BOILING AND CONDENSATION

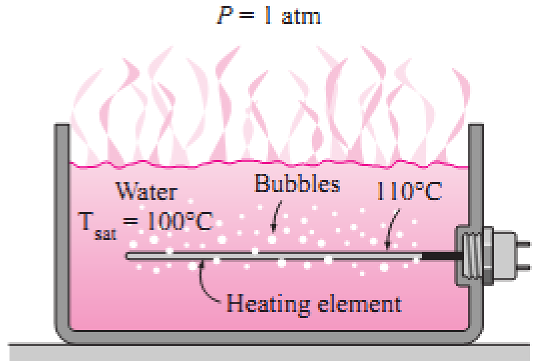


FIGURE 10–2
Boiling occurs when a liquid is brought into contact with a surface at a temperature above the saturation temperature of the liquid.

As a form of convection heat transfer, the *boiling heat flux* from a solid surface to the fluid is expressed from Newton's law of cooling as

$$\dot{q}_{\text{boiling}} = h(T_s - T_{\text{sat}}) = h\Delta T_{\text{excess}} \qquad (\text{W/m}^2) \qquad \textbf{(10-1)}$$

FIGURE 10–1
A liquid-to-vapor phase change process is called *evaporation* if it occurs at a liquid–vapor interface and *boiling* if it occurs at a solid–liquid interface.

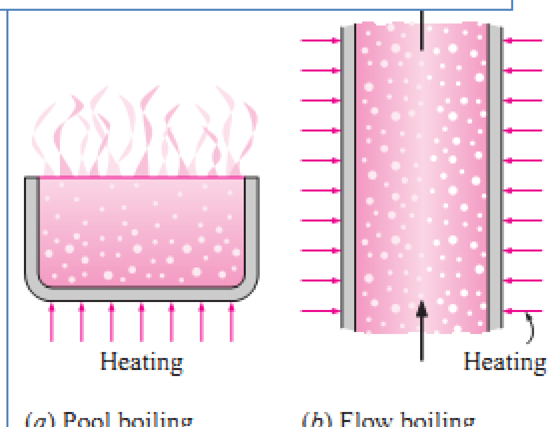
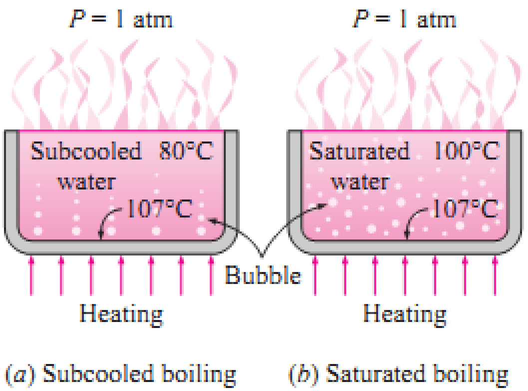
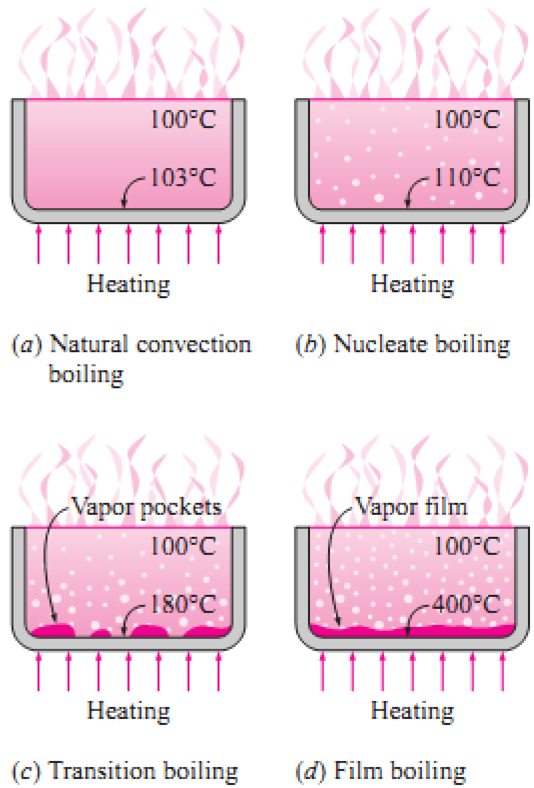


FIGURE 10–3
Classification of boiling on the basis of the presence of bulk fluid motion.



