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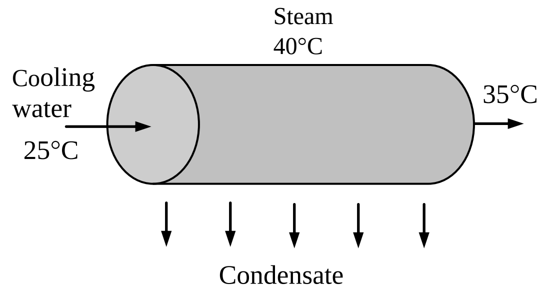
سایت آموزش مهندسی مکانیک

Review Problems

10-72 Steam at a saturation temperature of T_{sat} = 40°C condenses on the outside of a thin horizontal tube. Heat is transferred to the cooling water that enters the tube at 25°C and exits at 35°C. The rate of condensation of steam, the average overall heat transfer coefficient, and the tube length are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The tube can be taken to be isothermal at the bulk mean fluid temperature in the evaluation of the condensation heat transfer coefficient. **3** Liquid flow through the tube is fully developed. **4** The thickness and the thermal resistance of the tube is negligible.

Properties The properties of water at the saturation temperature of 40°C are $h_{fg} = 2407\times10^3$ J/kg and ρ_v = 0.05 kg/m^3. The properties of liquid water at the film temperature of $T_f = (T_{sat} + T_s)/2 = (50 + 20)/2$ = 35°C and at the bulk fluid temperature of $T_b = (T_{in} + T_{out})/2 = (25 + 35)/2$ = 30°C are (Table A-9),



At 35°C:

$$\rho_l = 994.0 \text{ kg/m}^3$$
$$\mu_l = 0.720\times10^{-3} \text{ kg/m}\cdot\text{s}$$
$$C_{pl} = 4178 \text{ J/kg}\cdot°\text{C}$$
$$k_l = 0.623 \text{ W/m}\cdot°\text{C}$$

At 30°C:

$$\rho_l = 996.0 \text{ kg/m}^3$$
$$\nu_l = \mu_l/\rho_l = 0.801\times10^{-6} \text{ m}^2\text{/s}$$
$$C_{pl} = 4178 \text{ J/kg}\cdot°\text{C}$$
$$k_l = 0.615 \text{ W/m}\cdot°\text{C}$$
$$\text{Pr} = 5.42$$

Analysis The mass flow rate of water and the rate of heat transfer to the water are

$$\dot{m}_{water} = \rho \mathcal{V} A_c = (996 \text{ kg/m}^3)(2 \text{ m/s})[\pi(0.03 \text{ m})^2/4] = 1.408 \text{ kg/s}$$

$$\dot{Q} = \dot{m}C_p(T_{out} - T_{in}) = (1.408 \text{ kg/s})(4178 \text{ J/kg}\cdot°\text{C})(35-25)°\text{C} = \mathbf{58{,}820\ W}$$

The modified latent heat of vaporization is

$$h^*_{fg} = h_{fg} + 0.68C_{pl}(T_{sat} - T_s)$$
$$= 2407\times10^3 \text{ J/kg} + 0.68\times4178 \text{ J/kg}\cdot°\text{C}(40-30)°\text{C} = 2435\times10^3 \text{ J/kg}$$

The heat transfer coefficient for condensation on a single horizontal tube is

$$h_o = h_{horizontal} = 0.729\left[\frac{g\rho_l(\rho_l-\rho_v)h^*_{fg}k_l^3}{\mu_l(T_{sat}-T_s)D}\right]^{1/4}$$

$$= 0.729\left[\frac{(9.8 \text{ m/s}^2)(994 \text{ kg/m}^3)(994-0.05 \text{ kg/m}^3)(2435\times10^3 \text{ J/kg})(0.623 \text{ W/m}\cdot°\text{C})^3}{(0.720\times10^{-3} \text{ kg/m}\cdot\text{s})(40-30)°\text{C}(0.03 \text{ m})}\right]^{1/4}$$

$$= 9292 \text{ W/m}^2\cdot°\text{C}$$

The average heat transfer coefficient for flow inside the tube is determined as follows:

$$\text{Re} = \frac{V_m D}{\nu} = \frac{(2 \text{ m/s})(0.03 \text{ m})}{0.801\times10^{-6}} = 74{,}906$$

$$\text{Nu} = 0.023\text{Re}^{0.8}\text{Pr}^{0.4} = 0.023(74{,}906)^{0.8}(5.42)^{0.4} = 359$$

$$h_i = \frac{k\text{Nu}}{D} = \frac{(0.615 \text{ W/m}\cdot°\text{C})\times359}{0.03 \text{ m}} = 7357 \text{ W/m}^2\cdot°\text{C}$$

Noting that the thermal resistance of the tube is negligible, the overall heat transfer coefficient becomes

$$U = \frac{1}{1/h_i + 1/h_o} = \frac{1}{1/7357 + 1/9292} = \mathbf{4106\ W/m^2\cdot°C}$$

The logarithmic mean temperature difference is: $\Delta T_{ln} = \dfrac{\Delta T_i - \Delta T_e}{\ln(\Delta T_i/\Delta T_o)} = \dfrac{15-5}{\ln(15/5)} = 9.10°\text{C}$

The tube length is determined from

$$\dot{Q} = hA_s \Delta T_{\ln} \;\rightarrow\; L = \frac{\dot{Q}}{h(\pi D)\Delta T_{\ln}} = \frac{58{,}820\,\text{W}}{(4106\,\text{W/m}^2\cdot{}^\circ\text{C})\pi(0.03\,\text{m})(9.10^\circ\text{C})} = \mathbf{16.7\,m}$$

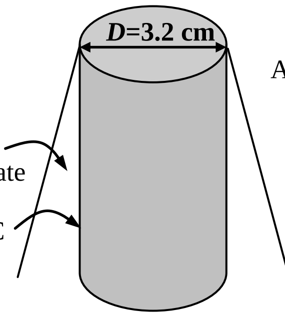
Note that the flow is turbulent, and thus the entry length in this case is *10D* = 0.3 m is much shorter than the total tube length. This verifies our assumption of fully developed flow.

