

<http://www.Drshokuhi.com>

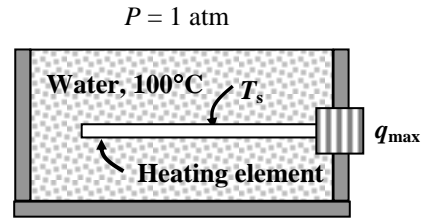
سایت آموزش مهندسی مکانیک

10-21 Water is boiled at 1 atm pressure and thus at a saturation (or boiling) temperature of $T_{\text{sat}} = 100^\circ\text{C}$ by a horizontal nickel plated copper heating element. The maximum (critical) heat flux and the temperature jump of the wire when the operating point jumps from nucleate boiling to film boiling regime 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 (Tables 10-1 and A-9)

$$\begin{aligned} \rho_l &= 957.9 \text{ kg/m}^3 & h_{fg} &= 2257 \times 10^3 \text{ J/kg} \\ \rho_v &= 0.60 \text{ kg/m}^3 & \mu_l &= 0.282 \times 10^{-3} \text{ kg}\cdot\text{m/s} \\ \sigma &= 0.0589 \text{ N/m} & C_{pl} &= 4217 \text{ J/kg}\cdot^\circ\text{C} \\ \text{Pr}_l &= 1.75 \end{aligned}$$



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. The vapor properties at the anticipated film temperature of $T_f = (T_s + T_{\text{sat}})/2$ of 100°C (will be checked) (Table A-16)

$$\begin{aligned} \rho_v &= 0.1725 \text{ kg/m}^3 \\ C_{pv} &= 2471 \text{ J/kg}\cdot^\circ\text{C} \\ k_v &= 0.1362 \text{ W/m}\cdot^\circ\text{C} \\ \mu_v &= 4.762 \times 10^{-5} \text{ kg/m}\cdot\text{s} \end{aligned}$$

Analysis (a) For a horizontal heating element, the coefficient C_{cr} is determined from Table 10-4 to be

$$\begin{aligned} L^* &= L \left(\frac{g(\rho_l - \rho_v)}{\sigma} \right)^{1/2} = (0.0015) \left(\frac{9.8(957.9 - 0.60)}{0.0589} \right)^{1/2} = 0.60 < 1.2 \\ C_{cr} &= 0.12 L^{*-0.25} = 0.12(0.60)^{-0.25} = 0.136 \end{aligned}$$

Then the maximum or critical heat flux is determined from

$$\begin{aligned} \dot{q}_{\text{max}} &= C_{cr} h_{fg} [\sigma g \rho_v^2 (\rho_l - \rho_v)]^{1/4} \\ &= 0.136(2257 \times 10^3) [0.0589 \times 9.8 \times (0.6)^2 (957.9 - 0.60)]^{1/4} \\ &= \mathbf{1,153,000 \text{ W/m}^2} \end{aligned}$$

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 the Rohsenow relation together with other properties gives

$$\begin{aligned} \dot{q}_{\text{nucleate}} &= \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{C_{p,l}(T_s - T_{\text{sat}})}{C_{sf} h_{fg} \text{Pr}_l^n} \right)^3 \\ 1,153,000 &= (0.282 \times 10^{-3})(2257 \times 10^3) \left[\frac{9.8(957.9 - 0.60)}{0.0060} \right]^{1/2} \left(\frac{4217(T_s - 100)}{0.0130(2257 \times 10^3)1.75} \right)^3 \end{aligned}$$

It gives

$$T_s = 109.3^\circ\text{C}$$

(b) Heat transfer in the film boiling region can be expressed as

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

Substituting,

$$1,153,000 = 0.62 \left[\frac{9.81(0.1362)^3 (0.1723)(957.9 - 0.1725)[2257 \times 10^3 + 0.4 \times 2471(T_s - 100)]}{(4.762 \times 10^{-5})(0.003)(T_s - 100)} \right]^{1/4} \times (T_s - 100) \\ + (0.5)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4) [(T_s + 273)^4 - (100 + 273)^4]$$

Solving for the surface temperature gives $T_s = 1871^\circ\text{C}$. Therefore, the temperature jump of the wire when the operating point jumps from nucleate boiling to film boiling is

Temperature jump: $\Delta T = T_{s,\text{film}} - T_{s,\text{crit}} = 1871 - 109 = \mathbf{1762^\circ\text{C}}$

Note that the film temperature is $(1871+100)/2=985^\circ\text{C}$, which is close enough to the assumed value of 1000°C for the evaluation of vapor properties.

