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**Condensation Heat Transfer**

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**10-34C** Condensation is a vapor-to-liquid phase change process. It occurs when the temperature of a vapor is reduced *below* its saturation temperature  $T_{\text{sat}}$ . This is usually done by bringing the vapor into contact with a solid surface whose temperature  $T_s$  is *below* the saturation temperature  $T_{\text{sat}}$  of the vapor.

**10-35C** In *film condensation*, the condensate wets the surface and forms a liquid film on the surface which slides down under the influence of gravity. The thickness of the liquid film increases in the flow direction as more vapor condenses on the film. This is how condensation normally occurs in practice. In *dropwise condensation*, the condensed vapor forms droplets on the surface instead of a continuous film, and the surface is covered by countless droplets of varying diameters. Dropwise condensation is a much more effective mechanism of heat transfer.

**10-36C** In condensate flow, the wetted perimeter is defined as the length of the surface-condensate interface at a cross-section of condensate flow. It differs from the ordinary perimeter in that the latter refers to the entire circumference of the condensate at some cross-section.

**10-37C** The modified latent heat of vaporization  $h_{fg}^*$  is the amount of heat released as a unit mass of vapor condenses at a specified temperature, plus the amount of heat released as the condensate is cooled further to some average temperature between  $T_{\text{sat}}$  and  $T_s$ . It is defined as  $h_{fg}^* = h_{fg} + 0.68C_{pl}(T_{\text{sat}} - T_s)$  where  $C_{pl}$  is the specific heat of the liquid at the average film temperature.

**10-38C** During film condensation on a vertical plate, heat flux at the top will be higher since the thickness of the film at the top, and thus its thermal resistance, is lower.

**10-39C** Setting the heat transfer coefficient relations for a vertical tube of height  $L$  and a horizontal tube of diameter  $D$  equal to each other yields  $L = 2.77D$ , which implies that for a tube whose length is 2.77 times its diameter, the average heat transfer coefficient for laminar film condensation will be the *same* whether the tube is positioned horizontally or vertically. For  $L = 10D$ , the heat transfer coefficient and thus the heat transfer rate will be higher in the horizontal position since  $L > 2.77D$  in that case.

**10-40C** The condensation heat transfer coefficient for the tubes will be the highest for the case of horizontal side by side (case b) since (1) for long tubes, the horizontal position gives the highest heat transfer coefficients, and (2) for tubes in a vertical tier, the average thickness of the liquid film at the lower tubes is much larger as a result of condensate falling on top of them from the tubes directly above, and thus the average heat transfer coefficient at the lower tubes in such arrangements is smaller.

**10-41C** The presence of noncondensable gases in the vapor has a detrimental effect on condensation heat transfer. Even small amounts of a noncondensable gas in the vapor cause significant drops in heat transfer coefficient during condensation.

**10-42** The hydraulic diameter  $D_h$  for all 4 cases are expressed in terms of the boundary layer thickness  $\delta$  as follows:

(a) Vertical plate:  $D_h = \frac{4A_c}{p} = \frac{4w\delta}{w} = 4\delta$

(b) Tilted plate:  $D_h = \frac{4A_c}{p} = \frac{4w\delta}{w} = 4\delta$

(c) Vertical cylinder:  $D_h = \frac{4A_c}{p} = \frac{4\pi D\delta}{\pi D} = 4\delta$

(d) Horizontal cylinder:  $D_h = \frac{4A_c}{p} = \frac{4(2L\delta)}{2L} = 4\delta$

(e) Sphere:  $D_h = \frac{4A_c}{p} = \frac{4\pi D\delta}{\pi D} = 4\delta$

Therefore, the Reynolds number for all 5 cases can be expressed as

$$\text{Re} = \frac{4\dot{m}}{p\mu_l} = \frac{4A_c\rho_l v_l}{p\mu_l} = \frac{D_h\rho_l v_l}{\mu_l} = \frac{4\delta\rho_l v_l}{\mu_l}$$

**10-43** There is film condensation on the outer surfaces of  $N$  horizontal tubes arranged in a vertical tier. The value of  $N$  for which the average heat transfer coefficient for the entire tier be equal to half of the value for a single horizontal tube is to be determined.

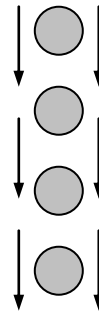
**Assumptions** Steady operating conditions exist.

**Analysis** The relation between the heat transfer coefficients for the two cases is given to be

$$h_{\text{horizontal, N tubes}} = \frac{h_{\text{horizontal, 1 tube}}}{N^{1/4}}$$

Therefore,

$$\frac{h_{\text{horizontal, N tubes}}}{h_{\text{horizontal, 1 tube}}} = \frac{1}{2} = \frac{1}{N^{1/4}} \longrightarrow N = 16$$

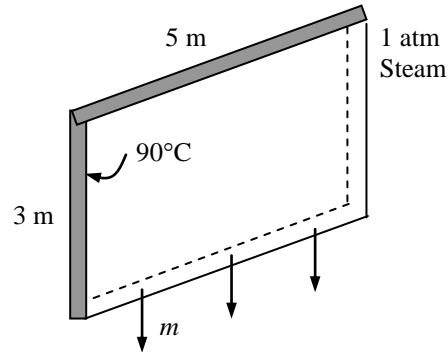


**10-44** Saturated steam at atmospheric pressure thus at a saturation temperature of  $T_{\text{sat}} = 100^\circ\text{C}$  condenses on a vertical plate which is maintained at  $90^\circ\text{C}$  by circulating cooling water through the other side. The rate of heat transfer to the plate and the rate of condensation of steam 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,  $\rho_v \ll \rho_l$ .

**Properties** The properties of water at the saturation temperature of  $100^\circ\text{C}$  are  $h_{fg} = 2257 \times 10^3 \text{ J/kg}$  and  $\rho_v = 0.60 \text{ kg/m}^3$ . The properties of liquid water at the film temperature of  $T_f = (T_{\text{sat}} + T_s) / 2 = (100 + 90) / 2 = 95^\circ\text{C}$  are (Table A-9),

$$\begin{aligned}\rho_l &= 961.5 \text{ kg/m}^3 \\ \mu_l &= 0.297 \times 10^{-3} \text{ kg/m}\cdot\text{s} \\ \nu_l &= \mu_l / \rho_l = 0.309 \times 10^{-6} \text{ m}^2/\text{s} \\ C_{pl} &= 4212 \text{ J/kg}\cdot^\circ\text{C} \\ k_l &= 0.677 \text{ W/m}\cdot^\circ\text{C}\end{aligned}$$



**Analysis** The modified latent heat of vaporization is

$$\begin{aligned}h_{fg}^* &= h_{fg} + 0.68C_{pl}(T_{\text{sat}} - T_s) \\ &= 2257 \times 10^3 \text{ J/kg} + 0.68 \times 4212 \text{ J/kg}\cdot^\circ\text{C}(100 - 90)^\circ\text{C} = 2,286 \times 10^3 \text{ J/kg}\end{aligned}$$

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

$$\begin{aligned}\text{Re} &= \text{Re}_{\text{vertical,wavy}} = \left[ 4.81 + \frac{3.70Lk_l(T_{\text{sat}} - T_s)}{\mu_l h_{fg}^*} \left( \frac{g}{\nu_l^2} \right)^{1/3} \right]^{0.820} \\ &= \left[ 4.81 + \frac{3.70 \times (3 \text{ m}) \times (0.677 \text{ W/m}\cdot^\circ\text{C}) \times (100 - 90)^\circ\text{C}}{(0.297 \times 10^{-3} \text{ kg/m}\cdot\text{s})(2286 \times 10^3 \text{ J/kg})} \left( \frac{9.8 \text{ m/s}^2}{(0.309 \times 10^{-6} \text{ m}^2/\text{s})^2} \right)^{1/3} \right]^{0.82} = 1112\end{aligned}$$

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

$$\begin{aligned}h &= h_{\text{vertical,wavy}} = \frac{\text{Re} k_l}{1.08 \text{Re}^{1.22} - 5.2} \left( \frac{g}{\nu_l^2} \right)^{1/3} \\ &= \frac{1112 \times (0.677 \text{ W/m}\cdot^\circ\text{C})}{1.08(1112)^{1.22} - 5.2} \left( \frac{9.8 \text{ m/s}^2}{(0.309 \times 10^{-6} \text{ m}^2/\text{s})^2} \right)^{1/3} = 6279 \text{ W/m}^2 \cdot ^\circ\text{C}\end{aligned}$$

The heat transfer surface area of the plate is

$$A_s = W \times L = (3 \text{ m})(5 \text{ m}) = 15 \text{ m}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{\text{sat}} - T_s) = (6279 \text{ W/m}^2 \cdot ^\circ\text{C})(15 \text{ m}^2)(100 - 90)^\circ\text{C} = \mathbf{941,850 \text{ W}}$$

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

$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h_{fg}^*} = \frac{941,850 \text{ J/s}}{2286 \times 10^3 \text{ J/kg}} = \mathbf{0.412 \text{ kg/s}}$$

**10-45** Saturated steam at a saturation temperature of  $T_{\text{sat}} = 100^\circ\text{C}$  condenses on a plate which is tilted  $60^\circ$  from the vertical and maintained at  $90^\circ\text{C}$  by circulating cooling water through the other side. The rate of heat transfer to the plate and the rate of condensation of the steam are to be determined.

