140	0.0509
160	0.0466
180	0.0422
200	0.0377
220	0.0331
240	0.0284
260	0.0237
280	0.0190
300	0.0144
320	0.0099
340	0.0056
360	0.0019
374	0.0

*Multiply by 0.06852 to convert to lbf/ft or by 2.2046 to convert to lbm/s².

TABLE 10-2

Surface tension of some fluids (from Suryanarayana, originally based on data from Jasper)

Substance and Temp. Range	Surface Tension, $\sigma, \text{N/m}^*$ (T in $^\circ\text{C}$)
Ammonia, -75 to -40°C :	$0.0264 + 0.000223T$
Benzene, 10 to 80°C :	$0.0315 - 0.000129T$
Butane, -70 to -20°C :	$0.0149 - 0.000121T$
Carbon dioxide, -30 to -20°C :	$0.0043 - 0.000160T$
Ethyl alcohol, 10 to 70°C :	$0.0241 - 0.000083T$
Mercury, 5 to 200°C :	$0.4906 - 0.000205T$
Methyl alcohol, 10 to 60°C :	$0.0240 - 0.000077T$
Pentane, 10 to 30°C :	$0.0183 - 0.000110T$
Propane, -90 to -10°C :	$0.0092 - 0.000087T$

*Multiply by 0.06852 to convert to lbf/ft or by 2.2046 to convert to lbm/s².

TABLE 10-3Values of the coefficient C_{sf} and n for various fluid–surface combinations

Fluid–Heating Surface Combination	C_{sf}	n
Water–copper (polished)	0.0130	1.0
Water–copper (scored)	0.0068	1.0
Water–stainless steel (mechanically polished)	0.0130	1.0
Water–stainless steel (ground and polished)	0.0060	1.0
Water–stainless steel (teflon pitted)	0.0058	1.0
Water–stainless steel (chemically etched)	0.0130	1.0
Water–brass	0.0060	1.0
Water–nickel	0.0060	1.0
Water–platinum	0.0130	1.0
n -Pentane–copper (polished)	0.0154	1.7
n -Pentane–chromium	0.0150	1.7
Benzene–chromium	0.1010	1.7
Ethyl alcohol–chromium	0.0027	1.7
Carbon tetrachloride–copper	0.0130	1.7
Isopropanol–copper	0.0025	1.7

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*

$$\dot{q}_{\min} = 0.09\rho_v h_{fg} \left[\frac{\sigma g(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2} \right]^{1/4}$$

- This relation above can be in error 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.

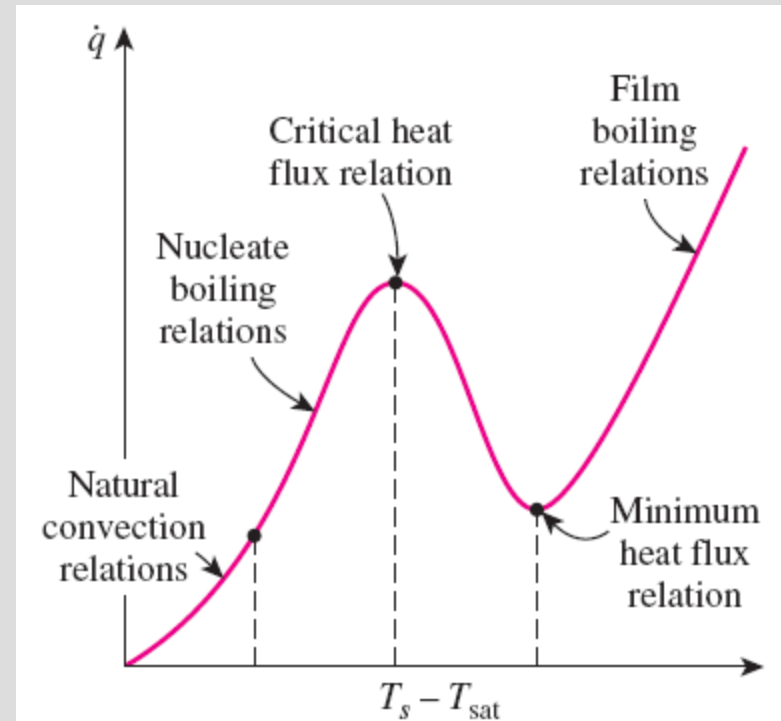


FIGURE 10-10

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

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

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

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

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

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

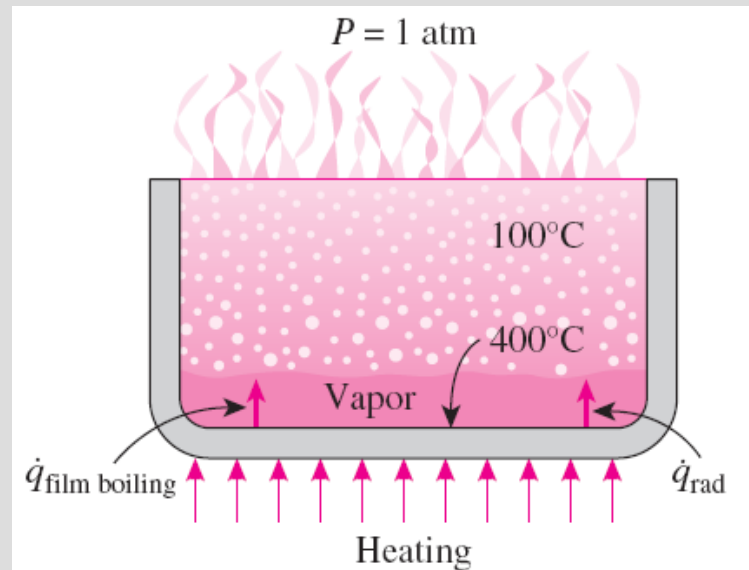


FIGURE 10-12

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