10-73 Saturated ammonia at a saturation temperature of T_{sat} = 25°C condenses on the outer surface of vertical tube which is maintained at 15°C by circulating cooling water. The rate of heat transfer to the coolant and the rate of condensation of ammonia are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The tube is isothermal. **3** The tube can be treated as a vertical plate. **4** The condensate flow is turbulentr over the entire tube (this assumption will be verified). **5** The density of vapor is much smaller than the density of liquid, $\rho_v << \rho_l$.

Properties The properties of ammonia at the saturation temperature of 25°C are h_{fg} = 1166×10^3 J/kg and ρ_v = 7.809 kg/m^3. The properties of liquid ammonia at the film temperature of $T_f = (T_{sat} + T_s)/2 = (25 + 15)/2$ = 20°C are (Table A-11),

$$\rho_l = 610.2 \text{ kg/m}^3$$
$$\mu_l = 1.519\times10^{-4} \text{ kg/m}\cdot\text{s}$$
$$\nu_l = \mu_l/\rho_l = 0.2489\times10^{-6} \text{ m}^2\text{/s}$$
$$C_{pl} = 4745 \text{ J/kg}\cdot°\text{C}$$
$$k_l = 0.4927 \text{ W/m}\cdot°\text{C}$$
$$\text{Pr}_l = 1.463$$



Analysis (*a*) The modified latent heat of vaporization is

$$h^*_{fg} = h_{fg} + 0.68C_{pl}(T_{sat} - T_s)$$
$$= 1166\times10^3 \text{ J/kg} + 0.68\times4745 \text{ J/kg}\cdot°\text{C}(25-15)°\text{C} = 1198\times10^3 \text{ J/kg}$$

Assuming turbulent flow, the Reynolds number is determined from

$$\text{Re} = \text{Re}_{\text{vertical,turb}} = \frac{\text{Re}\, k_l}{8750 + 58\,\text{Pr}^{-0.5}(\text{Re}^{0.75} - 253)\mu_l h^*_{fg}}\left(\frac{g}{\nu_l^2}\right)^{1/3}$$
$$= \frac{2149\times(0.4827 \text{ W/m}\cdot°\text{C})}{8750 + 58\times1.463^{-0.5}(2149^{0.75} - 253)(1.519\times10^{-4} \text{ kg/m.s})(1198\times10^3 \text{ J/kg})}\left(\frac{9.81 \text{ m/s}^2}{(0.2489\times10^{-6} \text{ m}^2/\text{s})^2}\right)^{1/3}$$
$$= 2140$$

which is greater than 1800, and thus our assumption of turbulent flow is verified. Then the condensation heat transfer coefficient is determined from

$$h = h_{\text{vertical,turbulent}} = \frac{\text{Re}\, k_l}{8750 + 58\,\text{Pr}^{-0.5}(\text{Re}^{0.75} - 253)}\left(\frac{g}{\nu_l^2}\right)^{1/3}$$
$$= \frac{2149\times(0.4827 \text{ W/m}\cdot°\text{C})}{8750 + 58\times1.463^{-0.5}(2149^{0.75} - 253)}\left(\frac{9.81 \text{ m/s}^2}{(0.2489\times10^{-6} \text{ m}^2/\text{s})^2}\right)^{1/3} = 4871 \text{ W/m}^2\cdot°\text{C}$$

The heat transfer surface area of the tube is $A_s = \pi DL = \pi(0.032 \text{ m})(2 \text{ m}) = 0.2011 \text{m}^2$. Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{sat} - T_s) = (4871 \text{W/m}^2\cdot°\text{C})(0.2011 \text{m}^2)(25-15)°\text{C} = \mathbf{9794\, W}$$

(*b*) The rate of condensation of ammonia is determined from

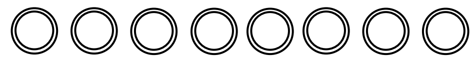
$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h^*_{fg}} = \frac{9794 \text{ J/s}}{1198\times10^3 \text{ J/kg}} = \mathbf{8.175\times10^{-3}\ kg/s}$$

10-74 There is film condensation on the outer surfaces of 8 horizontal tubes arranged in a horizontal or vertical tier. The ratio of the condensation rate for the cases of the tubes being arranged in a horizontal tier versus in a vertical tier is to be determined.

Assumptions Steady operating conditions exist.

Analysis The heat transfer coefficients for the two cases are related to the heat transfer coefficient on a single horizontal tube by

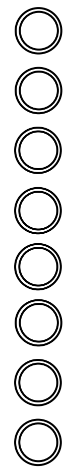
Horizontal tier: $h_{\text{horizontal tier of N tubes}} = h_{\text{horizontal, 1 tube}}$



Horizontal tier

Vertical tier: $h_{\text{vertical tier of N tubes}} = \dfrac{h_{\text{horizontal, 1 tube}}}{N^{1/4}}$

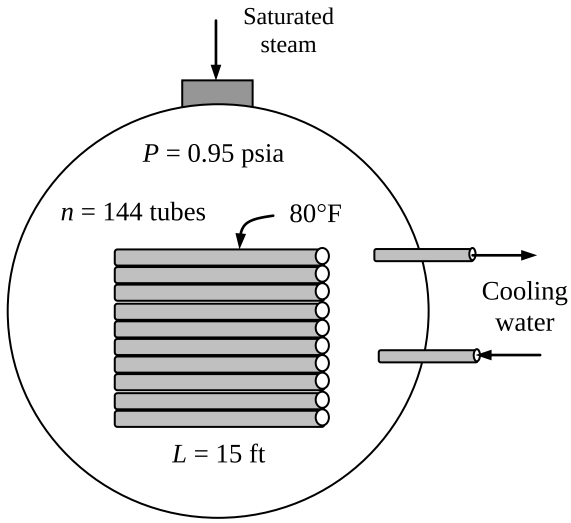
Vertical tier



Therefore,

$$\begin{aligned}
\text{Ratio} &= \frac{\dot{m}_{\text{horizontal tier of N tubes}}}{\dot{m}_{\text{vertical tier of N tubes}}} \\
&= \frac{h_{\text{horizontal tier of N tubes}}}{h_{\text{vertical tier of N tubes}}} \\
&= \frac{h_{\text{horizontal, 1 tube}}}{h_{\text{horizontal, 1 tube}} / N^{1/4}} \\
&= N^{1/4} \\
&= 8^{1/4} = \mathbf{1.68}
\end{aligned}$$

10-75E Saturated steam at a saturation pressure of 0.95 psia and thus at a saturation temperature of T_{sat} = 100°F (Table A-9E) condenses on the outer surfaces of 144 horizontal tubes which are maintained at 80°F by circulating cooling water and arranged in a 12 × 12 square array. The rate of heat transfer to the cooling water and the rate of condensation of steam are to be determined.