(a) Subcooled boiling (b) Saturated boiling

FIGURE 10–4
Classification of boiling on the basis of the presence of bulk liquid temperature.



(a) Natural convection boiling (b) Nucleate boiling (c) Transition boiling (d) Film boiling

FIGURE 10–5
Different boiling regimes in pool boiling.

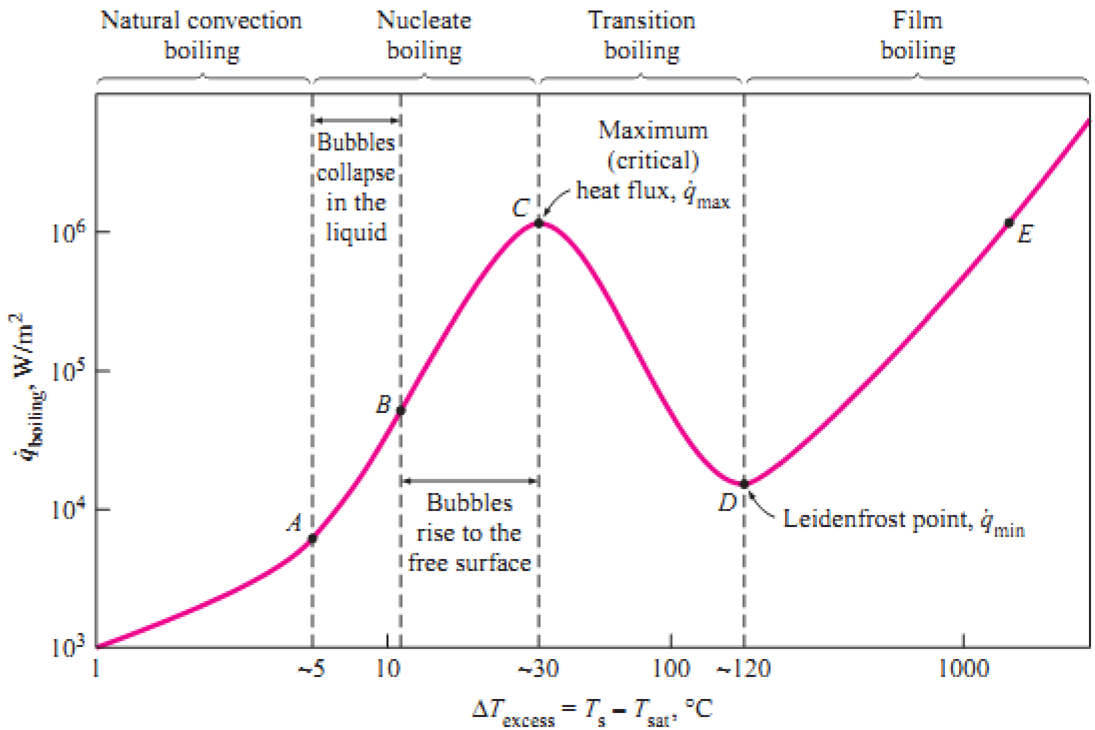


FIGURE 10–6
Typical boiling curve for water at 1 atm pressure.

