# Chapter 10
# BOILING AND CONDENSATION

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### Boiling Heat Transfer

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**10-1C** Boiling is the liquid-to-vapor phase change process that occurs at a solid-liquid interface when the surface is heated above the saturation temperature of the liquid. The formation and rise of the bubbles and the liquid entrainment coupled with the large amount of heat absorbed during liquid-vapor phase change at essentially constant temperature are responsible for the very high heat transfer coefficients associated with nucleate boiling.

**10-2C** Yes. Otherwise we can create energy by alternately vaporizing and condensing a substance.

**10-3C** Both boiling and evaporation are liquid-to-vapor phase change processes, but evaporation occurs at the *liquid-vapor interface* when the vapor pressure is less than the saturation pressure of the liquid at a given temperature, and it involves no bubble formation or bubble motion. Boiling, on the other hand, occurs at the *solid-liquid interface* when a liquid is brought into contact with a surface maintained at a temperature $T_S$ sufficiently above the saturation temperature $T_{sat}$ of the liquid.

**10-4C** Boiling is called *pool boiling* in the absence of bulk fluid flow, and *flow boiling* (or *forced convection boiling*) in the presence of it. In pool boiling, the fluid is stationary, and any motion of the fluid is due to natural convection currents and the motion of the bubbles due to the influence of buoyancy.

**10-5C** Boiling is said to be *subcooled* (or *local*) when the bulk of the liquid is subcooled (i.e., the temperature of the main body of the liquid is below the saturation temperature $T_{sat}$), and *saturated* (or *bulk*) when the bulk of the liquid is saturated (i.e., the temperature of all the liquid is equal to $T_{sat}$).

**10-6C** The boiling curve is given in Figure 10-6 in the text. In the *natural convection boiling* regime, the fluid motion is governed by natural convection currents, and heat transfer from the heating surface to the fluid is by natural convection. In the *nucleate boiling* regime, bubbles form at various preferential sites on the heating surface, and rise to the top. In the *transition boiling* regime, part of the surface is covered by a vapor film. In the *film boiling* regime, the heater surface is completely covered by a continuous stable vapor film, and heat transfer is by combined convection and radiation.

**10-7C** In the *film boiling* regime, the heater surface is completely covered by a continuous stable vapor film, and heat transfer is by combined convection and radiation. In the nucleate boiling regime, the heater surface is covered by the liquid. The boiling heat flux in the stable film boiling regime can be higher or lower than that in the nucleate boiling regime, as can be seen from the boiling curve.

**10-8C** The boiling curve is given in Figure 10-6 in the text. The burnout point in the curve is point C. The *burnout* during boiling is caused by the heater surface being blanketed by a continuous layer of vapor film at increased heat fluxes, and the resulting rise in heater surface temperature in order to maintain the same heat transfer rate across a low-conducting vapor film. Any attempt to increase the heat flux beyond $\dot{q}_{\max}$ will cause the operation point on the boiling curve to jump suddenly from point C to point E. However, the surface temperature that corresponds to point E is beyond the melting point of most heater materials, and burnout occurs. The burnout point is avoided in the design of boilers in order to avoid the disastrous explosions of the boilers.

**10-9C** Pool boiling heat transfer can be increased *permanently* by increasing the number of nucleation sites on the heater surface by *coating* the surface with a thin layer (much less than 1 mm) of very porous material, or by *forming cavities* on the surface mechanically to facilitate continuous vapor formation. Such surfaces are reported to enhance heat transfer in the nucleate boiling regime by a factor of up to 10, 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 critical heat flux.

**10-10C** The different boiling regimes that occur in a vertical tube during flow boiling are forced convection of liquid, bubbly flow, slug flow, annular flow, transition flow, mist flow, and forced convection of vapor.

**10-11** Water is boiled at 1 atm pressure and thus at a saturation (or boiling) temperature of $T_{sat}$ = 100°C in a mechanically polished stainless steel pan whose inner surface temperature is maintained at $T_s$ = 110°C. 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 boiler are negligible.