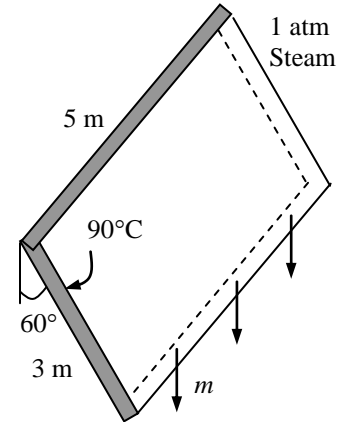
**Assumptions** 1 Steady operating conditions exist. 2 The plate is isothermal. 3 The condensate flow is wavy-laminar over the entire plate (this assumption will be verified). 4 The density of vapor is much smaller than the density of liquid,  $\rho_v \ll \rho_l$ .

**Properties** The properties of water at the saturation temperature of  $100^\circ\text{C}$  are  $h_{fg} = 2257 \times 10^3 \text{ J/kg}$  and  $\rho_v = 0.60 \text{ kg/m}^3$ . The properties of liquid water at the film temperature of  $T_f = (T_{\text{sat}} + T_s)/2 = (100 + 90)/2 = 95^\circ\text{C}$  are (Table A-9),

$$\begin{aligned}\rho_l &= 961.5 \text{ kg/m}^3 \\ \mu_l &= 0.297 \times 10^{-3} \text{ kg/m}\cdot\text{s} \\ \nu_l &= \mu_l / \rho_l = 0.309 \times 10^{-6} \text{ m}^2/\text{s} \\ C_{pl} &= 4212 \text{ J/kg}\cdot^\circ\text{C} \\ k_l &= 0.677 \text{ W/m}\cdot^\circ\text{C}\end{aligned}$$

**Analysis** The modified latent heat of vaporization is

$$\begin{aligned}h_{fg}^* &= h_{fg} + 0.68C_{pl}(T_{\text{sat}} - T_s) \\ &= 2257 \times 10^3 \text{ J/kg} + 0.68 \times 4212 \text{ J/kg}\cdot^\circ\text{C}(100 - 90)^\circ\text{C} \\ &= 2,286 \times 10^3 \text{ J/kg}\end{aligned}$$



Assuming wavy-laminar flow, the Reynolds number is determined from the vertical plate relation by replacing  $g$  by  $g \cos \theta$  where  $\theta = 60^\circ$  to be

$$\begin{aligned}\text{Re} &= \text{Re}_{\text{tilted, wavy}} = \left[ 4.81 + \frac{3.70Lk_l(T_{\text{sat}} - T_s)}{\mu_l h_{fg}^*} \left( \frac{g \cos 60^\circ}{\nu_l^2} \right)^{1/3} \right]^{0.820} \\ &= \left[ 4.81 + \frac{3.70 \times (3 \text{ m}) \times (0.677 \text{ W/m}\cdot^\circ\text{C}) \times (100 - 90)^\circ\text{C}}{(0.297 \times 10^{-3} \text{ kg/m}\cdot\text{s})(2286 \times 10^3 \text{ J/kg})} \left( \frac{(9.8 \text{ m/s}^2) \cos 60^\circ}{(0.309 \times 10^{-6} \text{ m}^2/\text{s})^2} \right)^{1/3} \right]^{0.82} = 950.5\end{aligned}$$

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

$$\begin{aligned}h &= h_{\text{tilted, wavy}} = \frac{\text{Re } k_l}{1.08 \text{Re}^{1.22} - 5.2} \left( \frac{g \cos \theta}{\nu_l^2} \right)^{1/3} \\ &= \frac{950.5 \times (0.677 \text{ W/m}\cdot^\circ\text{C})}{1.08(950.5)^{1.22} - 5.2} \left( \frac{(9.8 \text{ m/s}^2) \cos 60^\circ}{(0.309 \times 10^{-6} \text{ m}^2/\text{s})^2} \right)^{1/3} = 5159 \text{ W/m}^2\cdot^\circ\text{C}\end{aligned}$$

The heat transfer surface area of the plate is  $A_s = W \times L = (3 \text{ m})(5 \text{ m}) = 15 \text{ m}^2$ .

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{\text{sat}} - T_s) = (5159 \text{ W/m}^2\cdot^\circ\text{C})(15 \text{ m}^2)(100 - 90)^\circ\text{C} = \mathbf{773,850 \text{ W}}$$

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

$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h_{fg}^*} = \frac{773,850 \text{ J/s}}{2286 \times 10^3 \text{ J/kg}} = \mathbf{0.339 \text{ kg/s}}$$

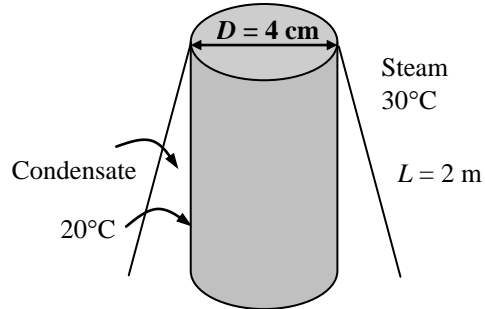
**Discussion** Using the heat transfer coefficient determined in the previous problem for the vertical plate, we could also determine the heat transfer coefficient from  $h_{\text{inclined}} = h_{\text{vert}}(\cos \theta)^{1/4}$ . It would give  $5280 \text{ W/m}^2\cdot^\circ\text{C}$ , which is 2.3% different than the value determined above.

**10-46** Saturated steam condenses outside of vertical tube. The rate of heat transfer to the coolant, the rate of condensation and the thickness of the condensate layer at the bottom 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 wavy-laminar over the entire tube (this assumption will be verified). 5 Nusselt's analysis can be used to determine the thickness of the condensate film layer. 6 The density of vapor is much smaller than the density of liquid,  $\rho_v \ll \rho_l$ .

**Properties** The properties of water at the saturation temperature of  $30^\circ\text{C}$  are  $h_{fg} = 2431 \times 10^3 \text{ J/kg}$  and  $\rho_v = 0.03 \text{ kg/m}^3$ . The properties of liquid water at the film temperature of  $T_f = (T_{\text{sat}} + T_s)/2 = (30 + 20)/2 = 25^\circ\text{C}$  are (Table A-9),

$$\begin{aligned}\rho_l &= 997.0 \text{ kg/m}^3 \\ \mu_l &= 1.002 \times 10^{-3} \text{ kg/m}\cdot\text{s} \\ \nu_l &= \mu_l / \rho_l = 1.005 \times 10^{-6} \text{ m}^2/\text{s} \\ C_{pl} &= 4180 \text{ J/kg}\cdot^\circ\text{C} \\ k_l &= 0.607 \text{ W/m}\cdot^\circ\text{C}\end{aligned}$$



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

$$\begin{aligned}h_{fg}^* &= h_{fg} + 0.68C_{pl}(T_{\text{sat}} - T_s) \\ &= 2431 \times 10^3 \text{ J/kg} + 0.68 \times 4180 \text{ J/kg}\cdot^\circ\text{C}(30 - 20)^\circ\text{C} = 2459 \times 10^3 \text{ J/kg}\end{aligned}$$

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

$$\begin{aligned}\text{Re} &= \text{Re}_{\text{vertical,wavy}} = \left[ 4.81 + \frac{3.70Lk_l(T_{\text{sat}} - T_s)}{\mu_l h_{fg}^*} \left( \frac{g}{\nu_l^2} \right)^{1/3} \right]^{0.820} \\ &= \left[ 4.81 + \frac{3.70 \times (2 \text{ m}) \times (0.607 \text{ W/m}\cdot^\circ\text{C}) \times (30 - 20)^\circ\text{C}}{(1.002 \times 10^{-3} \text{ kg/m}\cdot\text{s})(2459 \times 10^3 \text{ J/kg})} \left( \frac{9.8 \text{ m/s}^2}{(1.005 \times 10^{-6} \text{ m}^2/\text{s})^2} \right)^{1/3} \right]^{0.82} = 133.9\end{aligned}$$

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

$$\begin{aligned}h &= h_{\text{vertical,wavy}} = \frac{\text{Re} k_l}{1.08 \text{Re}^{1.22} - 5.2} \left( \frac{g}{\nu_l^2} \right)^{1/3} \\ &= \frac{133.9 \times (0.607 \text{ W/m}\cdot^\circ\text{C})}{1.08(133.9)^{1.22} - 5.2} \left( \frac{9.8 \text{ m/s}^2}{(1.005 \times 10^{-6} \text{ m}^2/\text{s})^2} \right)^{1/3} = 4132 \text{ W/m}^2\cdot^\circ\text{C}\end{aligned}$$

The heat transfer surface area of the tube is  $A_s = \pi DL = \pi(0.04 \text{ m})(2 \text{ m}) = 0.2513 \text{ m}^2$ . Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{\text{sat}} - T_s) = (4132 \text{ W/m}^2\cdot^\circ\text{C})(0.2513 \text{ m}^2)(30 - 20)^\circ\text{C} = \mathbf{10,385 \text{ W}}$$

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

$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h_{fg}^*} = \frac{10,385 \text{ J/s}}{2459 \times 10^3 \text{ J/kg}} = \mathbf{4.22 \times 10^{-3} \text{ kg/s}}$$

(c) Combining equations  $\delta_L = k_l / h_l$  and  $h = (4/3)h_L$ , the thickness of the liquid film at the bottom of the tube is determined to be

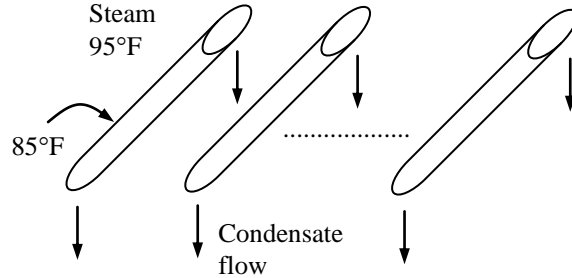
$$\delta_L = \frac{4k_l}{3h} = \frac{4(0.607 \text{ W/m}\cdot^\circ\text{C})}{3(4132 \text{ W/m}^2\cdot^\circ\text{C})} = 0.196 \times 10^{-3} = \mathbf{0.2 \text{ mm}}$$

**10-47E** Saturated steam at a saturation temperature of  $T_{\text{sat}} = 95^\circ\text{F}$  condenses on the outer surfaces of horizontal pipes which are maintained at  $85^\circ\text{F}$  by circulating cooling water. The rate of heat transfer to the cooling water and the rate of condensation per unit length of a single horizontal pipe are to be determined.