Assumptions **1** Steady operating conditions exist. **2** The tubes are isothermal.

Properties The properties of water at the saturation temperature of 100°F are h_{fg} = 1037 Btu/lbm and ρ_v = 0.00286 lbm/ft^3. The properties of liquid water at the film temperature of $T_f = (T_{sat} + T_s)/2 = (100 + 80)/2 = 90°F$ are (Table A-9E),

$$\rho_l = 62.12 \text{ lbm/ft}^3$$
$$\mu_l = 1.842 \text{ lbm/ft}\cdot\text{h}$$
$$\nu_l = \mu_l/\rho_l = 0.02965 \text{ ft}^2/\text{h}$$
$$C_{pl} = 0.999 \text{ Btu/lbm}\cdot°\text{F}$$
$$k_l = 0.358 \text{ Btu/h}\cdot\text{ft}\cdot°\text{F}$$

Analysis (*a*) The modified latent heat of vaporization is

$$\begin{aligned} h^*_{fg} &= h_{fg} + 0.68C_{pl}(T_{sat} - T_s) \\ &= 1037 \text{ Btu/lbm} + 0.68 \times (0.999 \text{ Btu/lbm}\cdot°\text{F})(100 - 80)°\text{F} \\ &= 1051 \text{ Btu/lbm} \end{aligned}$$

The heat transfer coefficient for condensation on a single horizontal tube is

$$h = h_{horiz} = 0.729\left[\frac{g\rho_l(\rho_l - \rho_v)h^*_{fg}k_l^3}{\mu_l(T_{sat} - T_s)D}\right]^{1/4}$$

$$= 0.729\left[\frac{(32.2 \text{ ft/s}^2)(62.12 \text{ lbm/ft}^3)(62.12 - 0.00286 \text{lbm/ft}^3)(1051 \text{Btu/lbm})(0.358 \text{ Btu/h}\cdot\text{ft}\cdot°\text{F})^3}{[(1 \text{ h}/3600 \text{ s})^2](1.842 \text{ lbm/ft}\cdot\text{h})(100 - 80)°\text{F}(1.2/12 \text{ ft})}\right]^{1/4}$$

$$= 1562 \text{ Btu/h}\cdot\text{ft}^2\cdot°\text{F}$$

Then the average heat transfer coefficient for a 4-tube high vertical tier becomes

$$h_{\text{horiz, N tubes}} = \frac{1}{N^{1/4}}h_{\text{horiz, 1 tube}} = \frac{1}{12^{1/4}}(1562 \text{ Btu/h}\cdot\text{ft}^2\cdot°\text{F}) = 839 \text{ Btu/h}\cdot\text{ft}^2\cdot°\text{F}$$

The surface area for all 144 tubes is

$$A_s = N_{total}\pi DL = 144\pi(1.2/12 \text{ ft})(15 \text{ ft}) = 678.6 \text{ ft}^2$$

Then the rate of heat transfer during this condensation process becomes

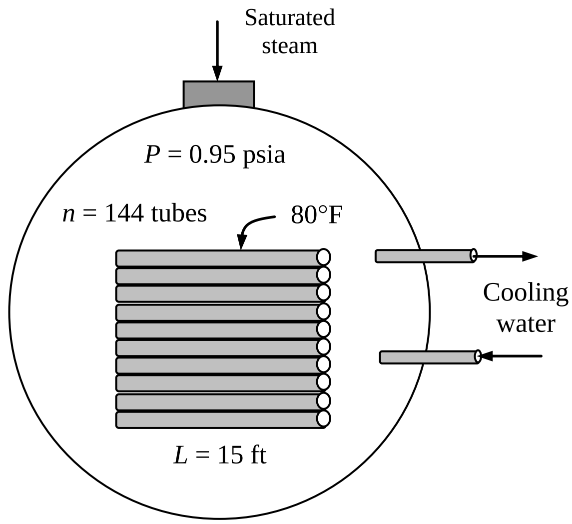
$$\dot{Q} = hA_s(T_{sat} - T_s) = (839 \text{ Btu/h.ft}^2\cdot°\text{F})(678.6 \text{ ft}^2)(100 - 80)°\text{F} = \mathbf{11{,}387{,}000 \text{ Btu/h}}$$

(*b*) The rate of condensation of steam is determined from

$$\dot{m}_{condensation} = \frac{\dot{Q}}{h^*_{fg}} = \frac{11{,}387{,}000 \text{ Btu/h}}{1051 \text{ Btu/lbm}} = \mathbf{10{,}830 \text{ lbm/h}}$$

10-76E Saturated steam at a saturation pressure of 0.95 psia and thus at a saturation temperature of T_{sat} = 100°F (Table A-9E) condenses on the outer surfaces of 144 horizontal tubes which are maintained at 80°F by circulating cooling water and arranged in a 12 × 12 square array. The rate of heat transfer to the cooling water and the rate of condensation of steam are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The tubes are isothermal.



Properties The properties of water at the saturation temperature of 10°F are h_{fg} = 1037 Btu/lbm and ρ_v = 0.00286 lbm/ft^3. The properties of liquid water at the film temperature of $T_f = (T_{sat} + T_s)/2 = (100 + 80)/2 = 90°F$ are (Table A-9E),

$$\rho_l = 62.12 \text{ lbm/ft}^3$$
$$\mu_l = 1.842 \text{ lbm/ft}\cdot\text{h}$$
$$\nu_l = \mu_l/\rho_l = 0.02965 \text{ ft}^2/\text{h}$$
$$C_{pl} = 0.999 \text{ Btu/lbm}\cdot°\text{F}$$
$$k_l = 0.358 \text{ Btu/h}\cdot\text{ft}\cdot°\text{F}$$

Analysis (*a*) The modified latent heat of vaporization is

$$h^*_{fg} = h_{fg} + 0.68C_{pl}(T_{sat} - T_s)$$
$$= 1037 \text{ Btu/lbm} + 0.68 \times (0.999 \text{ Btu/lbm}\cdot°\text{F})(100-80)°\text{F}$$
$$= 1051 \text{ Btu/lbm}$$