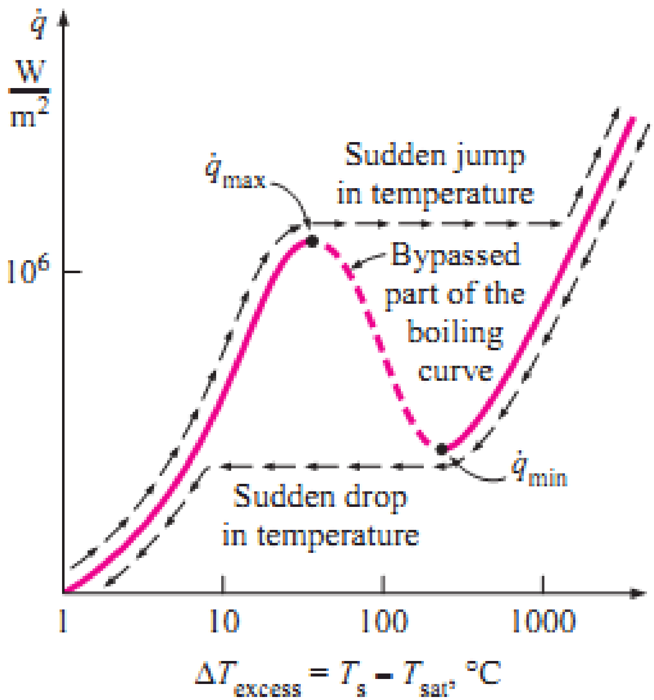
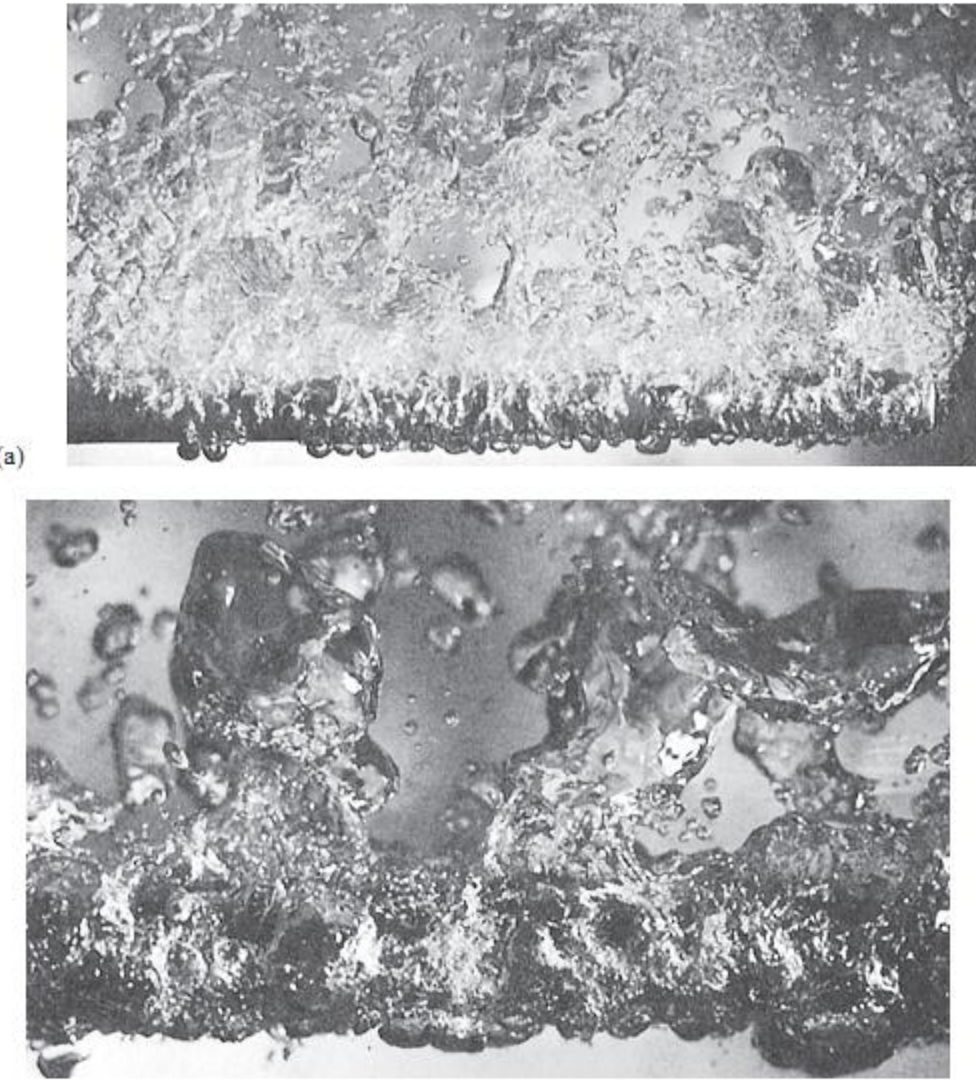


FIGURE 10–8
The actual boiling curve obtained with heated platinum wire in water as the heat flux is increased and then decreased.