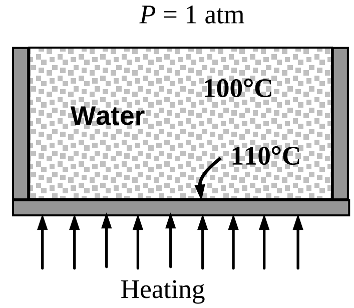
***Properties*** The properties of water at the saturation temperature of 100°C are (Tables 10-1 and A-9)

$\rho_l = 957.9 \text{ kg/m}^3$ $\quad h_{fg} = 2257 \times 10^3 \text{ J/kg}$

$\rho_v = 0.60 \text{ kg/m}^3$ $\quad \mu_l = 0.282 \times 10^{-3} \text{ kg}\cdot\text{m/s}$

$\sigma = 0.0589 \text{ N/m}$ $\quad C_{pl} = 4217 \text{ J/kg}\cdot°\text{C}$

$\Pr_l = 1.75$




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*** The excess temperature in this case is $\Delta T = T_s - T_{sat} = 110 - 100 = 10°\text{C}$ which is relatively low (less than 30°C). Therefore, nucleate boiling will occur. The heat flux in this case can be determined from Rohsenow relation to be

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

$$= (0.282\times10^{-3})(2257\times10^3)\left[\frac{9.8(957.9-0.60)}{0.0589}\right]^{1/2}\left(\frac{4217(110-100)}{0.0130(2257\times10^3)1.75}\right)^3$$

$$= 140{,}700 \text{ W/m}^2$$

The surface area of the bottom of the pan is

$$A_s = \pi D^2/4 = \pi(0.25\text{ m})^2/4 = 0.04909\text{ m}^2$$

Then the rate of heat transfer during nucleate boiling becomes

$$\dot{Q}_{boiling} = A_s \dot{q}_{nucleate} = (0.04909\text{ m}^2)(140{,}700\text{ W/m}^2) = \mathbf{6907\ W}$$

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

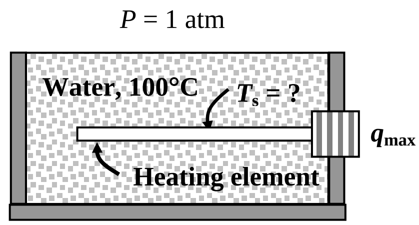
$$\dot{m}_{evaporation} = \frac{\dot{Q}_{boiling}}{h_{fg}} = \frac{6907\text{ J/s}}{2257\times10^3\text{ J/kg}} = \mathbf{3.06\times10^{-3}\ kg/s}$$

That is, water in the pan will boil at a rate of 3 grams per second.

**10-12** Water is boiled at 1 atm pressure and thus at a saturation (or boiling) temperature of $T_{sat}$ = 100°C by a mechanically polished stainless steel heating element. The maximum heat flux in the nucleate boiling regime and the surface temperature of the heater for that case 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)




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

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 Eqs. 10-2 and 10-3 in connection with their definitions in order to avoid unit manipulations. For a large horizontal heating element, $C_{cr}$ = 0.12 (Table 10-4). (It can be shown that $L^*$ = 5.99 > 1.2 and thus the restriction in Table 10-4 is satisfied).

***Analysis*** The maximum or critical heat flux is determined from

$$\begin{aligned}\dot{q}_{\max} &= C_{cr} h_{fg}[\sigma g \rho_v^2(\rho_l - \rho_v)]^{1/4}\\ &= 0.12(2257\times 10^3)[0.0589\times 9.8\times (0.6)^2(957.9-0.60)]^{1/4}\\ &= \mathbf{1{,}017{,}000\ W/m^2}\end{aligned}$$

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

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

$$1{,}017{,}000 = (0.282\times 10^{-3})(2257\times 10^3)\left[\frac{9.8(957.9-0.60)}{0.0589}\right]^{1/2}\left(\frac{4217(T_s-100)}{0.0130(2257\times 10^3)1.75}\right)^3$$

It gives

$$T_s = \mathbf{119.3°C}$$

Therefore, the temperature of the heater surface will be only 19.3°C above the boiling temperature of water when burnout occurs.