10-22 "PROBLEM 10-22"

"GIVEN"

L=0.3 "[m]"

D=0.003 "[m]"

"epsilon=0.5 parameter to be varied"

P=101.3 "[kPa], parameter to be varied"

"PROPERTIES"

Fluid\$='steam_NBS'

T_sat=temperature(Fluid\$, P=P, x=1)

rho_l=density(Fluid\$, T=T_sat, x=0)

rho_v=density(Fluid\$, T=T_sat, x=1)

sigma=SurfaceTension(Fluid\$, T=T_sat)

mu_l=Viscosity(Fluid\$, T=T_sat, x=0)

Pr_l=Prandtl(Fluid\$, T=T_sat, P=P)

C_l=CP(Fluid\$, T=T_sat, x=0)*Convert(kJ/kg-C, J/kg-C)

h_f=enthalpy(Fluid\$, T=T_sat, x=0)

h_g=enthalpy(Fluid\$, T=T_sat, x=1)

h_fg=(h_g-h_f)*Convert(kJ/kg, J/kg)

C_sf=0.0060 "from Table 8-3 of the text"

n=1 "from Table 8-3 of the text"

T_vapor=1000-273 "[C], assumed vapor temperature in the film boiling region"

rho_v_f=density(Fluid\$, T=T_vapor, P=P) "f stands for film"

C_v_f=CP(Fluid\$, T=T_vapor, P=P)*Convert(kJ/kg-C, J/kg-C)

k_v_f=Conductivity(Fluid\$, T=T_vapor, P=P)

mu_v_f=Viscosity(Fluid\$, T=T_vapor, P=P)

g=9.8 "[m/s^2], gravitational acceleraton"

sigma_rad=5.67E-8 "[W/m^2-K^4], Stefan-Boltzmann constant"

"ANALYSIS"

"(a)"

"C_cr is to be determined from Table 8-4 of the text"

C_cr=0.12*L_star^(-0.25)

L_star=D/2*((g*(rho_l-rho_v))/sigma)^0.5

q_dot_max=C_cr*h_fg*(sigma*g*rho_v^2*(rho_l-rho_v))^0.25

q_dot_nucleate=q_dot_max

q_dot_nucleate=mu_l*h_fg*(((g*(rho_l-rho_v))/sigma)^0.5)*((C_l*(T_s_crit-T_sat))/(C_sf*h_fg*Pr_l^n))^3

"(b)"

q_dot_total=q_dot_film+3/4*q_dot_rad "Heat transfer in the film boiling region"

q_dot_total=q_dot_nucleate

q_dot_film=0.62*((g*k_v_f^3*rho_v_f*(rho_l-rho_v_f)*(h_fg+0.4*C_v_f*(T_s_film-T_sat)))/(mu_v_f*D*(T_s_film-T_sat)))^0.25*(T_s_film-T_sat)

q_dot_rad=epsilon*sigma_rad*((T_s_film+273)^4-(T_sat+273)^4)

DELTA_T=T_s_film-T_s_crit

P [kPa]	q_{\max} [kW/m ²]	ΔT [C]
70	994227	1865
71.65	1003642	1870
73.29	1012919	1876
74.94	1022063	1881
76.59	1031078	1886
78.24	1039970	1891
79.88	1048741	1896
81.53	1057396	1900
83.18	1065939	1905
84.83	1074373	1909
86.47	1082702	1914
88.12	1090928	1918
89.77	1099055	1923
91.42	1107085	1927
93.06	1115022	1931
94.71	1122867	1935
96.36	1130624	1939
98.01	1138294	1943
99.65	1145883	1947
101.3	1153386	1951

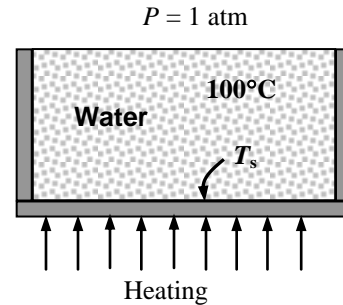
ϵ	q_{\max} [kW/m ²]	ΔT [C]
0.1	1153386	2800
0.15	1153386	2574
0.2	1153386	2418
0.25	1153386	2299
0.3	1153386	2205
0.35	1153386	2126
0.4	1153386	2059
0.45	1153386	2002
0.5	1153386	1951
0.55	1153386	1905
0.6	1153386	1864
0.65	1153386	1827
0.7	1153386	1793
0.75	1153386	1761
0.8	1153386	1732
0.85	1153386	1705
0.9	1153386	1680
0.95	1153386	1657
1	1153386	1634

10-23 Water is boiled at sea level (1 atm pressure) and thus at a saturation (or boiling) temperature of $T_{\text{sat}} = 100^\circ\text{C}$ in a teflon-pitted stainless steel pan placed on an electric burner. The water level drops by 10 cm in 30 min during boiling. The inner surface temperature of the pan is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat losses from the pan are negligible. 3 The boiling regime is nucleate boiling (this assumption will be checked later).

Properties The properties of water at the saturation temperature of 100°C are (Tables 10-1 and A-9)

$$\begin{aligned} \rho_l &= 957.9 \text{ kg/m}^3 & h_{fg} &= 2257 \times 10^3 \text{ J/kg} \\ \rho_v &= 0.60 \text{ kg/m}^3 & \mu_l &= 0.282 \times 10^{-3} \text{ kg}\cdot\text{m/s} \\ \sigma &= 0.0589 \text{ N/m} & C_{pl} &= 4217 \text{ J/kg}\cdot^\circ\text{C} \\ \text{Pr}_l &= 1.75 \end{aligned}$$



Also, $C_{sf} = 0.0058$ and $n = 1.0$ for the boiling of water on a teflon-pitted stainless steel surface (Table 10-3). Note that we expressed the properties in units specified under Eq. 10-2 connection with their definitions in order to avoid unit manipulations.