**Assumptions** 1 Steady operating conditions exist. 2 The pipe is isothermal. 3 There is no interference between the pipes (no drip of the condensate from one tube to another).

**Properties** The properties of water at the saturation temperature of  $95^\circ\text{F}$  are  $h_{\text{fg}} = 1040 \text{ Btu/lbm}$  and  $\rho_v = 0.0025 \text{ lbm/ft}^3$ . The properties of liquid water at the film temperature of  $T_f = (T_{\text{sat}} + T_s) / 2 = (95 + 85) / 2 = 90^\circ\text{F}$  are (Table A-9E),

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



**Analysis** The modified latent heat of vaporization is

$$\begin{aligned}h_{fg}^* &= h_{fg} + 0.68C_{pl}(T_{\text{sat}} - T_s) \\ &= 1040 \text{ Btu/lbm} + 0.68 \times (0.999 \text{ Btu/lbm}\cdot^\circ\text{F})(95 - 85)^\circ\text{F} \\ &= 1047 \text{ Btu/lbm}\end{aligned}$$

Noting that we have condensation on a horizontal tube, the heat transfer coefficient is determined from

$$\begin{aligned}h &= h_{\text{horiz}} = 0.729 \left[ \frac{g\rho_l(\rho_l - \rho_v)h_{fg}^*k_l^3}{\mu_l(T_{\text{sat}} - T_s)D} \right]^{1/4} \\ &= 0.729 \left[ \frac{(32.2 \text{ ft/s}^2)(62.12 \text{ lbm/ft}^3)(62.12 - 0.0025 \text{ lbm/ft}^3)(1047 \text{ Btu/lbm})(0.358 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F})^3}{[(1 \text{ h}/3600 \text{ s})^2](1.842 \text{ lbm/ft}\cdot\text{h})(95 - 85)^\circ\text{F}(1/12 \text{ ft})} \right]^{1/4} \\ &= 1942 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}\end{aligned}$$

The heat transfer surface area of the tube per unit length is

$$A_s = \pi DL = \pi(1/12 \text{ ft})(1 \text{ ft}) = 0.2618 \text{ ft}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{\text{sat}} - T_s) = (1942 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F})(0.2618 \text{ ft}^2)(95 - 85)^\circ\text{F} = \mathbf{5084 \text{ Btu/h}}$$

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

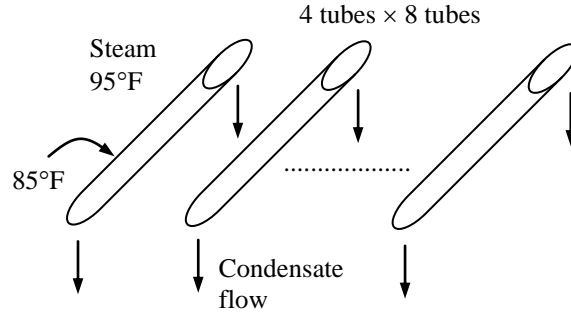
$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h_{fg}^*} = \frac{5084 \text{ Btu/h}}{1047 \text{ Btu/lbm}} = \mathbf{4.856 \text{ lbm/h}}$$

**10-48E** Saturated steam at a saturation temperature of  $T_{\text{sat}} = 95^\circ\text{F}$  condenses on the outer surfaces of 20 horizontal pipes which are maintained at  $85^\circ\text{F}$  by circulating cooling water and arranged in a rectangular array of 4 pipes high and 5 pipes wide. The rate of heat transfer to the cooling water and the rate of condensation per unit length of the pipes are to be determined.

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

**Properties** The properties of water at the saturation temperature of  $95^\circ\text{F}$  are  $h_{fg} = 1040 \text{ Btu/lbm}$  and  $\rho_v = 0.0025 \text{ lbm/ft}^3$ . The properties of liquid water at the film temperature of  $T_f = (T_{\text{sat}} + T_s) / 2 = (95 + 85) / 2 = 90^\circ\text{F}$  are (Table A-9E),

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



**Analysis** The modified latent heat of vaporization is

$$\begin{aligned} h_{fg}^* &= h_{fg} + 0.68C_{pl}(T_{\text{sat}} - T_s) \\ &= 1040 \text{ Btu/lbm} + 0.68 \times (0.999 \text{ Btu/lbm}\cdot^\circ\text{F})(95 - 85)^\circ\text{F} = 1047 \text{ Btu/lbm} \end{aligned}$$

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

$$\begin{aligned} h &= h_{\text{horiz}} = 0.729 \left[ \frac{g\rho_l(\rho_l - \rho_v)h_{fg}^*k_l^3}{\mu_l(T_{\text{sat}} - T_s)D} \right]^{1/4} \\ &= 0.729 \left[ \frac{(32.2 \text{ ft/s}^2)(62.12 \text{ lbm/ft}^3)(62.12 - 0.0025 \text{ lbm/ft}^3)(1047 \text{ Btu/lbm})(0.358 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F})^3}{[(1 \text{ h}/3600 \text{ s})^2](1.842 \text{ lbm/ft}\cdot\text{h})(95 - 85)^\circ\text{F}(1/12 \text{ ft})} \right]^{1/4} \\ &= 1942 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F} \end{aligned}$$

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

$$h_{\text{horiz, N tubes}} = \frac{1}{N^{1/4}} h_{\text{horiz, 1 tube}} = \frac{1}{4^{1/4}} (1942 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}) = 1373 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$$

The surface area for all 32 pipes per unit length of the pipes is

$$A_s = N_{\text{total}} \pi DL = 32\pi(1/12 \text{ ft})(1 \text{ ft}) = 8.378 \text{ ft}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{\text{sat}} - T_s) = (1373 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F})(8.378 \text{ ft}^2)(95 - 85)^\circ\text{F} = \mathbf{115,000 \text{ Btu/h}}$$

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

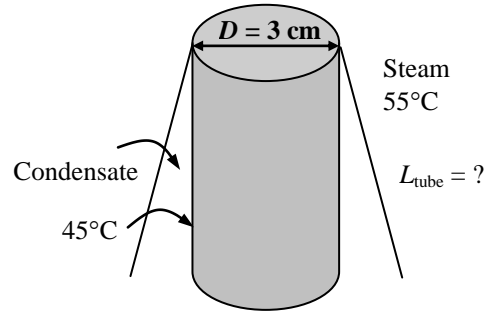
$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h_{fg}^*} = \frac{115,000 \text{ Btu/h}}{1047 \text{ Btu/lbm}} = \mathbf{109.91 \text{ lbm/h}}$$

**10-49** Saturated steam at a saturation temperature of  $T_{\text{sat}} = 55^\circ\text{C}$  condenses on the outer surface of a vertical tube which is maintained at  $45^\circ\text{C}$ . The required tube length to condense steam at a rate of  $10 \text{ kg/h}$  is to be determined.

**Assumptions** **1** Steady operating conditions exist. **2** The tube is isothermal. **3** The vertical tube can be treated as a vertical plate. **4** The density of vapor is much smaller than the density of liquid,  $\rho_v \ll \rho_l$ .