**10-13** "!PROBLEM 10-13"

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"GIVEN"
D=0.003 "[m]"
"P_sat=101.3 [kPa], parameter to be varied"

"PROPERTIES"
Fluid$='steam_NBS'
T_sat=temperature(Fluid$, P=P_sat, x=1)
rho_l=density(Fluid$, T=T_sat, x=0)
rho_v=density(Fluid$, T=T_sat, x=1)
sigma=SurfaceTension(Fluid$, T=T_sat)
mu_l=Viscosity(Fluid$,T=T_sat, x=0)
Pr_l=Prandtl(Fluid$, T=T_sat, P=P_sat)
C_l=CP(Fluid$, 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=0.0130 "from Table 8-3 of the text"
n=1 "from Table 8-3 of the text"
C_cr=0.12 "from Table 8-4 of the text"
g=9.8 "[m/s^2], gravitational acceleraton"

"ANALYSIS"
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-
T_sat))/(C_sf*h_fg*Pr_l^n))^3
DELTAT=T_s-T_sat
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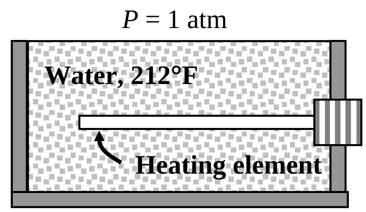
| $P_{sat}$ [kPa] | $q_{max}$ [kW/m$^2$] | $\Delta T$ [C] |
|---|---|---|
| 70 | 871.9 | 20.12 |
| 71.65 | 880.3 | 20.07 |
| 73.29 | 888.6 | 20.02 |
| 74.94 | 896.8 | 19.97 |
| 76.59 | 904.9 | 19.92 |
| 78.24 | 912.8 | 19.88 |
| 79.88 | 920.7 | 19.83 |
| 81.53 | 928.4 | 19.79 |
| 83.18 | 936.1 | 19.74 |
| 84.83 | 943.6 | 19.7 |
| 86.47 | 951.1 | 19.66 |
| 88.12 | 958.5 | 19.62 |
| 89.77 | 965.8 | 19.58 |
| 91.42 | 973 | 19.54 |
| 93.06 | 980.1 | 19.5 |
| 94.71 | 987.2 | 19.47 |
| 96.36 | 994.1 | 19.43 |
| 98.01 | 1001 | 19.4 |
| 99.65 | 1008 | 19.36 |
| 101.3 | 1015 | 19.33 |

**10-14E** Water is boiled at 1 atm pressure and thus at a saturation (or boiling) temperature of $T_{sat}$ = 212°F by a horizontal polished copper heating element whose surface temperature is maintained at $T_s$ = 788°F. 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 212°F are $\rho_l = 59.82 \text{ lbm/ft}^3$ and $h_{fg} = 970 \text{ Btu/lbm}$ (Table A-9E). The properties of the vapor at the film temperature of $T_f = (T_{sat} + T_s)/2 = (212+788)/2 = 500°\text{ F}$ are (Table A-16E)

$$\begin{aligned}\rho_v &= 0.02571 \text{ lbm/ft}^3\\ \mu_v &= 0.04564 \text{ Btu/lbm}\cdot\text{h}\\ C_{pv} &= 0.4707 \text{ Btu/lbm}\cdot°\text{F}\\ k_v &= 0.02267 \text{ Btu/h}\cdot\text{ft}\cdot°\text{F}\end{aligned}$$




Also, $g$ = 32.2 ft/s$^2$ = 32.2×(3600)$^2$ ft/h$^2$. 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-16E instead of the properties of saturated vapor from Table A-9E since the latter are at the saturation pressure of 680 psia (46 atm).