The heat transfer coefficient for condensation on a single horizontal tube is

$$h = h_{horiz} = 0.729\left[\frac{g\rho_l(\rho_l - \rho_v)h^*_{fg}k_l^3}{\mu_l(T_{sat} - T_s)D}\right]^{1/4}$$
$$= 0.729\left[\frac{(32.2 \text{ ft/s}^2)(62.12 \text{ lbm/ft}^3)(62.12 - 0.00286 \text{ lbm/ft}^3)(1051 \text{ Btu/lbm})(0.358 \text{ Btu/h}\cdot\text{ft}\cdot°\text{F})^3}{[(1 \text{ h}/3600 \text{ s})^2](1.842 \text{ lbm/ft}\cdot\text{h})(100-80)°\text{F}(2.0/12 \text{ ft})}\right]^{1/4}$$
$$= 1374 \text{ Btu/h}\cdot\text{ft}^2\cdot°\text{F}$$

Then the average heat transfer coefficient for a 4-tube high vertical tier becomes

$$h_{\text{horiz, N tubes}} = \frac{1}{N^{1/4}}h_{\text{horiz, 1 tube}} = \frac{1}{12^{1/4}}(1374 \text{ Btu/h}\cdot\text{ft}^2\cdot°\text{F}) = 739 \text{ Btu/h}\cdot\text{ft}^2\cdot°\text{F}$$

The surface area for all 144 tubes is

$$A_s = N_{total}\pi DL = 144\pi(2/12 \text{ ft})(15 \text{ ft}) = 1131 \text{ ft}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{sat} - T_s) = (739 \text{ Btu/h.ft}^2\cdot°\text{F})(1131 \text{ ft}^2)(100-80)°\text{F} = \mathbf{16{,}716{,}000 \text{ Btu/h}}$$

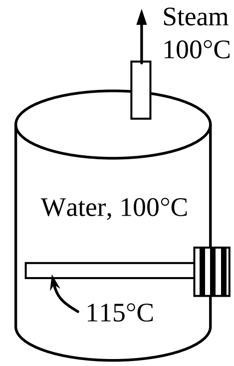
(*b*) The rate of condensation of steam is determined from

$$\dot{m}_{condensation} = \frac{\dot{Q}}{h^*_{fg}} = \frac{16{,}716{,}000 \text{ Btu/h}}{1051 \text{ Btu/lbm}} = \mathbf{15{,}900 \text{ lbm/h}}$$

10-77 Water is boiled at T_{sat} = 100°C by a chemically etched stainless steel electric heater whose surface temperature is maintained at T_s = 115°C. The rate of heat transfer to the water, the rate of evaporation of water, and the maximum rate of evaporation 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)



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

Also, C_{sf} = 0.0130 and n = 1.0 for the boiling of water on a chemically etched 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 $\Delta T = T_s - T_{sat} = 115-100 = 15°\text{C}$ 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

$$\dot{q}_{\text{nucleate}} = \mu_l h_{fg}\left[\frac{g(\rho_l-\rho_v)}{\sigma}\right]^{1/2}\left(\frac{C_{p,l}(T_s-T_{sat})}{C_{sf}h_{fg}\text{Pr}_l^n}\right)^3$$
$$= (0.282\times10^{-3})(2257\times10^3)\left[\frac{9.8(957.9-0.60)}{0.0589}\right]^{1/2}\left(\frac{4217(115-100)}{0.0130(2257\times10^3)1.75}\right)^3$$
$$= 474{,}900 \text{ W/m}^2$$

The surface area of the bottom of the heater is $A_s = \pi DL = \pi(0.002\text{ m})(0.8\text{m}) = 0.005027\text{m}^2$.

Then the rate of heat transfer during nucleate boiling becomes

$$\dot{Q}_{\text{boiling}} = A_s\dot{q}_{\text{nucleate}} = (0.005027\text{m}^2)(474{,}900\text{ W/m}^2) = \mathbf{2387\text{ W}}$$

The rate of evaporation of water is determined from

$$\dot{m}_{\text{evaporation}} = \frac{\dot{Q}_{\text{boiling}}}{h_{fg}} = \frac{2387\text{ J/s}}{2257\times10^3\text{ J/kg}} = \mathbf{1.058\times10^{-3}\text{ kg/s} = 3.81\text{kg/h}}$$

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

$$L^* = L\left(\frac{g(\rho_l-\rho_v)}{\sigma}\right)^{1/2} = (0.001)\left(\frac{9.8(957.9-0.60)}{0.0589}\right)^{1/2} = 0.399 < 1.2$$
$$C_{cr} = 0.12L^{*-0.25} = 0.12(0.399)^{-0.25} = 0.151$$

Then the maximum or critical heat flux is determined from

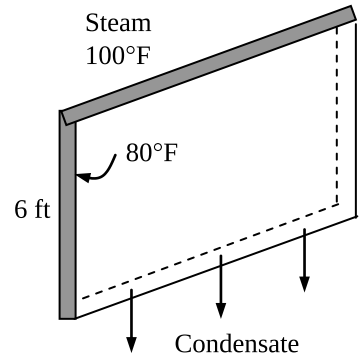
$$\dot{q}_{\max} = C_{cr}h_{fg}[\sigma g\rho_v^2(\rho_l-\rho_v)]^{1/4} = 0.151(2257\times10^3)[0.0589\times9.8\times(0.6)^2(957.9-0.60)]^{1/4}$$
$$= \mathbf{1{,}280{,}000\text{ W/m}^2}$$

10-78E Steam at a saturation temperature of T_{sat} = 100°F condenses on a vertical plate which is maintained at 80°C. The rate of heat transfer to the plate and the rate of condensation of steam per ft width of the plate are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The plate is isothermal. **3** The condensate flow is wavy-laminar over the entire plate (this assumption will be verified). **4** The density of vapor is much smaller than the density of liquid, $\rho_v << \rho_l$.