**Properties** The properties of water at the saturation temperature of  $55^\circ\text{C}$  are  $h_{fg} = 2371 \times 10^3 \text{ J/kg}$  and  $\rho_v = 0.1045 \text{ kg/m}^3$ . The properties of liquid water at the film temperature of  $T_f = (T_{\text{sat}} + T_s) / 2 = (55 + 45) / 2 = 50^\circ\text{C}$  are (Table A-9),

$$\begin{aligned}\rho_l &= 988.1 \text{ kg/m}^3 \\ \mu_l &= 0.547 \times 10^{-3} \text{ kg/m}\cdot\text{s} \\ \nu_l &= \mu_l / \rho_l = 0.554 \times 10^{-6} \text{ m}^2/\text{s} \\ C_{pl} &= 4181 \text{ J/kg}\cdot^\circ\text{C} \\ k_l &= 0.644 \text{ W/m}\cdot^\circ\text{C}\end{aligned}$$



**Analysis** The modified latent heat of vaporization is

$$\begin{aligned}h_{fg}^* &= h_{fg} + 0.68C_{pl}(T_{\text{sat}} - T_s) \\ &= 2371 \times 10^3 \text{ J/kg} + 0.68 \times 4181 \text{ J/kg}\cdot^\circ\text{C}(55 - 45)^\circ\text{C} = 2399 \times 10^3 \text{ J/kg}\end{aligned}$$

The Reynolds number is determined from its definition to be

$$\text{Re} = \frac{4\dot{m}}{p\mu_l} = \frac{4(10/3600 \text{ kg/s})}{\pi(0.03 \text{ m})(0.547 \times 10^{-3} \text{ kg/m}\cdot\text{s})} = 215.5$$

which is between 30 and 1800. Therefore the condensate flow is wavy laminar, and the condensation heat transfer coefficient is determined from

$$\begin{aligned}h &= h_{\text{vertical,wavy}} = \frac{\text{Re} k_l}{1.08 \text{Re}^{1.22} - 5.2} \left( \frac{g}{\nu_l^2} \right)^{1/3} \\ &= \frac{215.5 \times (0.644 \text{ W/m}\cdot^\circ\text{C})}{1.08(215.5)^{1.22} - 5.2} \left( \frac{9.8 \text{ m/s}^2}{(0.554 \times 10^{-6} \text{ m}^2/\text{s})^2} \right)^{1/3} = 5644 \text{ W/m}^2\cdot^\circ\text{C}\end{aligned}$$

The rate of heat transfer during this condensation process is

$$\dot{Q} = \dot{m}h_{fg}^* = (10/3600 \text{ kg/s})(2399 \times 10^3 \text{ J/kg}) = 6,664 \text{ W}$$

Heat transfer can also be expressed as

$$\dot{Q} = hA_s(T_{\text{sat}} - T_s) = h(\pi DL)(T_{\text{sat}} - T_s)$$

Then the required length of the tube becomes

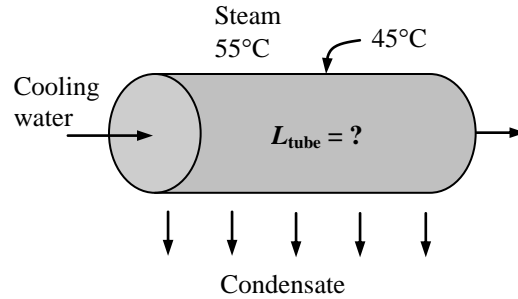
$$L = \frac{\dot{Q}}{h(\pi D)(T_{\text{sat}} - T_s)} = \frac{6664 \text{ W}}{(5644 \text{ W/m}^2\cdot^\circ\text{C})\pi(0.03 \text{ m})(55 - 45)^\circ\text{C}} = \mathbf{1.21 \text{ m}}$$

**10-50** Saturated steam at a saturation temperature of  $T_{\text{sat}} = 55^\circ\text{C}$  condenses on the outer surface of a horizontal tube which is maintained at  $45^\circ\text{C}$ . The required tube length to condense steam at a rate of 10 kg/h is to be determined.

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

**Properties** The properties of water at the saturation temperature of  $55^\circ\text{C}$  are  $h_{\text{fg}} = 2371 \times 10^3 \text{ J/kg}$  and  $\rho_v = 0.1045 \text{ kg/m}^3$ . The properties of liquid water at the film temperature of  $T_f = (T_{\text{sat}} + T_s) / 2 = (55 + 45) / 2 = 50^\circ\text{C}$  are (Table A-9),

$$\begin{aligned}\rho_l &= 988.1 \text{ kg/m}^3 \\ \mu_l &= 0.547 \times 10^{-3} \text{ kg/m}\cdot\text{s} \\ \nu_l &= \mu_l / \rho_l = 0.554 \times 10^{-6} \text{ m}^2/\text{s} \\ C_{pl} &= 4181 \text{ J/kg}\cdot^\circ\text{C} \\ k_l &= 0.644 \text{ W/m}\cdot^\circ\text{C}\end{aligned}$$



**Analysis** The modified latent heat of vaporization is

$$\begin{aligned}h_{fg}^* &= h_{fg} + 0.68C_{pl}(T_{\text{sat}} - T_s) \\ &= 2371 \times 10^3 \text{ J/kg} + 0.68 \times 4181 \text{ J/kg}\cdot^\circ\text{C}(55 - 45)^\circ\text{C} = 2399 \times 10^3 \text{ J/kg}\end{aligned}$$

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

$$\begin{aligned}h &= h_{\text{horizontal}} = 0.729 \left[ \frac{g\rho_l(\rho_l - \rho_v)h_{fg}^*k_l^3}{\mu_l(T_{\text{sat}} - T_s)D} \right]^{1/4} \\ &= 0.729 \left[ \frac{(9.8 \text{ m/s}^2)(988.1 \text{ kg/m}^3)(988.1 - 0.10 \text{ kg/m}^3)(2399 \times 10^3 \text{ J/kg})(0.644 \text{ W/m}\cdot^\circ\text{C})^3}{(0.547 \times 10^{-3} \text{ kg/m}\cdot\text{s})(55 - 45)^\circ\text{C}(0.03 \text{ m})} \right]^{1/4} \\ &= 10,135 \text{ W/m}^2\cdot^\circ\text{C}\end{aligned}$$

The rate of heat transfer during this condensation process is

$$\dot{Q} = \dot{m}h_{fg}^* = (10 / 3600 \text{ kg/s})(2399 \times 10^3 \text{ J/kg}) = 6,664 \text{ W}$$

Heat transfer can also be expressed as

$$\dot{Q} = hA_s(T_{\text{sat}} - T_s) = h(\pi DL)(T_{\text{sat}} - T_s)$$

Then the required length of the tube becomes

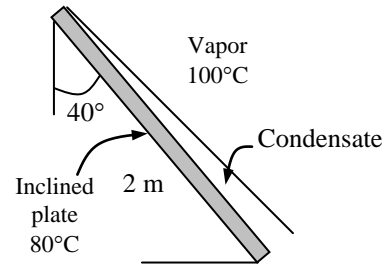
$$L = \frac{\dot{Q}}{h(\pi D)(T_{\text{sat}} - T_s)} = \frac{6664 \text{ W}}{(10,135 \text{ W/m}^2\cdot^\circ\text{C})\pi(0.03 \text{ m})(55 - 45)^\circ\text{C}} = \mathbf{0.70 \text{ m}}$$

**10-51** Saturated steam at a saturation temperature of  $T_{\text{sat}} = 100^\circ\text{C}$  condenses on a plate which is tilted  $40^\circ$  from the vertical and maintained at  $80^\circ\text{C}$  by circulating cooling water through the other side. The rate of heat transfer to the plate and the rate of condensation of the steam 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,  $\rho_v \ll \rho_l$ .

**Properties** The properties of water at the saturation temperature of  $100^\circ\text{C}$  are  $h_{fg} = 2257 \times 10^3 \text{ J/kg}$  and  $\rho_v = 0.60 \text{ kg/m}^3$ . The properties of liquid water at the film temperature of  $T_f = (T_{\text{sat}} + T_s) / 2 = (100 + 80) / 2 = 90^\circ\text{C}$  are (Table A-9),

$$\begin{aligned}\rho_l &= 965.3 \text{ kg/m}^3 \\ \mu_l &= 0.315 \times 10^{-3} \text{ kg/m}\cdot\text{s} \\ \nu_l &= \mu_l / \rho_l = 0.326 \times 10^{-6} \text{ m}^2/\text{s} \\ C_{pl} &= 4206 \text{ J/kg}\cdot^\circ\text{C} \\ k_l &= 0.675 \text{ W/m}\cdot^\circ\text{C}\end{aligned}$$



**Analysis** The modified latent heat of vaporization is

$$\begin{aligned}h_{fg}^* &= h_{fg} + 0.68C_{pl}(T_{\text{sat}} - T_s) \\ &= 2257 \times 10^3 \text{ J/kg} + 0.68 \times 4206 \text{ J/kg}\cdot^\circ\text{C}(100 - 80)^\circ\text{C} = 2,314 \times 10^3 \text{ J/kg}\end{aligned}$$

Assuming wavy-laminar flow, the Reynolds number is determined from the vertical plate relation by replacing  $g$  by  $g \cos \theta$  where  $\theta = 60^\circ$  to be

$$\begin{aligned}\text{Re} = \text{Re}_{\text{tilted, wavy}} &= \left[ 4.81 + \frac{3.70Lk_l(T_{\text{sat}} - T_s)}{\mu_l h_{fg}^*} \left( \frac{g \cos \theta}{\nu_l^2} \right)^{1/3} \right]^{0.820} \\ &= \left[ 4.81 + \frac{3.70 \times (2 \text{ m}) \times (0.675 \text{ W/m}\cdot^\circ\text{C}) \times (100 - 80)^\circ\text{C}}{(0.315 \times 10^{-3} \text{ kg/m}\cdot\text{s}) (2314 \times 10^3 \text{ J/kg})} \left( \frac{(9.8 \text{ m/s}^2) \cos 40}{(0.326 \times 10^{-6} \text{ m}^2/\text{s})^2} \right)^{1/3} \right]^{0.82} = 1197\end{aligned}$$

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

$$\begin{aligned}h &= h_{\text{tilted, wavy}} = \frac{\text{Re} k_l}{1.08 \text{Re}^{1.22} - 5.2} \left( \frac{g \cos \theta}{\nu_l^2} \right)^{1/3} \\ &= \frac{1197 \times (0.675 \text{ W/m}\cdot^\circ\text{C})}{1.08(1197)^{1.22} - 5.2} \left( \frac{(9.8 \text{ m/s}^2) \cos 40}{(0.326 \times 10^{-6} \text{ m}^2/\text{s})^2} \right)^{1/3} = \mathbf{5438 \text{ W/m}^2 \cdot ^\circ\text{C}}\end{aligned}$$

The heat transfer surface area of the plate is:  $A = w \times L = (2 \text{ m})(2 \text{ m}) = 4 \text{ m}^2$ .