Analysis The rate of heat transfer to the water and the heat flux are

$$\begin{aligned} \dot{m}_{\text{evap}} &= \frac{m_{\text{evap}}}{\Delta t} = \frac{\rho \Delta V}{\Delta t} = \frac{(957.9 \text{ kg/m}^3)(\pi \times 0.2 \text{ m} \times 0.10 \text{ m})}{30 \times 60 \text{ s}} = 0.03344 \text{ kg/s} \\ \dot{Q} &= \dot{m}_{\text{evap}} h_{fg} = (0.03344 \text{ kg/s})(2257 \text{ kJ/kg}) = 75.47 \text{ kW} \\ A_s &= \pi D^2 / 4 = \pi (0.20 \text{ m})^2 / 4 = 0.03142 \text{ m}^2 \\ \dot{q} &= \dot{Q} / A_s = (75,470 \text{ W}) / (0.03142 \text{ m}^2) = 2,402,000 \text{ W/m}^2 \end{aligned}$$

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. Assuming nucleate boiling, the temperature of the inner surface of the pan is determined from Rohsenow relation to be

$$\begin{aligned} \dot{q}_{\text{nucleate}} &= \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{C_{p,l}(T_s - T_{\text{sat}})}{C_{sf} h_{fg} \text{Pr}_l^n} \right)^3 \\ 2,402,000 &= (0.282 \times 10^{-3})(2257 \times 10^3) \left[\frac{9.8(957.9 - 0.60)}{0.0589} \right]^{1/2} \left(\frac{4217(T_s - 100)}{0.0058(2257 \times 10^3)1.75} \right)^3 \end{aligned}$$

It gives

$$T_s = 111.5^\circ\text{C}$$

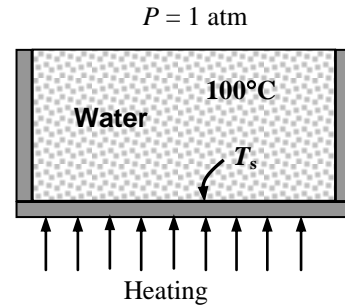
which is in the nucleate boiling range (5 to 30°C above surface temperature). Therefore, the nucleate boiling assumption is valid.

10-24 Water is boiled at sea level (1 atm pressure) and thus at a saturation (or boiling) temperature of $T_{\text{sat}} = 100^\circ\text{C}$ in a polished copper pan placed on an electric burner. The water level drops by 10 cm in 30 min during boiling. The inner surface temperature of the pan is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat losses from the pan are negligible. 3 The boiling regime is nucleate boiling (this assumption will be checked later).

Properties The properties of water at the saturation temperature of 100°C are (Tables 10-1 and A-9)

$$\begin{aligned} \rho_l &= 957.9 \text{ kg/m}^3 & h_{fg} &= 2257 \times 10^3 \text{ J/kg} \\ \rho_v &= 0.60 \text{ kg/m}^3 & \mu_l &= 0.282 \times 10^{-3} \text{ kg}\cdot\text{m/s} \\ \sigma &= 0.0589 \text{ N/m} & C_{pl} &= 4217 \text{ J/kg}\cdot^\circ\text{C} \\ \text{Pr}_l &= 1.75 \end{aligned}$$



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

Analysis The rate of heat transfer to the water and the heat flux are

$$\begin{aligned} \dot{m}_{\text{evap}} &= \frac{m_{\text{evap}}}{\Delta t} = \frac{\rho \Delta V}{\Delta t} = \frac{(957.9 \text{ kg/m}^3)(\pi \times 0.2 \text{ m} \times 0.10 \text{ m})}{30 \times 60 \text{ s}} = 0.03344 \text{ kg/s} \\ \dot{Q} &= \dot{m}_{\text{evap}} h_{fg} = (0.03344 \text{ kg/s})(2257 \text{ kJ/kg}) = 75.47 \text{ kW} \\ A_s &= \pi D^2 / 4 = \pi (0.20 \text{ m})^2 / 4 = 0.03142 \text{ m}^2 \\ \dot{q} &= \dot{Q} / A_s = (75,470 \text{ W}) / (0.03142 \text{ m}^2) = 2,402,000 \text{ W/m}^2 \end{aligned}$$

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. Assuming nucleate boiling, the temperature of the inner surface of the pan is determined from Rohsenow relation to be

$$\begin{aligned} \dot{q}_{\text{nucleate}} &= \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{C_{p,l}(T_s - T_{\text{sat}})}{C_{sf} h_{fg} \text{Pr}_l^n} \right)^3 \\ 2,402,000 &= (0.282 \times 10^{-3})(2257 \times 10^3) \left[\frac{9.8(957.9 - 0.60)}{0.0589} \right]^{1/2} \left(\frac{4217(T_s - 100)}{0.0130(2257 \times 10^3)1.75} \right)^3 \end{aligned}$$

It gives

$$T_s = 125.7^\circ\text{C}$$

which is in the nucleate boiling range (5 to 30°C above surface temperature). Therefore, the nucleate boiling assumption is valid.