Properties The properties of water at the saturation temperature of 100°F are h_{fg} = 1037 Btu/lbm and ρ_v = 0.00286 lbm/ft^3. The properties of liquid water at the film temperature of $T_f = (T_{sat} + T_s)/2 = (100 + 80)/2$ = 90°F are (Table A-9E),

$$\rho_l = 62.12 \text{ lbm/ft}^3$$
$$\mu_l = 1.842 \text{ lbm/ft}\cdot\text{h}$$
$$\nu_l = \mu_l/\rho_l = 0.02965 \text{ ft}^2/\text{h}$$
$$C_{pl} = 0.999 \text{ Btu/lbm}\cdot°\text{F}$$
$$k_l = 0.358 \text{ Btu/h}\cdot\text{ft}\cdot°\text{F}$$



Analysis The modified latent heat of vaporization is

$$h^*_{fg} = h_{fg} + 0.68C_{pl}(T_{sat} - T_s)$$
$$= 1037 \text{ Btu/lbm} + 0.68 \times (0.999 \text{ Btu/lbm}\cdot°\text{F})(100-80)°\text{F}$$
$$= 1051 \text{ Btu/lbm}$$

Assuming wavy-laminar flow, the Reynolds number is determined from

$$\text{Re} = \text{Re}_{\text{vertical,wavy}} = \left[4.81 + \frac{3.70Lk_l(T_{sat}-T_s)}{\mu_l h^*_{fg}}\left(\frac{g}{\nu_l^2}\right)^{1/3}\right]^{0.820}$$

$$= \left[4.81 + \frac{3.70\times(6\text{ ft})\times(0.358\text{ Btu/h}\cdot\text{ft}\cdot°\text{F})\times(100-80)°\text{F}}{(1.842\text{ lbm/ft}\cdot\text{h})(1051\text{ Btu/lbm})}\left(\frac{32.2\text{ ft/s}^2}{(0.02965\text{ft}^2/\text{h})^2}\frac{(3600\text{s})^2}{(1\text{ h})^2}\right)^{1/3}\right]^{0.82} = 201$$

which is between 30 and 1800, and thus our assumption of wavy laminar flow is verified. Then the condensation heat transfer coefficient is determined from

$$h = h_{\text{vertical,wavy}} = \frac{\text{Re}\, k_l}{1.08\,\text{Re}^{1.22} - 5.2}\left(\frac{g}{\nu_l^2}\right)^{1/3}$$

$$= \frac{201\times(0.358\text{ Btu/h}\cdot\text{ft}\cdot°\text{F})}{1.08(201)^{1.22}-5.2}\left(\frac{32.2\text{ ft/s}^2}{(0.02965\text{ft}^2/\text{h})^2}\frac{(3600\text{s})^2}{(1\text{ h})^2}\right)^{1/3} = 813\text{ Btu/h}\cdot\text{ft}^2\cdot°\text{F}$$

The heat transfer surface area of the plate is

$$A_s = W \times L = (6\text{ ft})(1\text{ft}) = 6\text{ ft}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{sat} - T_s) = (813\text{ Btu/h}\cdot\text{ft}^2\cdot°\text{F})(6\text{ ft}^2)(100-80)°\text{F} = \mathbf{97{,}530\,Btu/h}$$

The rate of condensation of steam is determined from

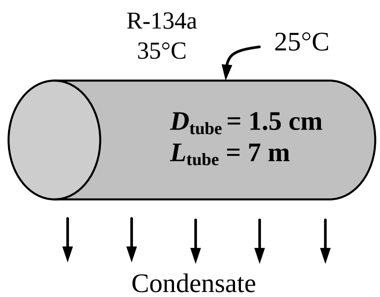
$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h^*_{fg}} = \frac{97{,}530\text{ Btu/h}}{1051\text{ Btu/lbm}} = \mathbf{92.8\ lbm/h}$$

10-79 Saturated refrigerant-134a vapor condenses on the outside of a horizontal tube maintained at a specified temperature. The rate of condensation of the refrigerant is to be determined.

Assumptions **1** Steady operating conditions exist. **2** The tube is isothermal.

Properties The properties of refrigerant-134a at the saturation temperature of 35°C are h_{fg} = 168.2×10^3 J/kg and ρ_v = 43.41 kg/m^3. The properties of liquid R-134a at the film temperature of $T_f = (T_{sat} + T_s)/2 = (35 + 25)/2 = 30°C$ are (Table A-10),

$$\rho_l = 1188\ \text{kg/m}^3$$
$$\mu_l = 1.888\times10^{-4}\ \text{kg/m.s}$$
$$\nu_l = \mu_l / \rho_l = 0.1590\times10^{-6}\ \text{m}^2\text{/s}$$
$$C_{pl} = 1448\ \text{J/kg.°C}$$
$$k_l = 0.0808\ \text{W/m.°C}$$



Analysis The modified latent heat of vaporization is

$$h^*_{fg} = h_{fg} + 0.68C_{pl}(T_{sat} - T_s)$$
$$= 168.2\times10^3\ \text{J/kg} + 0.68\times1448\ \text{J/kg}\cdot°\text{C}(35-25)°\text{C} = 178.0\times10^3\ \text{J/kg}$$

The heat transfer coefficient for condensation on a single horizontal tube is

$$h = h_{horizontal} = 0.729\left[\frac{g\rho_l(\rho_l - \rho_v)h^*_{fg}k_l^3}{\mu_l(T_{sat} - T_s)D}\right]^{1/4}$$
$$= 0.729\left[\frac{(9.81\ \text{m/s}^2)(1188\ \text{kg/m}^3)(1188-43.41\ \text{kg/m}^3)(178.0\times10^3\ \text{J/kg})(0.0808\ \text{W/m}\cdot°\text{C})^3}{(1.888\times10^{-4}\ \text{kg/m}\cdot\text{s})(35-25)°\text{C}(0.015\ \text{m})}\right]^{1/4}$$
$$= 1880\ \text{W/m}^2\cdot°\text{C}$$

The heat transfer surface area of the pipe is

$$A_s = \pi DL = \pi(0.015\ \text{m})(7\ \text{m}) = 0.3299\ \text{m}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{sat} - T_s) = (1880\ \text{W/m}^2\cdot°\text{C})(0.3299\ \text{m}^2)(35-25)°\text{C} = 6200\ \text{W}$$

The rate of condensation of steam is determined from

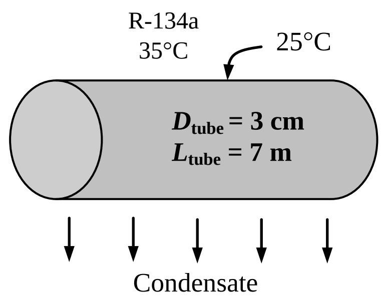
$$\dot{m}_{condensation} = \frac{\dot{Q}}{h^*_{fg}} = \frac{6200\ \text{J/s}}{178.0\times10^3\ \text{J/kg}} = 0.0348\ \text{kg/s} = \mathbf{2.09\ kg/min}$$

10-80 Saturated refrigerant-134a vapor condenses on the outside of a horizontal tube maintained at a specified temperature. The rate of condensation of the refrigerant is to be determined.