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA(T_{\text{sat}} - T_s) = (5438 \text{ W/m}^2 \cdot ^\circ\text{C})(4 \text{ m}^2)(100 - 80)^\circ\text{C} = 435,000 \text{ W}$$

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

$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h_{fg}^*} = \frac{435,000 \text{ J/s}}{2314 \times 10^3 \text{ J/kg}} = \mathbf{0.188 \text{ kg/s}}$$

**Discussion** We could also determine the heat transfer coefficient from  $h_{\text{inclined}} = h_{\text{vert}} (\cos \theta)^{1/4}$ .

## 10-52 "PROBLEM 10-52"

"GIVEN"

T\_sat=100 "[C]"

L=2 "[m]"

theta=40 "[degrees], parameter to be varied"

T\_s=80 "[C], parameter to be varied"

"PROPERTIES"

Fluid\$='steam\_NBS'

T\_f=1/2\*(T\_sat+T\_s)

P\_sat=pressure(Fluid\$, T=T\_sat, x=1)

rho\_l=density(Fluid\$, T=T\_f, x=0)

mu\_l=Viscosity(Fluid\$, T=T\_f, x=0)

nu\_l=mu\_l/rho\_l

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

k\_l=Conductivity(Fluid\$, T=T\_f, P=P\_sat+1)

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)

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

"ANALYSIS"

"(a)"

h\_fg\_star=h\_fg+0.68\*C\_l\*(T\_sat-T\_s)

Re=(4.81+(3.7\*L\*k\_l\*(T\_sat-T\_s))/(mu\_l\*h\_fg\_star))\*((g\*Cos(theta))/nu\_l^2)^(1/3)^0.820

h=(Re\*k\_l)/(1.08\*Re^1.22-5.2)\*((g\*Cos(theta))/nu\_l^2)^(1/3)

Q\_dot=h\*A\*(T\_sat-T\_s)

A=L^2

"(b)"

m\_dot\_cond=Q\_dot/h\_fg\_star

| $T_s$ [C] | $h$ [W/m <sup>2</sup> .C] | $m_{cond}$ [kg/s] |
|-----------|---------------------------|-------------------|
| 40        | 4073                      | 0.4027            |
| 42.5      | 4131                      | 0.3926            |
| 45        | 4191                      | 0.3821            |
| 47.5      | 4253                      | 0.3712            |
| 50        | 4317                      | 0.3599            |
| 52.5      | 4383                      | 0.3482            |
| 55        | 4453                      | 0.3361            |
| 57.5      | 4525                      | 0.3235            |
| 60        | 4601                      | 0.3105            |
| 62.5      | 4681                      | 0.2971            |
| 65        | 4766                      | 0.2832            |
| 67.5      | 4857                      | 0.2687            |
| 70        | 4954                      | 0.2538            |
| 72.5      | 5059                      | 0.2383            |
| 75        | 5173                      | 0.2222            |
| 77.5      | 5299                      | 0.2055            |
| 80        | 5440                      | 0.1881            |
| 82.5      | 5600                      | 0.1699            |
| 85        | 5786                      | 0.151             |
| 87.5      | 6009                      | 0.1311            |
| 90        | 6285                      | 0.11              |

| $\theta$ [degrees] | $h$ [W/m <sup>2</sup> .C] | $m_{cond}$ [kg/s] |
|--------------------|---------------------------|-------------------|
| 0                  | 5851                      | 0.2023            |
| 3                  | 5848                      | 0.2022            |
| 6                  | 5842                      | 0.202             |
| 9                  | 5831                      | 0.2016            |
| 12                 | 5815                      | 0.2011            |
| 15                 | 5796                      | 0.2004            |
| 18                 | 5771                      | 0.1995            |
| 21                 | 5742                      | 0.1985            |
| 24                 | 5708                      | 0.1974            |
| 27                 | 5669                      | 0.196             |
| 30                 | 5625                      | 0.1945            |
| 33                 | 5576                      | 0.1928            |
| 36                 | 5522                      | 0.1909            |
| 39                 | 5462                      | 0.1888            |
| 42                 | 5395                      | 0.1865            |
| 45                 | 5323                      | 0.184             |
| 48                 | 5243                      | 0.1813            |
| 51                 | 5156                      | 0.1783            |
| 54                 | 5061                      | 0.175             |
| 57                 | 4956                      | 0.1714            |
| 60                 | 4842                      | 0.1674            |

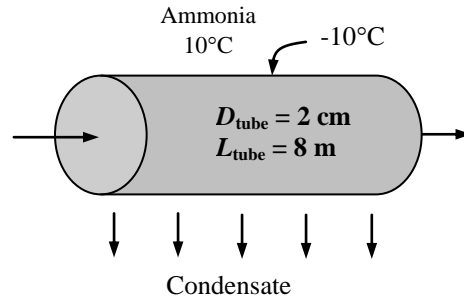


**10-53** Saturated ammonia vapor at a saturation temperature of  $T_{\text{sat}} = 10^\circ\text{C}$  condenses on the outer surface of a horizontal tube which is maintained at  $-10^\circ\text{C}$ . The rate of heat transfer from the ammonia and the rate of condensation of ammonia are to be determined.

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

**Properties** The properties of ammonia at the saturation temperature of  $10^\circ\text{C}$  are  $h_{fg} = 1226 \times 10^3 \text{ J/kg}$  and  $\rho_v = 4.870 \text{ kg/m}^3$  (Table A-11). The properties of liquid ammonia at the film temperature of  $T_f = (T_{\text{sat}} + T_s) / 2 = (10 + (-10)) / 2 = 0^\circ\text{C}$  are (Table A-11),

$$\begin{aligned}\rho_l &= 638.6 \text{ kg/m}^3 \\ \mu_l &= 1.896 \times 10^{-4} \text{ kg/m} \cdot \text{s} \\ \nu_l &= 0.2969 \times 10^{-6} \text{ m}^2/\text{s} \\ C_{pl} &= 4617 \text{ J/kg} \cdot ^\circ\text{C} \\ k_l &= 0.5390 \text{ W/m} \cdot ^\circ\text{C}\end{aligned}$$



**Analysis** The modified latent heat of vaporization is

$$\begin{aligned}h_{fg}^* &= h_{fg} + 0.68C_{pl}(T_{\text{sat}} - T_s) \\ &= 1226 \times 10^3 \text{ J/kg} + 0.68 \times 4617 \text{ J/kg} \cdot ^\circ\text{C} [10 - (-10)]^\circ\text{C} = 1288 \times 10^3 \text{ J/kg}\end{aligned}$$

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

$$\begin{aligned}h &= h_{\text{horizontal}} = 0.729 \left[ \frac{g\rho_l(\rho_l - \rho_v)h_{fg}^*k_l^3}{\mu_l(T_{\text{sat}} - T_s)D} \right]^{1/4} \\ &= 0.729 \left[ \frac{(9.81 \text{ m/s}^2)(638.6 \text{ kg/m}^3)(638.6 - 4.870 \text{ kg/m}^3)(1288 \times 10^3 \text{ J/kg})(0.5390 \text{ W/m} \cdot ^\circ\text{C})^3}{(1.896 \times 10^{-4} \text{ kg/m} \cdot \text{s})[10 - (-10)]^\circ\text{C}(0.02 \text{ m})} \right]^{1/4} \\ &= 7390 \text{ W/m}^2 \cdot ^\circ\text{C}\end{aligned}$$

The heat transfer surface area of the tube is

$$A_s = \pi DL = \pi(0.02 \text{ m})(8 \text{ m}) = 0.5027 \text{ m}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{\text{sat}} - T_s) = (7390 \text{ W/m}^2 \cdot ^\circ\text{C})(0.5027 \text{ m}^2)[10 - (-10)]^\circ\text{C} = \mathbf{74,300 \text{ W}}$$

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

$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h_{fg}^*} = \frac{74,300 \text{ J/s}}{1288 \times 10^3 \text{ J/kg}} = \mathbf{0.0577 \text{ kg/s}}$$

**10-54** Saturated steam at a pressure of 4.25 kPa and thus at a saturation temperature of  $T_{\text{sat}} = 30^\circ\text{C}$  (Table A-9) condenses on the outer surfaces of 100 horizontal tubes arranged in a  $10 \times 10$  square array maintained at  $20^\circ\text{C}$  by circulating cooling water. The rate of heat transfer to the cooling water and the rate of condensation of steam on the tubes 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  $30^\circ\text{C}$  are  $h_{fg} = 2431 \times 10^3 \text{ J/kg}$  and  $\rho_v = 0.030 \text{ kg/m}^3$ . The properties of liquid water at the film temperature of  $T_f = (T_{\text{sat}} + T_s)/2 = (30 + 20)/2 = 25^\circ\text{C}$  are (Table A-9),

$$\begin{aligned}\rho_l &= 997.0 \text{ kg/m}^3 \\ \mu_l &= 0.891 \times 10^{-3} \text{ kg/m}\cdot\text{s} \\ \nu_l &= \mu_l / \rho_l = 0.894 \times 10^{-6} \text{ m}^2/\text{s} \\ C_{pl} &= 4180 \text{ J/kg}\cdot^\circ\text{C} \\ k_l &= 0.607 \text{ W/m}\cdot^\circ\text{C}\end{aligned}$$