***Analysis*** The excess temperature in this case is $\Delta T = T_s - T_{sat} = 788 - 212 = 576°\text{ F}$, which is much larger than 30°C or 54°F. Therefore, film boiling will occur. The film boiling heat flux in this case can be determined to be

$$\begin{aligned}\dot{q}_{\text{film}} &= 0.62\left[\frac{g k_v^3 \rho_v (\rho_l - \rho_v)[h_{fg} + 0.4 C_{pv}(T_s - T_{sat})]}{\mu_v D (T_s - T_{sat})}\right]^{1/4} (T_s - T_{sat})\\ &= 0.62\left[\frac{32.2(3600)^2 (0.02267)^3 (0.02571)(59.82 - 0.02571)[970 + 0.4\times 0.4707(788-212)]}{(0.04564)(0.5/12)(788-212)}\right]^{1/4} \times (788-212)\\ &= 18{,}600 \text{ Btu/h}\cdot\text{ft}^2\end{aligned}$$

The radiation heat flux is determined from

$$\begin{aligned}\dot{q}_{\text{rad}} &= \varepsilon\sigma(T_s^4 - T_{sat}^4)\\ &= (0.08)(0.1714\times 10^{-8} \text{ Btu/h}\cdot\text{ft}^2\cdot\text{R}^4)\ (788+460 \text{ R})^4 - (212+460 \text{ R})^4\\ &= 305 \text{ Btu/h}\cdot\text{ft}^2\end{aligned}$$

Note that heat transfer by radiation is very small 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

$$\dot{q}_{\text{total}} = \dot{q}_{\text{film}} + \frac{3}{4}\dot{q}_{\text{rad}} = 18{,}600 + \frac{3}{4}\times 305 = 18{,}829 \text{ Btu/h}\cdot\text{ft}^2$$

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,

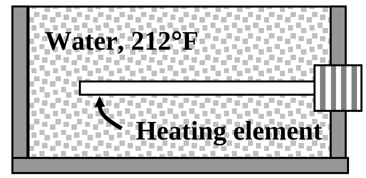
$$\begin{aligned}\dot{Q}_{\text{total}} &= A_s \dot{q}_{\text{total}} = (\pi D L)\dot{q}_{\text{total}}\\ &= (\pi\times 0.5/12 \text{ ft}\times 1 \text{ ft})(18{,}829 \text{ Btu/h}\cdot\text{ft}^2)\\ &= \mathbf{2465\ Btu/h}\end{aligned}$$

**10-15E** Water is boiled at 1 atm pressure and thus at a saturation (or boiling) temperature of $T_{sat}$ = 212°F by a horizontal polished copper heating element whose surface temperature is maintained at $T_s$ = 988°F. 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 212°F are $\rho_l = 59.82 \text{ lbm/ft}^3$ and $h_{fg} = 970 \text{ Btu/lbm}$ (Table A-9E). The properties of the vapor at the film temperature of $T_f = (T_{sat} + T_s)/2 = (212 + 988)/2 = 600°\text{ F}$ are, by interpolation, (Table A-16E)

$$\rho_v = 0.02395 \text{ lbm/ft}^3$$
$$\mu_v = 0.05101 \text{ Btu/lbm} \cdot \text{h}$$
$$C_{pv} = 0.4799 \text{ Btu/lbm} \cdot °\text{F}$$
$$k_v = 0.02640 \text{ Btu/h} \cdot \text{ft} \cdot °\text{F}$$




Also, $g$ = 32.2 ft/s$^2$ = 32.2×(3600)$^2$ ft/h$^2$. 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-16E instead of the properties of saturated vapor from Table A-9E since the latter are at the saturation pressure of 1541 psia (105 atm).