(a)

(b)

(c)

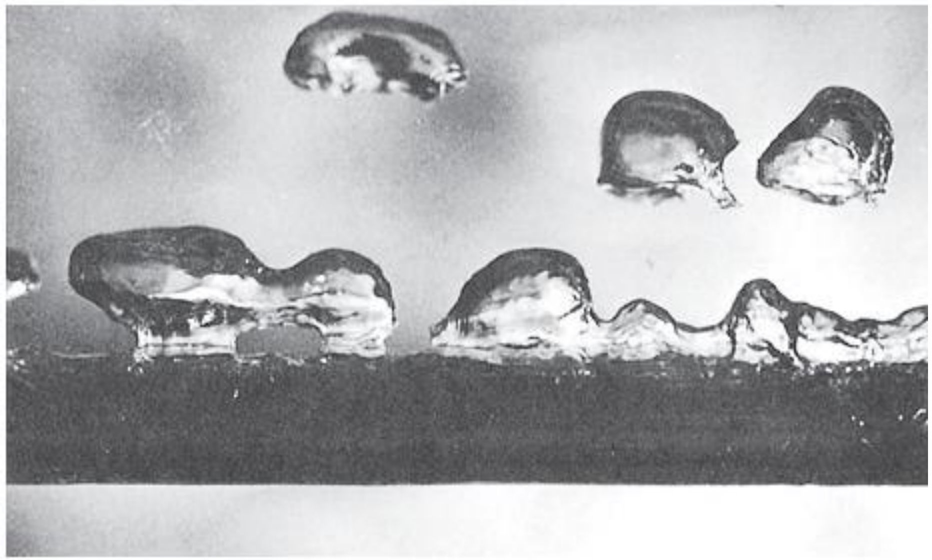


FIGURE 10–7

Various boiling regimes during boiling of methanol on a horizontal 1-cm-diameter steam-heated copper tube: (*a*) nucleate boiling, (*b*) transition boiling, and (*c*) film boiling (from J. W. Westwater and J. G. Santangelo, University of Illinois at Champaign-Urbana).

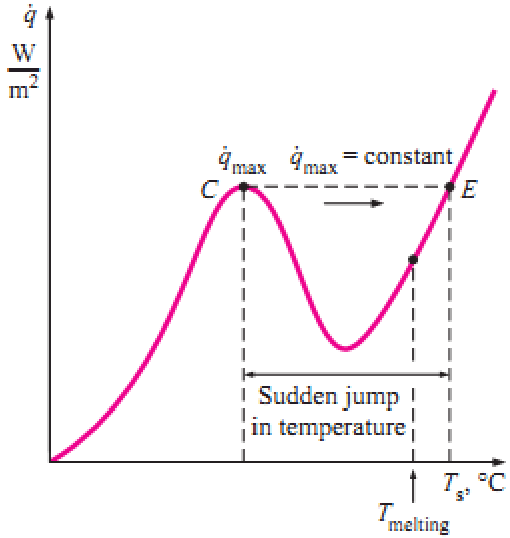


FIGURE 10–9
An attempt to increase the boiling heat flux beyond the *critical* value often causes the temperature of the heating element to jump suddenly to a value that is above the melting point, resulting in *burnout*.

$$\dot{q}_{nucleate} = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2} \left[\frac{C_{pl}(T_s - T_{sat})}{C_{sf} h_{fg} \Pr_l^n}\right]^3 \quad (10\text{-}2)$$

where

$\dot{q}_{nucleate}$ = 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

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

$$= \frac{\text{W}}{\text{m}}\left(\frac{1}{\text{m}^2}\right)^{1/2}(1)^3$$

$$= \text{W/m}^2$$

FIGURE 10–10
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

$$\dot{q}_{max} = C_{cr}\, h_{fg}[\sigma g \rho_v^2 (\rho_l - \rho_v)]^{1/4} \qquad (10\text{-}3)$$