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

$$\begin{aligned}h_{fg}^* &= h_{fg} + 0.68C_{pl}(T_{\text{sat}} - T_s) \\ &= 2431 \times 10^3 \text{ J/kg} + 0.68 \times 4180 \text{ J/kg}\cdot^\circ\text{C}(30 - 20)^\circ\text{C} = 2,459 \times 10^3 \text{ J/kg}\end{aligned}$$

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

$$\begin{aligned}h &= h_{\text{horizontal}} = 0.729 \left[ \frac{g\rho_l(\rho_l - \rho_v)h_{fg}^*k_l^3}{\mu_l(T_{\text{sat}} - T_s)D} \right]^{1/4} \\ &= 0.729 \left[ \frac{(9.8 \text{ m/s}^2)(997 \text{ kg/m}^3)(997 - 0.03 \text{ kg/m}^3)(2459 \times 10^3 \text{ J/kg})(0.607 \text{ W/m}\cdot^\circ\text{C})^3}{(0.891 \times 10^{-3} \text{ kg/m}\cdot\text{s})(30 - 20)^\circ\text{C}(0.03 \text{ m})} \right]^{1/4} \\ &= 8674 \text{ W/m}^2\cdot^\circ\text{C}\end{aligned}$$

Then the average heat transfer coefficient for a 10-pipe high vertical tier becomes

$$h_{\text{horiz, N tubes}} = \frac{1}{N^{1/4}} h_{\text{horiz, 1 tube}} = \frac{1}{10^{1/4}} (8674 \text{ W/m}^2\cdot^\circ\text{C}) = 4878 \text{ W/m}^2\cdot^\circ\text{C}$$

The surface area for all 100 tubes is

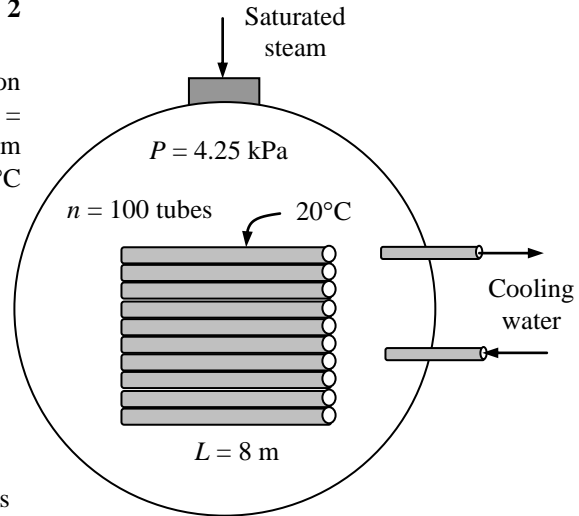
$$A_s = N_{\text{total}} \pi DL = 100\pi(0.03 \text{ m})(8 \text{ m}) = 75.40 \text{ m}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{\text{sat}} - T_s) = (4878 \text{ W/m}^2\cdot^\circ\text{C})(75.40 \text{ m}^2)(30 - 20)^\circ\text{C} = 3,678,000 \text{ W} = \mathbf{3678 \text{ kW}}$$

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

$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h_{fg}^*} = \frac{3,678,000 \text{ J/s}}{2459 \times 10^3 \text{ J/kg}} = \mathbf{1.496 \text{ kg/s}}$$



**10-55 "PROBLEM 10-55"****"GIVEN"****"P\_sat=4.25 [kPa], parameter to be varied"**

n\_tube=100

N=10

L=8 "[m]"

D=0.03 "[m]"

T\_s=20 "[C]"

**"PROPERTIES"**

Fluid\$='steam\_NBS'

T\_sat=temperature(Fluid\$, P=P\_sat, x=1)

T\_f=1/2\*(T\_sat+T\_s)

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)

rho\_v=density(Fluid\$, T=T\_sat, x=1)

rho\_l=density(Fluid\$, T=T\_f, x=0)

mu\_l=Viscosity(Fluid\$, T=T\_f, x=0)

nu\_l=mu\_l/rho\_l

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

k\_l=Conductivity(Fluid\$, T=T\_f, P=P\_sat+1)

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

**"ANALYSIS"****"(a)"**

h\_fg\_star=h\_fg+0.68\*C\_l\*(T\_sat-T\_s)

h\_1tube=0.729\*((g\*rho\_l\*(rho\_l-rho\_v)\*h\_fg\_star\*k\_l^3)/(mu\_l\*(T\_sat-T\_s)\*D))^0.25

h=1/N^0.25\*h\_1tube

Q\_dot=h\*A\*(T\_sat-T\_s)

A=n\_tube\*pi\*D\*L

**"(b)"**

m\_dot\_cond=Q\_dot/h\_fg\_star

| P <sub>sat</sub> [kPa] | Q [W]    | m <sub>cond</sub> [kg/s] |
|------------------------|----------|--------------------------|
| 3                      | 1836032  | 0.7478                   |
| 4                      | 3376191  | 1.374                    |
| 5                      | 4497504  | 1.829                    |
| 6                      | 5399116  | 2.194                    |
| 7                      | 6160091  | 2.502                    |
| 8                      | 6814744  | 2.766                    |
| 9                      | 7402573  | 3.004                    |
| 10                     | 7932545  | 3.218                    |
| 11                     | 8415994  | 3.413                    |
| 12                     | 8861173  | 3.592                    |
| 13                     | 9274152  | 3.758                    |
| 14                     | 9659732  | 3.914                    |
| 15                     | 10021650 | 4.059                    |



**10-56** Saturated steam at a saturation temperature of  $T_{\text{sat}} = 50^\circ\text{C}$  condenses on the outer surfaces of a tube bank with 20 tubes in each column maintained at  $20^\circ\text{C}$ . The average heat transfer coefficient and the rate of condensation of steam on the tubes are to be determined.

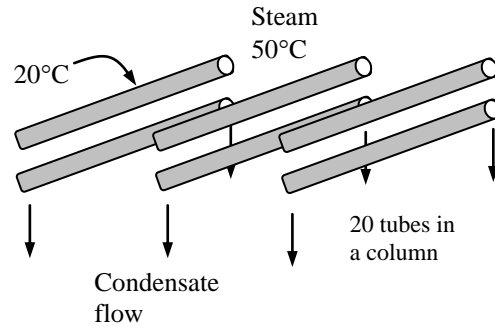
**Assumptions** 1 Steady operating conditions exist. 2 The tubes are isothermal.

**Properties** The properties of water at the saturation temperature of  $50^\circ\text{C}$  are  $h_{\text{fg}} = 2383 \times 10^3 \text{ J/kg}$  and  $\rho_v = 0.0831 \text{ kg/m}^3$ . The properties of liquid water at the film temperature of  $T_f = (T_{\text{sat}} + T_s) / 2 = (50 + 20) / 2 = 35^\circ\text{C}$  are (Table A-9),

$$\begin{aligned}\rho_l &= 994.0 \text{ kg/m}^3 \\ \mu_l &= 0.720 \times 10^{-3} \text{ kg/m}\cdot\text{s} \\ \nu_l &= \mu_l / \rho_l = 0.724 \times 10^{-6} \text{ m}^2/\text{s} \\ C_{pl} &= 4178 \text{ J/kg}\cdot^\circ\text{C} \\ k_l &= 0.623 \text{ W/m}\cdot^\circ\text{C}\end{aligned}$$

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

$$\begin{aligned}h_{fg}^* &= h_{fg} + 0.68C_{pl}(T_{\text{sat}} - T_s) \\ &= 2383 \times 10^3 \text{ J/kg} + 0.68 \times 4178 \text{ J/kg}\cdot^\circ\text{C}(50 - 20)^\circ\text{C} \\ &= 2468 \times 10^3 \text{ J/kg}\end{aligned}$$



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

$$\begin{aligned}h &= h_{\text{horizontal}} = 0.729 \left[ \frac{g\rho_l(\rho_l - \rho_v)h_{fg}^*k_l^3}{\mu_l(T_{\text{sat}} - T_s)D} \right]^{1/4} \\ &= 0.729 \left[ \frac{(9.8 \text{ m/s}^2)(994 \text{ kg/m}^3)(994 - 0.08 \text{ kg/m}^3)(2468 \times 10^3 \text{ J/kg})(0.623 \text{ W/m}\cdot^\circ\text{C})^3}{(0.720 \times 10^{-3} \text{ kg/m}\cdot\text{s})(50 - 20)^\circ\text{C}(0.015 \text{ m})} \right]^{1/4} \\ &= 8425 \text{ W/m}^2 \cdot ^\circ\text{C}\end{aligned}$$