***Analysis*** The excess temperature in this case is $\Delta T = T_s - T_{sat} = 988 - 212 = 776°\text{ F}$, which is much larger than 30°C or 54°F. Therefore, film boiling will occur. The film boiling heat flux in this case can be determined from

$$\dot{q}_{\text{film}} = 0.62\left[\frac{g k_v^3 \rho_v (\rho_l - \rho_v)[h_{fg} + 0.4 C_{pv}(T_s - T_{sat})]}{\mu_v D (T_s - T_{\text{sat}})}\right]^{1/4} (T_s - T_{\text{sat}})$$
$$= 0.62\left[\frac{32.2(3600)^2 (0.02640)^3 (0.02395)(59.82 - 0.02395)[970 + 0.4 \times 0.4799(988 - 212)]}{(0.05101)(0.5/12)(988 - 212)}\right]^{1/4} \times (988 - 212)$$
$$= 25{,}144 \text{ Btu/h} \cdot \text{ft}^2$$

The radiation heat flux is determined from

$$\dot{q}_{\text{rad}} = \varepsilon\sigma(T_s^4 - T_{\text{sat}}^4)$$
$$= (0.08)(0.1714 \times 10^{-8} \text{ Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4)\ (988 + 460 \text{ R})^4 - (212 + 460 \text{ R})^4$$
$$= 575 \text{ Btu/h} \cdot \text{ft}^2$$

Note that heat transfer by radiation is very small 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

$$\dot{q}_{\text{total}} = \dot{q}_{\text{film}} + \frac{3}{4}\dot{q}_{\text{rad}} = 25{,}144 + \frac{3}{4} \times 575 = 25{,}576 \text{ Btu/h} \cdot \text{ft}^2$$

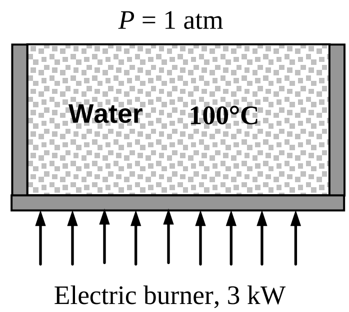
Finally, the rate of heat transfer from the heating element to the water is determined by multiplying the heat flux by the heat transfer surface area,

$$\dot{Q}_{\text{total}} = A_s \dot{q}_{\text{total}} = (\pi D L)\dot{q}_{\text{total}}$$
$$= (\pi \times 0.5/12 \text{ ft} \times 1 \text{ ft})(25{,}576 \text{ Btu/h} \cdot \text{ft}^2)$$
$$= \mathbf{3348\ Btu/h}$$

**10-16** Water is boiled at sea level (1 atm pressure) and thus at a saturation (or boiling) temperature of $T_{sat}$ = 100°C in a mechanically polished AISI 304 stainless steel pan placed on top of a 3-kW electric burner. Only 60% of the heat (1.8 kW) generated is transferred to the water. The inner surface temperature of the pan and the temperature difference across the bottom of the pan 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 (this assumption will be checked later). **4** Heat transfer through the bottom of the pan is one-dimensional.

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




$$\rho_l = 957.9 \text{ kg/m}^3 \qquad h_{fg} = 2257\times10^3 \text{ J/kg}$$
$$\rho_v = 0.60 \text{ kg/m}^3 \qquad \mu_l = 0.282\times10^{-3} \text{ kg}\cdot\text{m/s}$$
$$\sigma = 0.0589 \text{ N/m} \qquad C_{pl} = 4217 \text{ J/kg}\cdot°\text{C}$$
$$\text{Pr}_l = 1.75$$

Also, $k_{steel}$ = 14.9 W/m·°C (Table A-3), $C_{sf} = 0.0130$ 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 connection with their definitions in order to avoid unit manipulations.

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

$$\dot{Q} = 0.60\times3\text{ kW} = 1.8\text{ kW} = 1800\text{ W}$$
$$A_s = \pi D^2/4 = \pi(0.30\text{ m})^2/4 = 0.07069\text{ m}^2$$
$$\dot{q} = \dot{Q}/A_s = (1800\text{ W})/(0.07069\text{ m}^2) = 25.46\text{ W/m}^2$$