10-25 Water is boiled at a temperature of $T_{\text{sat}} = 150^\circ\text{C}$ by hot gases flowing through a mechanically polished stainless steel pipe submerged in water whose outer surface temperature is maintained at $T_s = 165^\circ\text{C}$. The rate of heat transfer to the water, the rate of evaporation, the ratio of critical heat flux to current heat flux, and the pipe surface temperature at critical heat flux conditions are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat losses from the boiler are negligible. 3 The boiling regime is nucleate boiling since $\Delta T = T_s - T_{\text{sat}} = 165 - 150 = 15^\circ\text{C}$ which is in the nucleate boiling range of 5 to 30°C for water.

Properties The properties of water at the saturation temperature of 150°C are (Tables 10-1 and A-9)

$$\begin{aligned} \rho_l &= 916.6 \text{ kg/m}^3 & h_{fg} &= 2114 \times 10^3 \text{ J/kg} \\ \rho_v &= 2.55 \text{ kg/m}^3 & \mu_l &= 0.183 \times 10^{-3} \text{ kg}\cdot\text{m/s} \\ \sigma &= 0.0488 \text{ N/m} & C_{pl} &= 4311 \text{ J/kg}\cdot^\circ\text{C} \\ Pr_l &= 1.16 \end{aligned}$$

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) Assuming nucleate boiling, the heat flux can be determined from Rohsenow relation to be

$$\begin{aligned} \dot{q}_{\text{nucleate}} &= \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{C_{p,l}(T_s - T_{\text{sat}})}{C_{sf} h_{fg} Pr_l^n} \right)^3 \\ &= (0.183 \times 10^{-3})(2114 \times 10^3) \left[\frac{9.8(916.6 - 2.55)}{0.0488} \right]^{1/2} \left(\frac{4311(165 - 150)}{(0.0130)(2114 \times 10^3)(1.16)} \right)^3 \\ &= 1,383,000 \text{ W/m}^2 \end{aligned}$$

The heat transfer surface area is

$$A_s = \pi DL = \pi(0.05 \text{ m})(50 \text{ m}) = 7.854 \text{ m}^2$$

Then the rate of heat transfer during nucleate boiling becomes

$$\dot{Q}_{\text{boiling}} = A_s \dot{q}_{\text{nucleate}} = (7.854 \text{ m}^2)(1,383,000 \text{ W/m}^2) = \mathbf{10,865,000 \text{ W}}$$

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

$$\dot{m}_{\text{evaporation}} = \frac{\dot{Q}_{\text{boiling}}}{h_{fg}} = \frac{10,865 \text{ kJ/s}}{2114 \text{ kJ/kg}} = \mathbf{5.139 \text{ kg/s}}$$

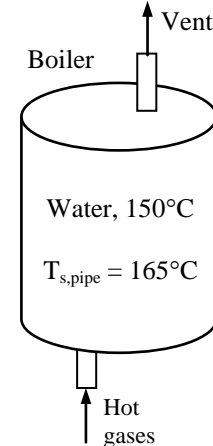
(c) For a horizontal cylindrical heating element, the coefficient C_{cr} is determined from Table 10-4 to be

$$L^* = L \left(\frac{g(\rho_l - \rho_v)}{\sigma} \right)^{1/2} = (0.025) \left(\frac{9.8(916.6 - 2.55)}{0.0488} \right)^{1/2} = 10.7 > 0.12$$

$$C_{cr} = 0.12 \quad (\text{since } L^* > 1.2 \text{ and thus large cylinder})$$

Then the maximum or critical heat flux is determined from

$$\begin{aligned} \dot{q}_{\text{max}} &= C_{cr} h_{fg} [\sigma g \rho_v^2 (\rho_l - \rho_v)]^{1/4} \\ &= 0.12(2114 \times 10^3)[0.0488 \times 9.8 \times (2.55)^2(916.6 - 2.55)]^{1/4} \\ &= 1,852,000 \text{ W/m}^2 \end{aligned}$$



Therefore,
$$\frac{\dot{q}_{\max}}{\dot{q}_{\text{current}}} = \frac{1,852,000}{1,383,000} = \mathbf{1.34}$$

(d) The surface temperature of the pipe at the burnout point is determined from Rohsenow relation at the critical heat flux value to be

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

$$1,852,000 = (0.183 \times 10^{-3})(2114 \times 10^3) \left[\frac{9.8(916.6 - 2.55)}{0.0488} \right]^{1/2} \left(\frac{4311(T_{s,cr} - 150)}{0.0130(2114 \times 10^3)1.16} \right)^3$$

$$T_{s,cr} = \mathbf{166.5^\circ\text{C}}$$

10-26 Water is boiled at a temperature of $T_{\text{sat}} = 160^\circ\text{C}$ by hot gases flowing through a mechanically polished stainless steel pipe submerged in water whose outer surface temperature is maintained at $T_s = 165^\circ\text{C}$. The rate of heat transfer to the water, the rate of evaporation, the ratio of critical heat flux to current heat flux, and the pipe surface temperature at critical heat flux conditions are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat losses from the boiler are negligible. 3 The boiling regime is nucleate boiling since $\Delta T = T_s - T_{\text{sat}} = 165 - 160 = 5^\circ\text{C}$ which is in the nucleate boiling range of 5 to 30°C for water.