TABLE 10–1

Surface tension of liquid–vapor interface for water

T, °C	σ, 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, Ref. 26; originally based on data from Jasper, Ref. 14)

Substance and Temp. Range	Surface Tension, σ, N/m* (T in °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 10–3

Values 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

Minimum Heat Flux

$$\dot{q}_{\min} = 0.09\rho_v h_{fg}\left[\frac{\sigma g(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2}\right]^{1/4} \qquad (10\text{-}4)$$

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

Film Boiling

$$\dot{q}_{film} = C_{film}\left[\frac{gk_v^3\rho_v(\rho_l - \rho_v)[h_{fg} + 0.4C_{pv}(T_s - T_{sat})]}{\mu_v D(T_s - T_{sat})}\right]^{1/4}(T_s - T_{sat}) \qquad (10\text{-}5)$$

where k_v is the thermal conductivity of the vapor in W/m · °C and

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

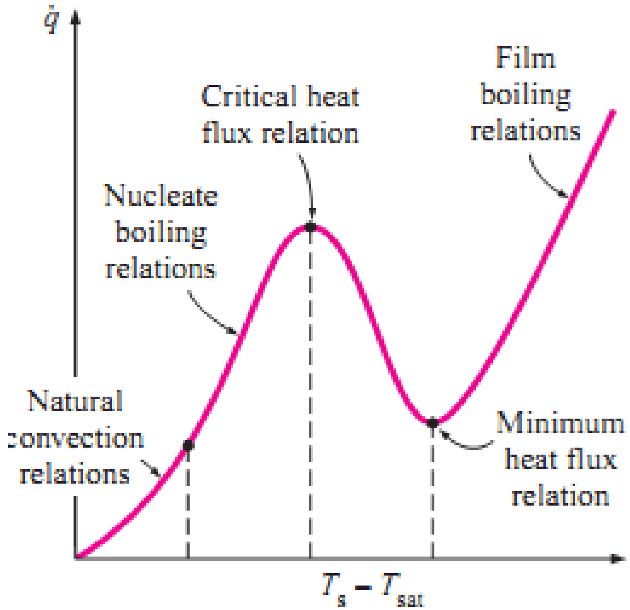


FIGURE 10–11
Different relations are used to determine the heat flux in different boiling regimes.

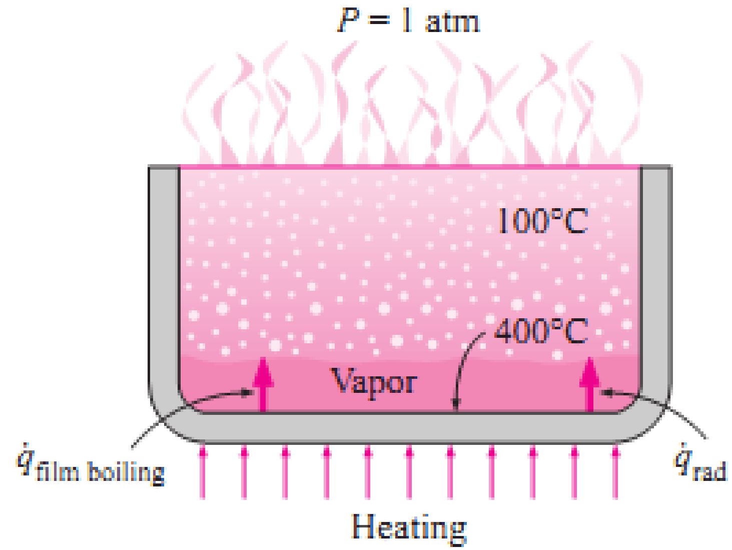


FIGURE 10–12
At high heater surface temperatures, radiation heat transfer becomes significant during film boiling.

radiation heat transfer can be determined from

$$\dot{q}_{rad} = \varepsilon\sigma\,(T_s^4 - T_{sat}^4) \qquad \textbf{(10-6)}$$

where ε is the emissivity of the heating surface and $\sigma = 5.67 \times 10^{-8}$ W/m$^2 \cdot$ K^4 is the Stefan–Boltzman constant. Note that the temperature in this case *must* be expressed in K, not °C, and that surface tension and the Stefan–Boltzman constant share the same symbol.

the thickness of the vapor film, which impedes convection heat transfer. For $\dot{q}_{rad} < \dot{q}_{film}$, Bromley determined that the relation

$$\dot{q}_{total} = \dot{q}_{film} + \frac{3}{4}\dot{q}_{rad} \qquad \text{(10-7)}$$

correlates experimental data well.