Then the average heat transfer coefficient for a 10-pipe high vertical tier becomes

$$h_{\text{horiz, N tubes}} = \frac{1}{N^{1/4}} h_{\text{horiz, 1 tube}} = \frac{1}{20^{1/4}} (8425 \text{ W/m}^2 \cdot ^\circ\text{C}) = 3984 \text{ W/m}^2 \cdot ^\circ\text{C}$$

The surface area for all 20 tubes per unit length is

$$A_s = N_{\text{total}} \pi DL = 20\pi(0.015 \text{ m})(1 \text{ m}) = 0.9425 \text{ m}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{\text{sat}} - T_s) = (3984 \text{ W/m}^2 \cdot ^\circ\text{C})(0.9425 \text{ m}^2)(50 - 20)^\circ\text{C} = 112,650 \text{ W}$$

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

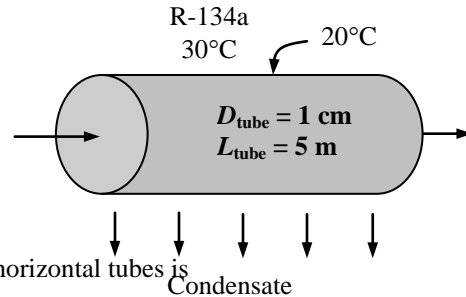
$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h_{fg}^*} = \frac{112,650 \text{ J/s}}{2468 \times 10^3 \text{ J/kg}} = 0.0456 \text{ kg/s}$$

**10-57** Saturated refrigerant-134a vapor at a saturation temperature of  $T_{\text{sat}} = 30^\circ\text{C}$  condenses inside a horizontal tube which is maintained at  $20^\circ\text{C}$ . The fraction of the refrigerant that will condense at the end of the tube is to be determined.

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

**Properties** The properties of refrigerant-134a at the saturation temperature of  $30^\circ\text{C}$  are  $h_{fg} = 173.1 \times 10^3 \text{ J/kg}$  and  $\rho_v = 37.53 \text{ kg/m}^3$ . The properties of liquid R-134a at the film temperature of  $T_f = (T_{\text{sat}} + T_s) / 2 = (30 + 20) / 2 = 25^\circ\text{C}$  are (Table A-10)

$$\begin{aligned}\rho_l &= 1207 \text{ kg/m}^3 \\ \mu_l &= 2.012 \times 10^{-4} \text{ kg/m}\cdot\text{s} \\ \nu_l &= \mu_l / \rho_l = 0.1667 \times 10^{-6} \text{ m}^2/\text{s} \\ C_{pl} &= 1427 \text{ J/kg}\cdot^\circ\text{C} \\ k_l &= 0.08325 \text{ W/m}\cdot^\circ\text{C}\end{aligned}$$



**Analysis** The heat transfer coefficient for condensation inside horizontal tubes is

$$\begin{aligned}h &= h_{\text{internal}} = 0.555 \left[ \frac{g\rho_l(\rho_l - \rho_v)k_l^3}{\mu_l(T_{\text{sat}} - T_s)} \left( h_{fg} + \frac{3}{8} C_{pl}(T_{\text{sat}} - T_s) \right) \right]^{1/4} \\ &= 0.555 \left[ \frac{(9.81 \text{ m/s}^2)(1207 \text{ kg/m}^3)(1207 - 37.53) \text{ kg/m}^3(0.08325 \text{ W/m}\cdot^\circ\text{C})^3}{(2.012 \times 10^{-4} \text{ kg/m}\cdot\text{s})(30 - 20)^\circ\text{C}} \right. \\ &\quad \left. \times \left( 173.1 \times 10^3 \text{ J/kg} + \frac{3}{8} (1427 \text{ J/kg}\cdot^\circ\text{C})(30 - 20)^\circ\text{C} \right) \right]^{1/4} \\ &= 509.2 \text{ W/m}^2 \cdot ^\circ\text{C}\end{aligned}$$

The heat transfer surface area of the pipe is

$$A_s = \pi DL = \pi(0.01 \text{ m})(5 \text{ m}) = 0.1571 \text{ m}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{\text{sat}} - T_s) = (509.2 \text{ W/m}^2 \cdot ^\circ\text{C})(0.1571 \text{ m}^2)(30 - 20)^\circ\text{C} = 800.0 \text{ W}$$

The modified latent heat of vaporization in this case is, as indicated in the  $h$  relation,

$$h_{fg}^* = h_{fg} + \frac{3}{8} C_{pl}(T_{\text{sat}} - T_s) = 173.1 \times 10^3 \text{ J/kg} + \frac{3}{8} (1427 \text{ J/kg}\cdot^\circ\text{C})(30 - 20)^\circ\text{C} = 178.5 \times 10^3 \text{ J/kg}$$

Then the rate of condensation becomes

$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h_{fg}^*} = \frac{800 \text{ J/s}}{178.5 \times 10^3 \text{ J/kg}} = 0.004482 \text{ kg/s} = 0.2689 \text{ kg/min}$$

Therefore, the fraction of the refrigerant that will condense at the end of the tube is

$$\text{Fraction condensed} = \frac{\dot{m}_{\text{condensed}}}{\dot{m}_{\text{total}}} = \frac{0.2689 \text{ kg/min}}{2.5 \text{ kg/min}} = \mathbf{0.108 \text{ (or 10.8\%)}}$$

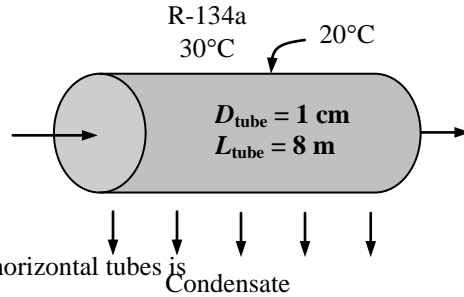
**Discussions** Note that we used the modified  $h_{fg}^*$  instead of just  $h_{fg}$  in heat transfer calculations to account for heat transfer due to the cooling of the condensate below the saturation temperature.

**10-58** Saturated refrigerant-134a vapor condenses inside a horizontal tube maintained at a uniform temperature. The fraction of the refrigerant that will condense at the end of the tube is to be determined.

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

**Properties** The properties of refrigerant-134a at the saturation temperature of  $30^\circ\text{C}$  are  $h_{fg} = 173.1 \times 10^3$  J/kg and  $\rho_v = 37.53$  kg/m<sup>3</sup>. The properties of liquid R-134a at the film temperature of  $T_f = (T_{\text{sat}} + T_s) / 2 = (30 + 20) / 2 = 25^\circ\text{C}$  are (Table A-10)

$$\begin{aligned}\rho_l &= 1207 \text{ kg/m}^3 \\ \mu_l &= 2.012 \times 10^{-4} \text{ kg/m}\cdot\text{s} \\ \nu_l &= \mu_l / \rho_l = 0.1667 \times 10^{-6} \text{ m}^2/\text{s} \\ C_{pl} &= 1427 \text{ J/kg}\cdot^\circ\text{C} \\ k_l &= 0.08325 \text{ W/m}\cdot^\circ\text{C}\end{aligned}$$



**Analysis** The heat transfer coefficient for condensation inside horizontal tubes is

$$\begin{aligned}h &= h_{\text{internal}} = 0.555 \left[ \frac{g\rho_l(\rho_l - \rho_v)k_l^3}{\mu_l(T_{\text{sat}} - T_s)} \left( h_{fg} + \frac{3}{8} C_{pl}(T_{\text{sat}} - T_s) \right) \right]^{1/4} \\ &= 0.555 \left[ \frac{(9.81 \text{ m/s}^2)(1207 \text{ kg/m}^3)(1207 - 37.53) \text{ kg/m}^3(0.08325 \text{ W/m}\cdot^\circ\text{C})^3}{(2.012 \times 10^{-4} \text{ kg/m}\cdot\text{s})(30 - 20)^\circ\text{C}} \right. \\ &\quad \left. \times \left( 173.1 \times 10^3 \text{ J/kg} + \frac{3}{8} (1427 \text{ J/kg}\cdot^\circ\text{C})(30 - 20)^\circ\text{C} \right) \right]^{1/4} \\ &= 509.2 \text{ W/m}^2 \cdot ^\circ\text{C}\end{aligned}$$

The heat transfer surface area of the pipe is

$$A_s = \pi DL = \pi(0.01 \text{ m})(8 \text{ m}) = 0.2513 \text{ m}^2$$

Then the rate of heat transfer during this condensation process becomes

$$\dot{Q} = hA_s(T_{\text{sat}} - T_s) = (509.2 \text{ W/m}^2 \cdot ^\circ\text{C})(0.2513 \text{ m}^2)(30 - 20)^\circ\text{C} = 1280 \text{ W}$$

The modified latent heat of vaporization in this case is, as indicated in the  $h$  relation,

$$h_{fg}^* = h_{fg} + \frac{3}{8} C_{pl}(T_{\text{sat}} - T_s) = 173.1 \times 10^3 \text{ J/kg} + \frac{3}{8} (1427 \text{ J/kg}\cdot^\circ\text{C})(30 - 20)^\circ\text{C} = 178.5 \times 10^3 \text{ J/kg}$$

Then the rate of condensation becomes

$$\dot{m}_{\text{condensation}} = \frac{\dot{Q}}{h_{fg}^*} = \frac{1280 \text{ J/s}}{178.5 \times 10^3 \text{ J/kg}} = 0.007169 \text{ kg/s} = 0.4301 \text{ kg/min}$$