Properties The properties of water at the saturation temperature of 160°C are (Tables 10-1 and A-9)

$$\begin{aligned} \rho_l &= 907.4 \text{ kg/m}^3 & h_{fg} &= 2083 \times 10^3 \text{ J/kg} \\ \rho_v &= 3.26 \text{ kg/m}^3 & \mu_l &= 0.170 \times 10^{-3} \text{ kg}\cdot\text{m/s} \\ \sigma &= 0.0466 \text{ N/m} & C_{pl} &= 4340 \text{ J/kg}\cdot^\circ\text{C} \\ Pr_l &= 1.09 \end{aligned}$$

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) Assuming nucleate boiling, the heat flux can be determined from Rohsenow relation to be

$$\begin{aligned} \dot{q}_{\text{nucleate}} &= \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{C_{p,l}(T_s - T_{\text{sat}})}{C_{sf} h_{fg} Pr_l^n} \right)^3 \\ &= (0.170 \times 10^{-3})(2083 \times 10^3) \left[\frac{9.8(907.4 - 3.26)}{0.0466} \right]^{1/2} \left(\frac{4340(165 - 160)}{(0.0130)(2083 \times 10^3)(1.09)} \right)^3 \\ &= 61,359 \text{ W/m}^2 \end{aligned}$$

The heat transfer surface area is

$$A_s = \pi DL = \pi(0.05 \text{ m})(50 \text{ m}) = 7.854 \text{ m}^2$$

Then the rate of heat transfer during nucleate boiling becomes

$$\dot{Q}_{\text{boiling}} = A_s \dot{q}_{\text{nucleate}} = (7.854 \text{ m}^2)(61,359 \text{ W/m}^2) = \mathbf{481,900 \text{ W}}$$

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

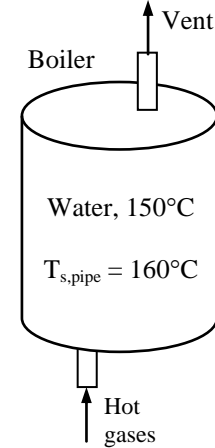
$$\dot{m}_{\text{evaporation}} = \frac{\dot{Q}_{\text{boiling}}}{h_{fg}} = \frac{481.9 \text{ kJ/s}}{2083 \text{ kJ/kg}} = \mathbf{0.231 \text{ kg/s}}$$

(c) For a horizontal cylindrical heating element, the coefficient C_{cr} is determined from Table 10-4 to be

$$\begin{aligned} L^* &= L \left(\frac{g(\rho_l - \rho_v)}{\sigma} \right)^{1/2} = (0.025) \left(\frac{9.8(907.4 - 3.26)}{0.0466} \right)^{1/2} = 10.9 > 0.12 \\ C_{cr} &= 0.12 \quad (\text{since } L^* > 1.2 \text{ and thus large cylinder}) \end{aligned}$$

Then the maximum or critical heat flux is determined from

$$\begin{aligned} \dot{q}_{\text{max}} &= C_{cr} h_{fg} [\sigma g \rho_v^2 (\rho_l - \rho_v)]^{1/4} \\ &= 0.12(2083 \times 10^3)[0.0466 \times 9.8 \times (3.26)^2(907.4 - 3.26)]^{1/4} \\ &= 2,034,000 \text{ W/m}^2 \end{aligned}$$



Therefore,
$$\frac{\dot{q}_{\max}}{\dot{q}_{\text{current}}} = \frac{2,034,000}{61,359} = \mathbf{33.2}$$

(d) The surface temperature of the pipe at the burnout point is determined from Rohsenow relation at the critical heat flux value to be

$$\dot{q}_{\text{nucleate,cr}} = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{C_{p,l}(T_{s,cr} - T_{\text{sat}})}{C_{s,f} h_{fg} \text{Pr}_l^n} \right)^3$$

$$2,034,000 = (0.170 \times 10^{-3})(2083 \times 10^3) \left[\frac{9.8(907.4 - 3.26)}{0.0466} \right]^{1/2} \left(\frac{4340(T_{s,cr} - 160)}{0.0130(2083 \times 10^3)1.09} \right)^3$$

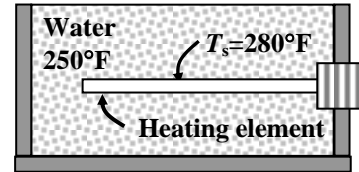
$$T_{s,cr} = \mathbf{176.1^\circ\text{C}}$$

10-27E Water is boiled at a temperature of $T_{\text{sat}} = 250^\circ\text{F}$ by a nickel-plated heating element whose surface temperature is maintained at $T_s = 280^\circ\text{F}$. The boiling heat transfer coefficient, the electric power consumed, and the rate of evaporation of water are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat losses from the boiler are negligible. 3 The boiling regime is nucleate boiling since $\Delta T = T_s - T_{\text{sat}} = 280 - 250 = 30^\circ\text{F}$ which is in the nucleate boiling range of 9 to 55°F for water.