Then temperature difference across the bottom of the pan is determined directly from the steady one-dimensional heat conduction relation to be

$$\dot{q} = k_{steel}\frac{\Delta T}{L} \to \Delta T = \frac{\dot{q}L}{k_{steel}} = \frac{(25{,}460\text{ W/m}^2)(0.006\text{m})}{14.9\text{ W/m}\cdot°\text{C}} = \mathbf{10.3°C}$$

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

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

$$25{,}460 = (0.282\times10^{-3})(2257\times10^3)\left[\frac{9.8(957.9-0.60)}{0.0589}\right]^{1/2}\left(\frac{4217(T_s-100)}{0.0130(2257\times10^3)1.75}\right)^3$$

It gives

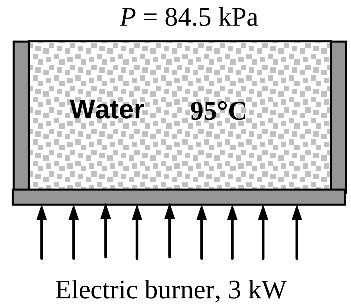
$$T_s = \mathbf{105.7°C}$$

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

**10-17** Water is boiled at 84.5 kPa pressure and thus at a saturation (or boiling) temperature of $T_{sat}$ = 95°C in a mechanically polished AISI 304 stainless steel pan placed on top of a 3-kW electric burner. Only 60% of the heat (1.8 kW) generated is transferred to the water. The inner surface temperature of the pan and the temperature difference across the bottom of the pan 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 (this assumption will be checked later). **4** Heat transfer through the bottom of the pan is one-dimensional.

***Properties*** The properties of water at the saturation temperature of 95°C are (Tables 10-1 and A-9)




$$\rho_l = 961.5 \text{ kg/m}^3 \qquad h_{fg} = 2270\times10^3 \text{ J/kg}$$
$$\rho_v = 0.50 \text{ kg/m}^3 \qquad \mu_l = 0.297\times10^{-3} \text{ kg}\cdot\text{m/s}$$
$$\sigma = 0.0599 \text{ N/m} \qquad C_{pl} = 4212 \text{ J/kg}\cdot°\text{C}$$
$$\text{Pr}_l = 1.85$$

Also, $k_{steel}$ = 14.9 W/m·°C (Table A-3), $C_{sf} = 0.0130$ 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*** The rate of heat transfer to the water and the heat flux are

$$\dot{Q} = 0.60\times3\text{ kW} = 1.8\text{ kW} = 1800\text{ W}$$
$$A_s = \pi D^2/4 = \pi(0.30\text{ m})^2/4 = 0.07069\text{ m}^2$$
$$\dot{q} = \dot{Q}/A_s = (1800\text{ W})/(0.07069\text{ m}^2) = 25{,}460\text{ W/m}^2 = 25.46\text{ kW/m}^2$$

Then temperature difference across the bottom of the pan is determined directly from the steady one-dimensional heat conduction relation to be

$$\dot{q} = k_{steel}\frac{\Delta T}{L} \rightarrow \Delta T = \frac{\dot{q}L}{k_{steel}} = \frac{(25{,}460\text{ W/m}^2)(0.006\text{m})}{14.9\text{ W/m}\cdot°\text{C}} = \mathbf{10.3°C}$$

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

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

$$25{,}460 = (0.297\times10^{-3})(2270\times10^3)\left[\frac{9.8(961.5-0.50)}{0.0599}\right]^{1/2}\left(\frac{4212(T_s-95)}{0.0130(2270\times10^3)1.85}\right)^3$$

It gives

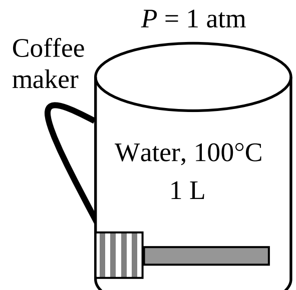
$$T_s = \mathbf{100.9°C}$$

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

**10-18** Water is boiled at sea level (1 atm pressure) and thus at a saturation (or boiling) temperature of $T_{sat}$ = 100°C by a stainless steel heating element. The surface temperature of the heating element and its power rating are to be determined.