EXAMPLE 10–1 Nucleate Boiling of Water in a Pan

Water is to be boiled at atmospheric pressure in a mechanically polished stainless steel pan placed on top of a heating unit, as shown in Figure 10–15. The inner surface of the bottom of the pan is maintained at 108°C. If the diameter of the bottom of the pan is 30 cm, determine (*a*) the rate of heat transfer to the water and (*b*) the rate of evaporation of water.

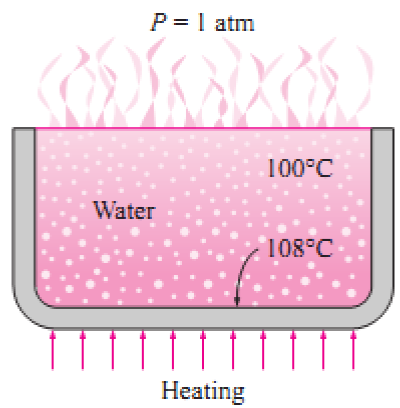


FIGURE 10–15
Schematic for Example 10–1.

SOLUTION Water is boiled at 1 atm pressure on a stainless steel surface. The rate of heat transfer to the water and the rate of evaporation of water are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat losses from the heater and the pan are negligible.

Properties The properties of water at the saturation temperature of 100°C are $\sigma = 0.0589$ N/m (Table 10–1) and, from Table A-9,

$$\rho_l = 957.9 \text{ kg/m}^3 \qquad h_{fg} = 2257.0 \times 10^3 \text{ J/kg}$$
$$\rho_v = 0.6 \text{ kg/m}^3 \qquad \mu_l = 0.282 \times 10^{-3} \text{ kg}\cdot\text{m/s}$$
$$\text{Pr}_l = 1.75 \qquad C_{pl} = 4217 \text{ J/kg}\cdot°\text{C}$$

Also, $C_{sf} = 0.0130$ and $n = 1.0$ for the boiling of water on a mechanically polished stainless steel surface (Table 10–3). Note that we expressed the properties in units specified under Eq. 10–2 in connection with their definitions in order to avoid unit manipulations.

Analysis (*a*) The excess temperature in this case is $\Delta T = T_s - T_{sat} = 108 - 100 = 8°\text{C}$ which is relatively low (less than 30°C). Therefore, nucleate boiling will occur. The heat flux in this case can be determined from the Rohsenow relation to be

$$\dot{q}_{\text{nucleate}} = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma}\right]^{1/2} \left[\frac{C_{pl}(T_s - T_{sat})}{C_{sf} h_{fg} \text{Pr}_l^n}\right]^3$$
$$= (0.282 \times 10^{-3})(2257 \times 10^3)\left[\frac{9.81 \times (957.9 - 0.6)}{0.0589}\right]^{1/2}$$
$$\times \left(\frac{4217(108 - 100)}{0.0130(2257 \times 10^3)1.75}\right)^3$$
$$= 7.20 \times 10^4 \text{ W/m}^2$$

The surface area of the bottom of the pan is

$$A = \pi D^2/4 = \pi(0.3 \text{ m})^2/4 = 0.07069 \text{ m}^2$$

Then the rate of heat transfer during nucleate boiling becomes

$$\dot{Q}_{\text{boiling}} = A\dot{q}_{\text{nucleate}} = (0.07069 \text{ m}^2)(7.20 \times 10^4 \text{ W/m}^2) = \mathbf{5093 \text{ W}}$$

(*b*) The rate of evaporation of water is determined from

$$\dot{m}_{\text{evaporation}} = \frac{\dot{Q}_{\text{boiling}}}{h_{fg}} = \frac{5093 \text{ J/s}}{2257 \times 10^3 \text{ J/kg}} = \mathbf{2.26 \times 10^{-3} \text{ kg/s}}$$

That is, water in the pan will boil at a rate of more than 2 grams per second.