Assumptions **1** Steady operating conditions exist. **2** The tube is isothermal.

Properties The properties of refrigerant-134a at the saturation temperature of 35°C are $h_{fg} = 168.2\times10^3$ J/kg and $\rho_v = 43.41$ kg/m^3. The properties of liquid R-134a at the film temperature of $T_f = (T_{sat} + T_s)/2 = (35 + 25)/2 = 30$°C are (Table A-10),

$$\rho_l = 1188\ \text{kg/m}^3$$
$$\mu_l = 1.888\times10^{-4}\ \text{kg/m.s}$$
$$\nu_l = \mu_l/\rho_l = 0.1590\times10^{-6}\ \text{m}^2\text{/s}$$
$$C_{pl} = 1448\ \text{J/kg.°C}$$
$$k_l = 0.0808\ \text{W/m.°C}$$



Analysis The modified latent heat of vaporization is

$$h^*_{fg} = h_{fg} + 0.68C_{pl}(T_{sat} - T_s)$$
$$= 168.2\times10^3\ \text{J/kg} + 0.68\times1448\ \text{J/kg}\cdot\text{°C}(35-25)\text{°C} = 178.0\times10^3\ \text{J/kg}$$

The heat transfer coefficient for condensation on a single horizontal tube is

$$h = h_{horizontal} = 0.729\left[\frac{g\rho_l(\rho_l - \rho_v)h^*_{fg}k_l^3}{\mu_l(T_{sat} - T_s)D}\right]^{1/4}$$
$$= 0.729\left[\frac{(9.81\ \text{m/s}^2)(1188\ \text{kg/m}^3)(1188-43.41\ \text{kg/m}^3)(178.0\times10^3\ \text{J/kg})(0.0808\ \text{W/m}\cdot\text{°C})^3}{(1.888\times10^{-4}\ \text{kg/m}\cdot\text{s})(35-25)\text{°C}(0.03\ \text{m})}\right]^{1/4}$$
$$= 1581\ \text{W/m}^2\cdot\text{°C}$$

The heat transfer surface area of the pipe is

$$A_s = \pi DL = \pi(0.03\ \text{m})(7\ \text{m}) = 0.6597\ \text{m}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{sat} - T_s) = (1581\ \text{W/m}^2\cdot\text{°C})(0.6597\ \text{m}^2)(35-25)\text{°C} = 10{,}428\ \text{W}$$

The rate of condensation of steam is determined from

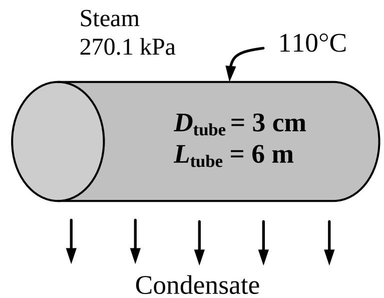
$$\dot{m}_{condensation} = \frac{\dot{Q}}{h^*_{fg}} = \frac{10{,}428\ \text{J/s}}{178.0\times10^3\ \text{J/kg}} = 0.05858\ \text{kg/s} = \mathbf{3.52\ kg/min}$$

10-81 Saturated steam at 270 kPa pressure and thus at a saturation temperature of T_{sat} = 130°C (Table A-9) condenses inside a horizontal tube which is maintained at 110°C. The average heat transfer coefficient and the rate of condensation of steam are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The tube is isothermal. **3** The vapor velocity is low so that $Re_{vapor} < 35{,}000$.

Properties The properties of water at the saturation temperature of 130°C are $h_{fg} = 2174\times10^3$ J/kg and ρ_v = 1.50 kg/m³. The properties of liquid water at the film temperature of $T_f = (T_{sat} + T_s)/2 = (130 + 110)/2 =$ 120°C are (Table A-9),

$$\rho_l = 943.4 \text{ kg/m}^3$$
$$\mu_l = 0.232\times10^{-3} \text{ kg/m.s}$$
$$\nu_l = \mu_l/\rho_l = 0.246\times10^{-6} \text{ m}^2/\text{s}$$
$$C_{pl} = 4244 \text{ J/kg.°C}$$
$$k_l = 0.683 \text{ W/m.°C}$$



Analysis The condensation heat transfer coefficient is determined from

$$h = h_{internal} = 0.555\left[\frac{g\rho_l(\rho_l-\rho_v)k_l^3}{\mu_l(T_{sat}-T_s)}\left(h_{fg}+\frac{3}{8}C_{pl}(T_{sat}-T_s)\right)\right]^{1/4}$$

$$= 0.555\left[\frac{(9.8\text{ m/s}^2)(943.4\text{ kg/m}^3)(943.4-1.50)\text{ kg/m}^3)(0.683\text{ W/m}\cdot\text{°C})^3}{(0.232\times10^{-3}\text{ kg/m}\cdot\text{s})(130-110)\text{°C}}\right.$$
$$\left.\times\left(2174\times10^3\text{ J/kg}+\frac{3}{8}(4244\text{ kJ/kg}\cdot\text{°C})(130-110)\text{°C}\right)\right]^{1/4}$$
$$= \mathbf{3345\ W/m^2\cdot°C}$$

The heat transfer surface area of the pipe is

$$A_s = \pi DL = \pi(0.03\text{ m})(6\text{ m}) = 0.5655\text{ m}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{sat}-T_s) = (3345\text{ W/m}^2\cdot\text{°C})(0.5655\text{ m}^2)(130-110)\text{°C} = 37{,}831\text{ W}$$

The rate of condensation of steam is determined from

$$\dot{m}_{condensation} = \frac{\dot{Q}}{h_{fg}} = \frac{37{,}831\text{ J/s}}{2174\times10^3\text{ J/kg}} = \mathbf{0.0174\ kg/s}$$

10-82 Saturated steam condenses on a suspended silver sphere which is initially at 30°C. The time needed for the temperature of the sphere to rise to 50°C and the amount of steam condenses are to be determined.