***Assumptions*** **1** Steady operating conditions exist. **2** Heat losses from the coffee maker 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)




$$\rho_l = 957.9 \text{ kg/m}^3 \qquad h_{fg} = 2257\times10^3 \text{ J/kg}$$
$$\rho_v = 0.60 \text{ kg/m}^3 \qquad \mu_l = 0.282\times10^{-3} \text{ kg}\cdot\text{m/s}$$
$$\sigma = 0.0589 \text{ N/m} \qquad C_{pl} = 4217 \text{ J/kg}\cdot°\text{C}$$
$$\text{Pr}_l = 1.75$$

Also, $C_{sf}$ = 0.0130 and $n$ = 1.0 for the boiling of water on a 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 density of water at room temperature is very nearly 1 kg/L, and thus the mass of 1 L water at 18°C is nearly 1 kg. The rate of energy transfer needed to evaporate half of this water in 25 min and the heat flux are

$$Q = \dot{Q}\Delta t = m h_{fg} \;\rightarrow\; \dot{Q} = \frac{m h_{fg}}{\Delta t} = \frac{(0.5\text{ kg})(2257\text{kJ/kg})}{(25\times60\text{ s})} = 0.7523\text{kW}$$
$$A_s = \pi DL = \pi(0.04\text{ m})(0.2\text{m}) = 0.02513\text{m}^2$$
$$\dot{q} = \dot{Q}/A_s = (0.7523\text{kW})/(0.02513\text{m}^2) = 29.94\text{kW/m}^2 = 29{,}940\text{W/m}^2$$

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

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

$$29{,}940 = (0.282\times10^{-3})(2257\times10^3)\left[\frac{9.8(957.9-0.60)}{0.0589}\right]^{1/2}\left(\frac{4217(T_s-100)}{0.0130(2257\times10^3)1.75}\right)^3$$

It gives

$$T_s = \mathbf{106.0°C}$$

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

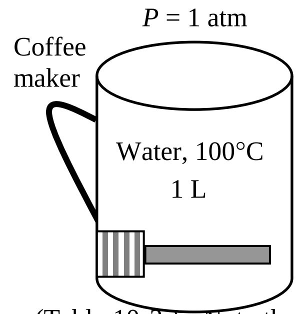
The specific heat of water at the average temperature of (18+100)/2 = 59°C is $C_p$ = 4.184 kJ/kg·°C. Then the time it takes for the entire water to be heated from 18°C to 100°C is determined to be

$$Q = \dot{Q}\Delta t = mC_p\Delta T \;\rightarrow\; \Delta t = \frac{mC_p\Delta T}{\dot{Q}} = \frac{(1\text{ kg})(4.184\text{ kJ/kg}\cdot°\text{C})(100-18)°\text{C}}{0.7523\text{ kJ/s}} = 456\text{ s} = \mathbf{7.60\text{ min}}$$

**10-19** Water is boiled at sea level (1 atm pressure) and thus at a saturation (or boiling) temperature of $T_{sat}$ = 100°C by a copper heating element. The surface temperature of the heating element and its power rating are to be determined.

***Assumptions*** **1** Steady operating conditions exist. **2** Heat losses from the coffee maker 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)




$$\rho_l = 957.9 \text{ kg/m}^3 \qquad h_{fg} = 2257\times10^3 \text{ J/kg}$$
$$\rho_v = 0.60 \text{ kg/m}^3 \qquad \mu_l = 0.282\times10^{-3} \text{ kg}\cdot\text{m/s}$$
$$\sigma = 0.0589 \text{ N/m} \qquad C_{pl} = 4217 \text{ J/kg}\cdot°\text{C}$$
$$\text{Pr}_l = 1.75$$