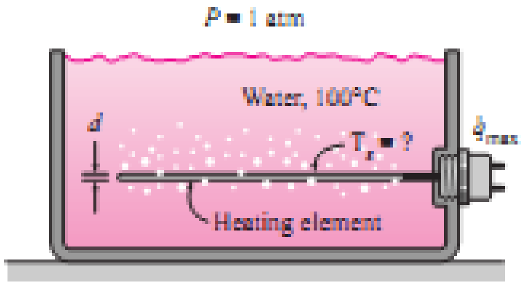


FIGURE 10–16
Schematic for Example 10–2.

EXAMPLE 10–2 Peak Heat Flux in Nucleate Boiling

Water in a tank is to be boiled at sea level by a 1-cm-diameter nickel plated steel heating element equipped with electrical resistance wires inside, as shown in Figure 10–16. Determine the maximum heat flux that can be attained in the nucleate boiling regime and the surface temperature of the heater surface in that case.

SOLUTION Water is boiled at 1 atm pressure on a nickel plated steel surface. The maximum (critical) heat flux and the surface temperature are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Heat losses from the boiler are negligible.

Properties The properties of water at the saturation temperature of 100°C are $\sigma = 0.0589$ N/m (Table 10–1) and, from Table A-9,

$$\rho_l = 957.9 \text{ kg/m}^3 \qquad h_{fg} = 2257 \times 10^3 \text{ J/kg}$$
$$\rho_v = 0.6 \text{ kg/m}^3 \qquad \mu_l = 0.282 \times 10^{-3} \text{ kg} \cdot \text{m/s}$$
$$\text{Pr}_l = 1.75 \qquad C_{pl} = 4217 \text{ J/kg} \cdot \text{°C}$$

Also, $C_{sf} = 0.0060$ and $n = 1.0$ for the boiling of water on a nickel plated surface (Table 10–3). Note that we expressed the properties in units specified under Eqs. 10–2 and 10–3 in connection with their definitions in order to avoid unit manipulations.

Analysis The heating element in this case can be considered to be a short cylinder whose characteristic dimension is its radius. That is, $L = r = 0.005$ m. The dimensionless parameter L^* and the constant C_{cr} are determined from Table 10–4 to be

$$L^* = L\left(\frac{g(\rho_l - \rho_v)}{\sigma}\right)^{1/2} = (0.005)\left(\frac{(9.81)(957.8 - 0.6)}{0.0589}\right)^{1/2} = 2.00 > 1.2$$

which corresponds to $C_{cr} = 0.12$.

Then the maximum or critical heat flux is determined from Eq. 10–3 to be

$$\begin{aligned}\dot{q}_{max} &= C_{cr} h_{fg} [\sigma g \rho_v^2 (\rho_l - \rho_v)]^{1/4} \\ &= 0.12(2257 \times 10^3)[0.0589 \times 9.8 \times (0.6)^2(957.9 - 0.6)]^{1/4} \\ &= \mathbf{1.02 \times 10^6\ W/m^2}\end{aligned}$$

The Rohsenow relation, which gives the nucleate boiling heat flux for a specified surface temperature, can also be used to determine the surface temperature when the heat flux is given. Substituting the maximum heat flux into Eq. 10–2 together with other properties gives

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

$$1{,}017{,}200 = (0.282 \times 10^{-3})(2257 \times 10^3)\left[\frac{9.81(957.9 - 0.6)}{0.0589}\right]^{1/2} \left[\frac{4217(T_s - 100)}{0.0130(2257 \times 10^3)\,1.75}\right]^3$$

$$T_s = 119°C$$

Discussion Note that heat fluxes on the order of 1 MW/m² can be obtained in nucleate boiling with a temperature difference of less than 20°C.