Assumptions **1** The temperature of the sphere changes uniformly and thus the lumped system analysis is applicable. **2** The average condensation heat transfer coefficient evaluated for the average temperature can be used for the entire process. **3** Constant properties at room temperature can be used for the silver ball.

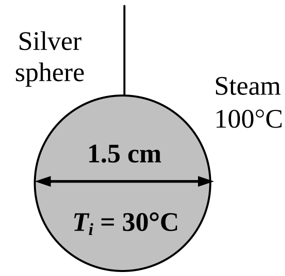
Properties The properties of water at the saturation temperature of 100°C are $h_{fg} = 2257\times10^3$ J/kg and $\rho_v = 0.60$ kg/m^3. The properties of the silver ball at room temperature and the properties of liquid water at the average film temperature of $T_f = (T_{sat} + T_{s,ave})/2 = (100 + 40)/2 = 70$°C are (Tables A-3 and A-9),

Silver Ball:

$$\rho = 10{,}500 \text{ kg/m}^3$$
$$\alpha = 174\times10^{-6} \text{ m}^2/\text{s}$$
$$C_p = 235 \text{ J/kg}\cdot°\text{C}$$
$$k_l = 429 \text{ W/m}\cdot°\text{C}$$

Liquid Water:

$$\rho_l = 977.5 \text{ kg/m}^3$$
$$\mu_l = 0.404\times10^{-3} \text{ kg/m}\cdot\text{s}$$
$$C_{pl} = 4190 \text{ J/kg}\cdot°\text{C}$$
$$k_l = 0.663 \text{ W/m}\cdot°\text{C}$$



Analysis The modified latent heat of vaporization is

$$h^*_{fg} = h_{fg} + 0.68C_{pl}(T_{sat} - T_s)$$
$$= 2257\times10^3 \text{ J/kg} + 0.68\times4190 \text{ J/kg}\cdot°\text{C}(100-40)°\text{C} = 2428\times10^3 \text{ J/kg}$$

Noting that the tube is horizontal, the condensation heat transfer coefficient is determined from

$$h = h_{sph} = 0.813\left[\frac{g\rho_l(\rho_l - \rho_v)h^*_{fg}k_l^3}{\mu_l(T_{sat} - T_s)D}\right]^{1/4}$$
$$= 0.813\left[\frac{(9.8 \text{ m/s}^2)(977.5 \text{ kg/m}^3)(977.5 - 0.60 \text{ kg/m}^3)(2428\times10^3 \text{ J/kg})(0.663 \text{ W/m}\cdot°\text{C})^3}{(0.404\times10^{-3} \text{ kg/m}\cdot\text{s})(100-40)°\text{C}(0.015 \text{ m})}\right]^{1/4}$$
$$= 9445 \text{ W/m}^2\cdot°\text{C}$$

The characteristic length and the Biot number for the lumped system analysis is (see Chap. 4)

$$L_c = \frac{V}{A} = \frac{\pi D^3/6}{\pi D^2} = \frac{D}{6} = \frac{0.015 \text{ m}}{6} = 0.0025 \text{ m}$$
$$Bi = \frac{hL_c}{k} = \frac{(9445 \text{ W/m}^2\cdot°\text{C})(0.0025 \text{ m})}{(429 \text{ W/m}\cdot°\text{C})} = 0.055 < 0.1$$

The lumped system analysis is applicable since Bi < 0.1. Then the time needed for the temperature of the sphere to rise from 30 to 50°C is determined to be

$$b = \frac{hA_s}{\rho C_p V} = \frac{h}{\rho C_p L_c} = \frac{9445 \text{ W/m}^2\cdot°\text{C}}{(10{,}500 \text{ kg/m}^3)(235 \text{ J/kg}\cdot°\text{C})(0.0025 \text{ m})} = 1.531 \text{ s}^{-1}$$
$$\frac{T(t) - T_\infty}{T_i - T_\infty} = e^{-bt} \longrightarrow \frac{50-100}{30-100} = e^{-1.531t} \longrightarrow t = \mathbf{0.22 s}$$

The total heat transfer to the ball and the amount of steam that condenses become

$$m_{sphere} = \rho V = \rho\frac{\pi D^3}{6} = (10{,}500 \text{ kg/m}^3)\frac{\pi(0.015 \text{ m})^3}{6} = 0.0186 \text{ kg}$$
$$Q = mC_p[T(t) - T_i]_{sphere} = (0.0186 \text{ kg})(235 \text{ J/kg}\cdot°\text{C})(50-30)°\text{C} = 87.2 \text{ J}$$
$$\dot{m}_{condensation} = \frac{\dot{Q}}{h^*_{fg}} = \frac{87.2 \text{ J/s}}{2428\times10^3 \text{ J/kg}} = \mathbf{0.0359\times10^{-3} \text{ kg/s}}$$

10-83 Steam at a saturation temperature of T_{sat} = 100°C condenses on a suspended silver sphere which is initially at 30°C. The time needed for the temperature of the sphere to rise to 50°C and the amount of steam condenses during this process are to be determined.

Assumptions **1** The temperature of the sphere changes uniformly and thus the lumped system analysis is applicable. **2** The average condensation heat transfer coefficient evaluated for the average temperature can be used for the entire process. **3** Constant properties at room temperature can be used for the silver ball.

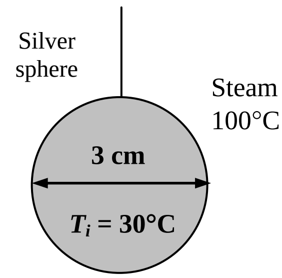
Properties The properties of water at the saturation temperature of 100°C are h_{fg} = 2257×10^3 J/kg and ρ_v = 0.60 kg/m^3. The properties of the silver ball at room temperature and the properties of liquid water at the average film temperature of $T_f = (T_{sat} + T_{s,ave})/2$ = (100 + 40)/2 = 70°C are (Tables A-3 and A-9),

Silver Ball:

$$\rho = 10{,}500 \text{ kg/m}^3$$
$$\alpha = 174\times10^{-6} \text{ m}^2/\text{s}$$
$$C_p = 235 \text{ J/kg}\cdot°\text{C}$$
$$k_l = 429 \text{ W/m}\cdot°\text{C}$$