Properties The properties of water at the saturation temperature of 250°F are (Tables 10-1 and A-9E)

$$\begin{aligned} \rho_l &= 58.82 \text{ lbm} / \text{ft}^3 & h_{fg} &= 946 \text{ Btu} / \text{lbm} \\ \rho_v &= 0.0723 \text{ lbm} / \text{ft}^3 & \mu_l &= 0.556 \text{ lbm} / \text{h} \cdot \text{ft} \\ \sigma &= 0.003755 \text{ lbf} / \text{ft} = 0.1208 \text{ lbm} / \text{s}^2 & C_{pl} &= 1.015 \text{ Btu} / \text{lbm} \cdot ^\circ\text{F} \\ Pr_l &= 1.43 \end{aligned}$$



Also, $g = 32.2 \text{ ft/s}^2$ and $C_{sf} = 0.0060$ 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 that will cancel each other in boiling heat transfer relations.

Analysis (a) Assuming nucleate boiling, the heat flux can be determined from Rohsenow relation to be

$$\begin{aligned} \dot{q}_{\text{nucleate}} &= \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{C_{p,l}(T_s - T_{\text{sat}})}{C_{sf} h_{fg} Pr_l^n} \right)^3 \\ &= (0.556)(946) \left[\frac{32.2(58.82 - 0.0723)}{0.1208} \right]^{1/2} \left(\frac{1.015(280 - 250)}{0.0060(946)1.43} \right)^3 \\ &= 3,475,221 \text{ Btu/h} \cdot \text{ft}^2 \end{aligned}$$

Then the convection heat transfer coefficient becomes

$$\dot{q} = h(T_s - T_{\text{sat}}) \rightarrow h = \frac{\dot{q}}{T_s - T_{\text{sat}}} = \frac{3,471,670 \text{ Btu} / \text{h} \cdot \text{ft}^2}{(280 - 250)^\circ\text{F}} = 115,840 \text{ Btu} / \text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$$

(b) The electric power consumed is equal to the rate of heat transfer to the water, and is determined from

$$\begin{aligned} \dot{W}_e = \dot{Q} &= \dot{q} A_s = (\pi DL)\dot{q} = (\pi \times 0.5 / 12 \text{ ft} \times 2 \text{ ft})(3,475,221 \text{ Btu/h} \cdot \text{ft}^2) = 909,811 \text{ Btu/h} \\ &= \mathbf{266.6 \text{ kW}} \quad (\text{since } 1 \text{ kW} = 3412 \text{ Btu/h}) \end{aligned}$$

(c) Finally, the rate of evaporation of water is determined from

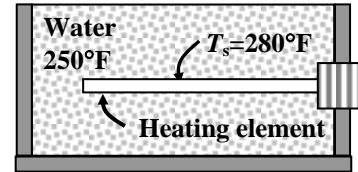
$$\dot{m}_{\text{evaporation}} = \frac{\dot{Q}_{\text{boiling}}}{h_{fg}} = \frac{909,811 \text{ Btu/h}}{946 \text{ Btu/lbm}} = \mathbf{961.71 \text{ lbm/h}}$$

10-28E Water is boiled at a temperature of $T_{\text{sat}} = 250^\circ\text{F}$ by a platinum-plated heating element whose surface temperature is maintained at $T_s = 280^\circ\text{F}$. The boiling heat transfer coefficient, the electric power consumed, and the rate of evaporation of water are to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat losses from the boiler are negligible. 3 The boiling regime is nucleate boiling since $\Delta T = T_s - T_{\text{sat}} = 280 - 250 = 30^\circ\text{F}$ which is in the nucleate boiling range of 9 to 55°F for water.

Properties The properties of water at the saturation temperature of 250°F are (Tables 10-1 and A-9E)

$$\begin{aligned} \rho_l &= 58.82 \text{ lbm/ft}^3 & h_{fg} &= 946 \text{ Btu/lbm} \\ \rho_v &= 0.0723 \text{ lbm/ft}^3 & \mu_l &= 0.556 \text{ lbm/h}\cdot\text{ft} \\ \sigma &= 0.003755 \text{ lbf/ft} = 0.1208 \text{ lbm/s}^2 & C_{pl} &= 1.015 \text{ Btu/lbm}\cdot^\circ\text{F} \\ Pr_l &= 1.43 \end{aligned}$$



Also, $g = 32.2 \text{ ft/s}^2$ and $C_{sf} = 0.0130$ and $n = 1.0$ for the boiling of water on a platinum plated surface (Table 10-3). Note that we expressed the properties in units that will cancel each other in boiling heat transfer relations.

Analysis (a) Assuming nucleate boiling, the heat flux can be determined from Rohsenow relation to be

$$\begin{aligned} \dot{q}_{\text{nucleate}} &= \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{C_{p,l}(T_s - T_{\text{sat}})}{C_{sf} h_{fg} Pr_l^n} \right)^3 \\ &= (0.556)(946) \left[\frac{32.2(58.82 - 0.0723)}{0.1208} \right]^{1/2} \left(\frac{1.015(280 - 250)}{0.0130(0.1208 \times 10^3)^{1.43}} \right)^3 \\ &= 341,670 \text{ Btu/h}\cdot\text{ft}^2 \end{aligned}$$

Then the convection heat transfer coefficient becomes

$$\dot{q} = h(T_s - T_{\text{sat}}) \rightarrow h = \frac{\dot{q}}{T_s - T_{\text{sat}}} = \frac{341,670 \text{ Btu/h}\cdot\text{ft}^2}{(280 - 250)^\circ\text{F}} = \mathbf{11,390 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}}$$