EXAMPLE 10–3 **Film Boiling of Water on a Heating Element**

Water is boiled at atmospheric pressure by a horizontal polished copper heating element of diameter D = 5 mm and emissivity ε = 0.05 immersed in water, as shown in Figure 10–17. If the surface temperature of the heating wire is 350°C, determine the rate of heat transfer from the wire to the water per unit length of the wire.

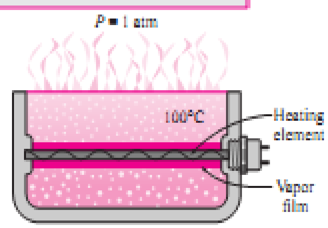


FIGURE 10–17
Schematic for Example 10–3.

SOLUTION Water is boiled at 1 atm by a horizontal polished copper heating element. The rate of heat transfer to the water per unit length of the heater is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat losses from the boiler are negligible.

Properties The properties of water at the saturation temperature of 100°C are h_{fg} = 2257 × 10³ J/kg and ρ_l = 957.9 kg/m³ (Table A-9). The properties of vapor at the film temperature of $T_f = (T_{sat} + T_s)/2$ = (100 + 350)/2 = 225°C = 498 K (which is sufficiently close to 500 K) are, from Table A-16,

$$\rho_v = 0.441 \text{ kg/m}^3 \qquad C_{pv} = 1977 \text{ J/kg}\cdot°C$$
$$\mu_v = 1.73 \times 10^{-5} \text{ kg/m}\cdot\text{s} \qquad k_v = 0.0357 \text{ W/m}\cdot°C$$

Note that we expressed the properties in units that will cancel each other in boiling heat transfer relations. Also note that we used vapor properties at 1 atm pressure from Table A-16 instead of the properties of saturated vapor from Table A-9 at 250°C since the latter are at the saturation pressure of 4.0 MPa.

Analysis The excess temperature in this case is $\Delta T = T_s - T_{sat}$ = 350 − 100 = 250°C, which is much larger than 30°C for water. Therefore, film boiling will occur. The film boiling heat flux in this case can be determined from Eq. 10–5 to be

$$\dot{q}_{film} = 0.62\left[\frac{gk_v^3 \rho_v(\rho_l - \rho_v)[h_{fg} + 0.4C_{pv}(T_s - T_{sat})]}{\mu_v D(T_s - T_{sat})}\right]^{1/4}(T_s - T_{sat})$$

$$= 0.62\left[\frac{9.81(0.0357)^3(0.441)(957.9 - 0.441)\,[(2257 \times 10^3 + 0.4 \times 1977(250)]}{(1.73 \times 10^{-5})(5 \times 10^{-3})(250)}\right]^{1/4} \times 250$$

$$= 5.93 \times 10^4 \text{ W/m}^2$$

The radiation heat flux is determined from Eq. 10–6 to be

$$\dot{q}_{rad} = \varepsilon\sigma(T_s^4 - T_{sat}^4)$$
$$= (0.05)(5.67 \times 10^{-8} \text{ W/m}^2\cdot\text{K}^4)[(250 + 273 \text{ K})^4 - (100 + 273 \text{ K})^4]$$
$$= 157 \text{ W/m}^2$$

Note that heat transfer by radiation is negligible in this case because of the low emissivity of the surface and the relatively low surface temperature of the heating element. Then the total heat flux becomes (Eq. 10–7)

$$\dot{q}_{total} = \dot{q}_{film} + \frac{3}{4}\dot{q}_{rad} = 5.93 \times 10^4 + \frac{3}{4} \times 157 = 5.94 \times 10^4 \text{ W/m}^2$$

Finally, the rate of heat transfer from the heating element to the water is determined by multiplying the heat flux by the heat transfer surface area,

$$\dot{Q}_{total} = A\dot{q}_{total} = (\pi DL)\dot{q}_{total}$$
$$= (\pi \times 0.005 \text{ m} \times 1 \text{ m})(5.94 \times 10^4 \text{ W/m}^2)$$
$$= 933 \text{ W}$$

Discussion Note that the 5-mm-diameter copper heating element will consume about 1 kW of electric power per unit length in steady operation in the film boiling regime. This energy is transferred to the water through the vapor film that forms around the wire.