Liquid Water:

$$\rho_l = 977.5 \text{ kg/m}^3$$
$$\mu_l = 0.404\times10^{-3} \text{ kg/m}\cdot\text{s}$$
$$C_{pl} = 4190 \text{ J/kg}\cdot°\text{C}$$
$$k_l = 0.663 \text{ W/m}\cdot°\text{C}$$



Analysis The modified latent heat of vaporization is

$$h^*_{fg} = h_{fg} + 0.68 C_{pl}(T_{sat} - T_s)$$
$$= 2257\times10^3 \text{ J/kg} + 0.68\times4190 \text{ J/kg}\cdot°\text{C}(100-40)°\text{C} = 2428\times10^3 \text{ J/kg}$$

Noting that the tube is horizontal, the condensation heat transfer coefficient is determined from

$$h = h_{sph} = 0.813\left[\frac{g\rho_l(\rho_l - \rho_v)h^*_{fg}k_l^3}{\mu_l(T_{sat} - T_s)D}\right]^{1/4}$$
$$= 0.813\left[\frac{(9.8 \text{ m/s}^2)(977.5 \text{ kg/m}^3)(977.5 - 0.60 \text{ kg/m}^3)(2428\times10^3 \text{ J/kg})(0.663 \text{ W/m}\cdot°\text{C})^3}{(0.404\times10^{-3} \text{ kg/m}\cdot\text{s})(100-40)°\text{C}(0.03 \text{ m})}\right]^{1/4}$$
$$= 7942 \text{ W/m}^2\cdot°\text{C}$$

The characteristic length and the Biot number for the lumped system analysis is (see Chap. 4)

$$L_c = \frac{V}{A_s} = \frac{\pi D^3/6}{\pi D^2} = \frac{D}{6} = \frac{0.03 \text{ m}}{6} = 0.005 \text{ m}$$
$$Bi = \frac{hL_c}{k} = \frac{(7942 \text{ W/m}^2\cdot°\text{C})(0.005 \text{ m})}{(429 \text{ W/m}\cdot°\text{C})} = 0.093 < 0.1$$

The lumped system analysis is applicable since Bi < 0.1. Then the time needed for the temperature of the sphere to rise from 30 to 50°C is determined to be

$$b = \frac{hA_s}{\rho C_p V} = \frac{h}{\rho C_p L_c} = \frac{7942 \text{ W/m}^2\cdot°\text{C}}{(10{,}500 \text{ kg/m}^3)(235 \text{ J/kg}\cdot°\text{C})(0.005 \text{ m})} = 0.644 \text{ s}^{-1}$$
$$\frac{T(t) - T_\infty}{T_i - T_\infty} = e^{-bt} \longrightarrow \frac{50-100}{30-100} = e^{-0.644t} \longrightarrow t = \mathbf{0.52 \text{ s}}$$

The total heat transfer to the ball and the amount of steam that condenses become

$$m_{sphere} = \rho V = \rho\frac{\pi D^3}{6} = (10{,}500 \text{ kg/m}^3)\frac{\pi(0.03 \text{ m})^3}{6} = 0.148 \text{ kg}$$
$$Q = mC_p[T(t) - T_i]_{sphere} = (0.148 \text{ kg})(235 \text{ J/kg}\cdot°\text{C})(50-30)°\text{C} = 698 \text{ J}$$
$$\dot{m}_{condensation} = \frac{\dot{Q}}{h^*_{fg}} = \frac{698 \text{ J/s}}{2428\times10^3 \text{ J/kg}} = \mathbf{0.287\times10^{-3} \text{ kg/s}}$$

10-84 Saturated steam at a saturation temperature of T_{sat} = 95°C (Table A-9) condenses on a canned drink at 5°C in a dropwise manner. The heat transfer coefficient for this dropwise condensation is to be determined.

Assumptions The heat transfer coefficient relation for dropwise condensation that was developed for copper surfaces is also applicable for aluminum surfaces.

Analysis Noting that the saturation temperature is less than 100°C, the heat transfer coefficient for dropwise condensation can be determined from Griffith's relation to be

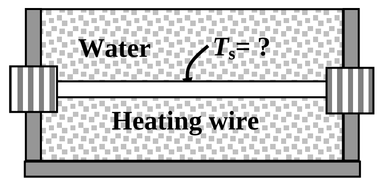
$$h = h_{\text{dropwise}} = 51{,}104 + 2044T_{\text{sat}} = 51{,}104 + 2044 \times 95 = \mathbf{245{,}284\ W/m^2 \cdot {}^\circ C}$$

10-85 Water is boiled at 1 atm pressure and thus at a saturation temperature of T_{sat} = 100°C by a nickel electric heater whose diameter is 2 mm. The highest temperature at which this heater can operate without burnout is to be determined.

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

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

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



Also, C_{sf} = 0.0060 and n = 1.0 for the boiling of water on a nickel surface (Table 10-3).

Analysis The maximum rate of heat transfer without the burnout is simply the critical heat flux. For a horizontal heating wire, the coefficient C_{cr} is determined from Table 10-4 to be

$$L^* = L\left(\frac{g(\rho_l - \rho_v)}{\sigma}\right)^{1/2} = (0.001)\left(\frac{9.8(957.9 - 0.60)}{0.0589}\right)^{1/2} = 0.399 < 1.2$$

$$C_{cr} = 0.12L^{*-0.25} = 0.12(0.399)^{-0.25} = 0.151$$

Then the maximum or critical heat flux is determined from

$$\dot{q}_{\max} = C_{cr} h_{fg}[\sigma g \rho_v^2(\rho_l - \rho_v)]^{1/4} = 0.151(2257 \times 10^3)[0.0589 \times 9.8 \times (0.6)^2(957.9 - 0.60)]^{1/4}$$
$$= 1{,}280{,}000\ \text{W/m}^2$$

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 Rohsenow relation together with other properties gives

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

$$1{,}280{,}000 = (0.282 \times 10^{-3})(2257 \times 10^3)\left[\frac{9.8(957.9 - 0.60)}{0.0589}\right]^{1/2}\left(\frac{4217(T_s - 100)}{0.0060(2257 \times 10^3)1.75}\right)^3$$

It gives the maximum temperature to be: $T_s = \mathbf{109.6^\circ C}$

10-86 ... 10-93 Design and Essay Problems