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 density of water at room temperature is very nearly 1 kg/L, and thus the mass of 1 L water at 18°C is nearly 1 kg. The rate of energy transfer needed to evaporate half of this water in 25 min and the heat flux are

$$Q = \dot{Q}\Delta t = mh_{fg} \;\to\; \dot{Q} = \frac{mh_{fg}}{\Delta t} = \frac{(0.5\text{ kg})(2257\text{kJ/kg})}{(25\times60\text{ s})} = 0.7523\text{kW}$$
$$A_s = \pi DL = \pi(0.04\text{ m})(0.2\text{m}) = 0.02513\text{m}^2$$
$$\dot{q} = \dot{Q}/A_s = (0.7523\text{kW})/(0.02513\text{m}^2) = 29.94\text{kW/m}^2 = 29{,}940\text{W/m}^2$$

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

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

$$29{,}940 = (0.282\times10^{-3})(2257\times10^3)\left[\frac{9.8(957.9-0.60)}{0.0589}\right]^{1/2}\left(\frac{4217(T_s-100)}{0.0130(2257\times10^3)1.75}\right)^3$$

It gives

$$T_s = \mathbf{106.0°C}$$

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

The specific heat of water at the average temperature of (18+100)/2 = 59°C is $C_p$ = 4.184 kJ/kg·°C. Then the time it takes for the entire water to be heated from 18°C to 100°C is determined to be

$$Q = \dot{Q}\Delta t = mC_p\Delta T \;\to\; \Delta t = \frac{mC_p\Delta T}{\dot{Q}} = \frac{(1\text{ kg})(4.184\text{ kJ/kg}\cdot°\text{C})(100-18)°\text{C}}{0.7523\text{ kJ/s}} = 456\text{ s} = \mathbf{7.60\ min}$$

**10-20** Water is boiled at a saturation (or boiling) temperature of $T_{sat}$ = 120°C by a brass heating element whose temperature is not to exceed $T_s$ = 125°C. The highest rate of steam production is 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 $\Delta T = T_s - T_{sat} = 125 - 120 = 5°C$ which is in the nucleate boiling range of 5 to 30°C for water.

***Properties*** The properties of water at the saturation temperature of 120°C are (Tables 10-1 and A-9)

$\rho_l = 943.4 \text{ kg/m}^3$

$\rho_v = 1.12 \text{ kg/m}^3$

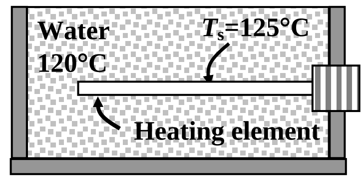
$\sigma = 0.0550 \text{ N/m}$

$\Pr_l = 1.44$

$h_{fg} = 2203 \times 10^3 \text{ J/kg}$

$\mu_l = 0.232 \times 10^{-3} \text{ kg} \cdot \text{m/s}$

$C_{pl} = 4244 \text{ J/kg} \cdot °\text{C}$




Also, $C_{sf} = 0.0060$ and $n$ = 1.0 for the boiling of water on a brass 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*** Assuming nucleate boiling, the heat flux in this case can be determined from Rohsenow relation to be

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

$$= (0.232\times10^{-3})(2203\times10^3)\left[\frac{9.8(943.4-1.12)}{0.0550}\right]^{1/2}\left(\frac{4244(125-120)}{0.0060(2203\times10^3)1.44}\right)^3$$

$$= 290{,}190 \text{ W/m}^2$$

The surface area of the heater is

$$A_s = \pi DL = \pi(0.02\text{ m})(0.65\text{m}) = 0.04084\text{m}^2$$

Then the rate of heat transfer during nucleate boiling becomes

$$\dot{Q}_{boiling} = A_s \dot{q}_{nucleate} = (0.04084\text{m}^2)(290{,}190\text{ W/m}^2) = 11{,}852\text{ W}$$

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

$$\dot{m}_{evaporation} = \frac{\dot{Q}_{boiling}}{h_{fg}} = \frac{11{,}852\text{ J/s}}{2203\times10^3\text{ J/kg}}\left(\frac{3600\text{s}}{1\text{ h}}\right) = \mathbf{19.4\ kg/h}$$

Therefore, steam can be produced at a rate of about 20 kg/h by this heater.