(b) The electric power consumed is equal to the rate of heat transfer to the water, and is determined from

$$\begin{aligned} \dot{W}_e = \dot{Q} &= \dot{q} A_s = (\pi DL)\dot{q} = (\pi \times 0.5 / 12 \text{ ft} \times 2 \text{ ft})(341,670 \text{ Btu/h}\cdot\text{ft}^2) = 89,450 \text{ Btu/h} \\ &= \mathbf{26.2 \text{ kW}} \quad (\text{since } 1 \text{ kW} = 3412 \text{ Btu/h}) \end{aligned}$$

(c) Finally, the rate of evaporation of water is determined from

$$\dot{m}_{\text{evaporation}} = \frac{\dot{Q}_{\text{boiling}}}{h_{fg}} = \frac{89,450 \text{ Btu/h}}{946 \text{ Btu/lbm}} = \mathbf{94.6 \text{ lbm/h}}$$

10-29E "PROBLEM 10-29E"

"GIVEN"

T_sat=250 "[F]"

L=2 "[ft]"

D=0.5/12 "[ft]"

"T_s=280 [F], parameter to be varied"

"PROPERTIES"

Fluid\$='steam_NBS'

P_sat=pressure(Fluid\$, T=T_sat, x=1)

rho_l=density(Fluid\$, T=T_sat, x=0)

rho_v=density(Fluid\$, T=T_sat, x=1)

sigma=SurfaceTension(Fluid\$, T=T_sat)*Convert(lbf/ft, lbm/s^2)

mu_l=Viscosity(Fluid\$, T=T_sat, x=0)

Pr_l=Prandtl(Fluid\$, T=T_sat, P=P_sat+1) "P=P_sat+1 is used to get liquid state"

C_l=CP(Fluid\$, T=T_sat, x=0)

h_f=enthalpy(Fluid\$, T=T_sat, x=0)

h_g=enthalpy(Fluid\$, T=T_sat, x=1)

h_fg=h_g-h_f

C_sf=0.0060 "from Table 8-3 of the text"

n=1 "from Table 8-3 of the text"

g=32.2 "[ft/s^2], gravitational acceleration"

"ANALYSIS"

"(a)"

$$q_{\text{dot_nucleate}} = \mu_l h_{fg} \left(\frac{g(\rho_l - \rho_v)}{\sigma} \right)^{0.5} \left(C_l (T_s - T_{\text{sat}}) \right) / (C_{sf} h_{fg} Pr_l^n)^{1/3}$$

$$q_{\text{dot_nucleate}} = h (T_s - T_{\text{sat}})$$

"(b)"

$$W_{\text{dot_e}} = q_{\text{dot_nucleate}} A \text{Convert}(\text{Btu/h}, \text{kW})$$

$$A = \pi D L$$

"(c)"

$$m_{\text{dot_evap}} = Q_{\text{dot_boiling}} / h_{fg}$$

$$Q_{\text{dot_boiling}} = W_{\text{dot_e}} \text{Convert}(\text{kW}, \text{Btu/h})$$

Chapter 10 Boiling and Condensation

T_s [F]	h [Btu/h.ft².F]	W_e [kW]	m_{evap} [lbm/h]
260	12908	9.903	35.74
262	18587	17.11	61.76
264	25299	27.18	98.07
266	33043	40.56	146.4
268	41821	57.76	208.4
270	51630	79.23	285.9
272	62473	105.5	380.5
274	74348	136.9	494.1
276	87255	174.1	628.1
278	101195	217.4	784.5
280	116168	267.4	964.9
282	132174	324.5	1171
284	149212	389.2	1405
286	167282	462.1	1667
288	186386	543.4	1961
290	206521	633.8	2287
292	227690	733.7	2648
294	249891	843.6	3044
296	273125	964	3479
298	297391	1095	3952
300	322690	1238	4467

10-30 Cold water enters a steam generator at 15°C and is boiled, and leaves as saturated vapor at $T_{\text{sat}} = 100^\circ\text{C}$. The fraction of heat used to preheat the liquid water from 15°C to saturation temperature of 100°C is to be determined.

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

Properties The heat of vaporization of water at 100°C is $h_{\text{fg}} = 2257 \text{ kJ/kg}$ and the specific heat of liquid water at the average temperature of $(15+100)/2 = 57.5^\circ\text{C}$ is $C_{pl} = 4.184 \text{ kJ/kg}\cdot^\circ\text{C}$ (Table A-9).