Therefore, the fraction of the refrigerant that will condense at the end of the tube is

$$\text{Fraction condensed} = \frac{\dot{m}_{\text{condensed}}}{\dot{m}_{\text{total}}} = \frac{0.4301 \text{ kg/min}}{2.5 \text{ kg/min}} = \mathbf{0.172 \text{ (or 17.2\%)}}$$

10-59 "PROBLEM 10-59"

"GIVEN"

"T<sub>sat</sub>=30 [C], parameter to be varied"

L=5 "[m]"

D=0.01 "[m]"

T<sub>s</sub>=20 "[C]"

m<sub>dot</sub><sub>total</sub>=2.5 "[kg/min]"

"PROPERTIES"

rho<sub>l</sub>=1187 "[kg/m<sup>3</sup>]"

rho<sub>v</sub>=37.5 "[kg/m<sup>3</sup>]"

mu<sub>l</sub>=0.201E-3 "[kg/m-s]"

C<sub>l</sub>=1447 "[J/kg-C]"

k<sub>l</sub>=0.0796 "[W/m-C]"

h<sub>fg</sub>=173.3E3 "[J/kg]"

g=9.8 "[m/s<sup>2</sup>], gravitational acceleraton"

"ANALYSIS"

$h = 0.555 * ((g * \rho_l * (\rho_l - \rho_v) * k_l^3) / (\mu_l * (T_{sat} - T_s))) * (h_{fg} + 3/8 * C_l * (T_{sat} - T_s))^{0.25}$

$Q_{dot} = h * A * (T_{sat} - T_s)$

$A = \pi * D * L$

$m_{dot\_cond} = Q_{dot} / h_{fg} * \text{Convert}(\text{kg/s}, \text{kg/min})$

$f_{condensed} = m_{dot\_cond} / m_{dot\_total} * \text{Convert}(, \%)$

| T <sub>sat</sub> [C] | f <sub>condensed</sub> [%] |
|----------------------|----------------------------|
| 25                   | 6.293                      |
| 26.25                | 7.447                      |
| 27.5                 | 8.546                      |
| 28.75                | 9.603                      |
| 30                   | 10.62                      |
| 31.25                | 11.62                      |
| 32.5                 | 12.58                      |
| 33.75                | 13.53                      |
| 35                   | 14.45                      |
| 36.25                | 15.36                      |
| 37.5                 | 16.26                      |
| 38.75                | 17.14                      |
| 40                   | 18                         |
| 41.25                | 18.86                      |
| 42.5                 | 19.7                       |
| 43.75                | 20.53                      |
| 45                   | 21.36                      |
| 46.25                | 22.18                      |
| 47.5                 | 22.98                      |
| 48.75                | 23.78                      |
| 50                   | 24.58                      |



**Special Topic: Heat Pipes**

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**10-60C** A heat pipe is a simple device with no moving parts which can transfer large quantities of heat over fairly large distances essentially at a constant temperature without requiring any power input. A heat pipe is basically a sealed slender tube containing a wick structure lined on the inner surface and a small amount of fluid such as water at the saturated state. It is composed of three sections: the evaporator section at one end where heat is absorbed and the fluid is vaporized, a condenser section at the other end where the vapor is condensed and heat is rejected, and the adiabatic section in between where the vapor and the liquid phases of the fluid flow in opposite directions through the core and the wick, respectively, to complete the cycle with no significant heat transfer between the fluid and the surrounding medium.

**10-61C** The boiling and condensation processes are associated with extremely high heat transfer coefficients, and thus it is natural to expect the heat pipe to be an extremely effective heat transfer device since its operation is based on alternate boiling and condensation of the working fluid.

**10-62C** The non-condensable gases such as air degrade the performance of the heat pipe, and can destroy it in a short time.

**10-63C** The heat pipes with water as the working fluid are designed to remove heat at temperatures below the boiling temperature of water at atmospheric pressure (i.e., 100°C). Therefore, the pressure inside the heat pipe must be maintained below the atmospheric pressure to provide boiling at such temperatures.

**10-64C** Liquid motion in the wick depends on the dynamic balance between two opposing effects: the capillary pressure which pumps the liquid through the pores, and the internal resistance to flow due to the friction between the mesh surface and the liquid. Small pores increase the capillary action, but it also increases the friction force opposing the fluid motion. At optimum core size, the difference between the capillary force and the friction force is maximum.

**10-65C** The orientation of the heat pipe affects its performance. The performance of a heat pipe will be best when the capillary and gravity forces act in the same direction (evaporator end down), and it will be worst when these two forces act in opposite directions (evaporator end up).

**10-66C** The capillary pressure which creates the suction effect to draw the liquid forces the liquid in a heat pipe to move up against the gravity without a pump. For the heat pipes which work against the gravity, it is better to have fine wicks since the capillary pressure is inversely proportional to the effective capillary radius of the mesh.

**10-67C** The most important consideration in the design of a heat pipe is the compatibility of the materials used for the tube, wick and the fluid.

**10-68C** The major cause for the premature degradation of the performance of some heat pipes is contamination which occurs during the sealing of the ends of the heat pipe tube.

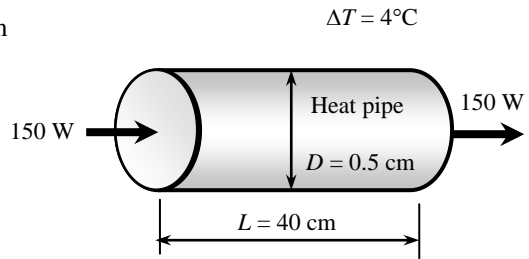
**10-69** A 40-cm long cylindrical heat pipe dissipates heat at a rate of 150 W. The diameter and mass of a 40-cm long copper rod that can conduct heat at the same rate are to be determined.

**Assumptions** Steady operating conditions exist.

**Properties** The properties of copper at room temperature are  $\rho = 8950 \text{ kg/m}^3$  and  $k = 386 \text{ W/m}\cdot^\circ\text{C}$ .

**Analysis** The rate of heat transfer through the copper rod can be expressed as

$$\dot{Q} = kA \frac{\Delta T}{L}$$



Solving for the cross-sectional area  $A$  and the diameter  $D$  gives

$$A = \frac{L}{k\Delta T} \dot{Q} = \frac{0.4 \text{ m}}{(386 \text{ W/m}\cdot^\circ\text{C})(4^\circ\text{C})} (150 \text{ W}) = 0.03886 \text{ m}^2 = 388.6 \text{ cm}^2$$

$$A = \frac{\pi D^2}{4} \longrightarrow D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(388.6 \text{ cm}^2)}{\pi}} = \mathbf{22.2 \text{ cm}}$$

The mass of this copper rod is

$$m = \rho V = \rho AL = (8950 \text{ kg/m}^3)(0.03886 \text{ m}^2)(0.4 \text{ m}) = \mathbf{139 \text{ kg}}$$

**10-70** A 40-cm long cylindrical heat pipe dissipates heat at a rate of 150 W. The diameter and mass of a 40-cm long copper rod that can conduct heat at the same rate are to be determined.

**Assumptions** Steady operating conditions exist.

**Properties** The properties of copper at room temperature are  $\rho = 2702 \text{ kg/m}^3$  and  $k = 237 \text{ W/m}\cdot^\circ\text{C}$ .

**Analysis** The rate of heat transfer through the aluminum rod can be expressed as

$$\dot{Q} = kA \frac{\Delta T}{L}$$

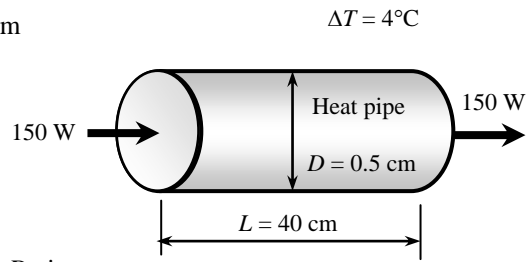
Solving for the cross-sectional area  $A$  and the diameter  $D$  gives

$$A = \frac{L}{k\Delta T} \dot{Q} = \frac{0.4 \text{ m}}{(237 \text{ W/m}\cdot^\circ\text{C})(4^\circ\text{C})} (150 \text{ W}) = 0.06329 \text{ m}^2 = 632.9 \text{ cm}^2$$

$$A = \frac{\pi D^2}{4} \longrightarrow D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(632.9 \text{ cm}^2)}{\pi}} = \mathbf{28.4 \text{ cm}}$$

The mass of this aluminum rod is

$$m = \rho V = \rho AL = (2702 \text{ kg/m}^3)(0.06329 \text{ m}^2)(0.4 \text{ m}) = \mathbf{68.4 \text{ kg}}$$



**10-71E** A plate that supports 10 power transistors is to be cooled with heat pipes. The number of pipes need to be attached to this plate is to be determined.

**Assumptions** Steady operating conditions exist.

**Analysis** The heat removal rate of heat pipes that have an outside diameter of 0.635 cm and length of 30.5 cm is given in Table 10-5 to be 175 W. The total rate of heat dissipated by 10 transistors each dissipating 35 W is

$$\dot{Q}_{total} = (10)(35 \text{ W}) = 350 \text{ W}$$

Then the number of heat pipes need to be attached to the plate becomes

$$n = \frac{\dot{Q}_{total}}{\dot{Q}} = \frac{350 \text{ W}}{175 \text{ W}} = \mathbf{2}$$