Analysis The heat of vaporization of water represents the amount of heat needed to vaporize a unit mass of liquid at a specified temperature. Using the average specific heat, the amount of heat needed to preheat a unit mass of water from 15°C to 100°C is determined to be

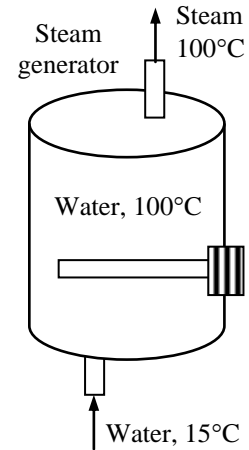
$$q_{\text{preheating}} = C_{pl}\Delta T = (4.184 \text{ kJ/kg}\cdot^\circ\text{C})(100-15)^\circ\text{C} = 355.6 \text{ kJ/kg}$$

and

$$q_{\text{total}} = q_{\text{boiling}} + q_{\text{preheating}} = 2257 + 355.6 = 2612.6 \text{ kJ/kg}$$

Therefore, the fraction of heat used to preheat the water is

$$\text{Fraction to preheat} = \frac{q_{\text{preheating}}}{q_{\text{total}}} = \frac{355.6}{2612.6} = \mathbf{0.136 \text{ (or 13.6\%)}}$$



10-31 Cold water enters a steam generator at 20°C and is boiled, and leaves as saturated vapor at boiler pressure. The boiler pressure at which the amount of heat needed to preheat the water to saturation temperature is equal to the heat of vaporization is to be determined.

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

Properties The properties needed to solve this problem are the heat of vaporization h_{fg} and the specific heat of water C_p at specified temperatures, and they can be obtained from Table A-9.

Analysis The heat of vaporization of water represents the amount of heat needed to vaporize a unit mass of liquid at a specified temperature, and $C_p \Delta T$ represents the amount of heat needed to preheat a unit mass of water from 20°C to the saturation temperature. Therefore,

$$q_{\text{preheating}} = q_{\text{boiling}}$$

$$C_{p,ave}(T_{\text{sat}} - 20) = h_{fg@T_{\text{sat}}}$$

The solution of this problem requires choosing a boiling temperature, reading the heat of vaporization at that temperature, evaluating the specific heat at the average temperature, and substituting the values into the relation above to see if it is satisfied. By trial and error, the temperature that satisfies this condition is determined to be 315°C at which (Table A-9)

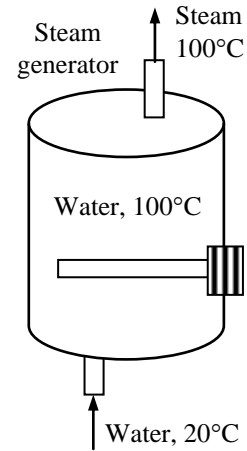
$$h_{fg@315^\circ\text{C}} = 1281 \text{ kJ/kg} \quad \text{and} \quad T_{\text{ave}} = (20+315)/2 = 167.5^\circ\text{C} \quad \rightarrow \quad C_{p,ave} = 4.37 \text{ kJ/kg}\cdot^\circ\text{C}$$

Substituting,

$$C_{p,ave}(T_{\text{sat}} - 20) = (4.37 \text{ kJ/kg}\cdot^\circ\text{C})(315 - 20)^\circ\text{C} = 1289 \text{ kJ/kg}$$

which is practically identical to the heat of vaporization. Therefore,

$$P_{\text{boiler}} = P_{\text{sat}@T_{\text{sat}}} = \mathbf{10.6 \text{ MPa}}$$



10-32 "PROBLEM 10-32"

"GIVEN"

 $T_{\text{cold}}=20$ [C], parameter to be varied"

"ANALYSIS"

Fluid\$='steam_NBS'

 $q_{\text{preheating}}=q_{\text{boiling}}$

$$q_{\text{preheating}}=C_p(T_{\text{sat}}-T_{\text{cold}})$$

$$T_{\text{sat}}=\text{temperature}(\text{Fluid}\$, P=P, x=1)$$

$$C_p=\text{CP}(\text{Fluid}\$, T=T_{\text{ave}}, x=0)$$

$$T_{\text{ave}}=1/2(T_{\text{cold}}+T_{\text{sat}})$$

$$q_{\text{boiling}}=h_{\text{fg}}$$

$$h_{\text{f}}=\text{enthalpy}(\text{Fluid}\$, T=T_{\text{sat}}, x=0)$$

$$h_{\text{g}}=\text{enthalpy}(\text{Fluid}\$, T=T_{\text{sat}}, x=1)$$

$$h_{\text{fg}}=h_{\text{g}}-h_{\text{f}}$$

T_{cold} [C]	P [kPa]
8	10031
9	10071
10	10112
11	10152
12	10193
13	10234
14	10274
15	10315
16	10356
17	10396
18	10437
19	10478
20	10519
21	10560
22	10601
23	10641
24	10682
25	10723
26	10764
27	10805
28	10846
29	10887
30	10928

10-33 Boiling experiments are conducted by heating water at 1 atm pressure with an electric resistance wire, and measuring the power consumed by the wire as well as temperatures. The boiling heat transfer coefficient is to be determined.

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

Analysis The heat transfer area of the heater wire is

$$A_s = \pi DL = \pi(0.002\text{ m})(0.50\text{ m}) = 0.003142\text{ m}^2$$

Noting that 3800 W of electric power is consumed when the heater surface temperature is 130°C, the boiling heat transfer coefficient is determined from Newton's law of cooling to be

$$\dot{Q} = hA_s(T_s - T_{\text{sat}}) \rightarrow h = \frac{\dot{Q}}{A_s(T_s - T_{\text{sat}})} = \frac{3800\text{ W}}{(0.003142\text{ m}^2)(130 - 100)^\circ\text{C}} = 40,320\text{ W/m}^2 \cdot ^\circ\text{C}$$

