14-18 Heat generated by the electrical resistance of a bare cable is dissipated to the surrounding air. The surface temperature of the cable is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Air is an ideal gas with constant properties. **3** The local atmospheric pressure is 1 atm. **4** The temperature of the surface of the cable is constant.

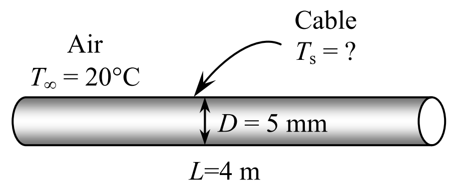
Properties We assume the surface temperature to be 100°C. Then the properties of air at 1 atm and the film temperature of $(T_s+T_\infty)/2 = (100+20)/2 = 60°C$ are (Table A-22)

$$k = 0.02808 \text{ W/m.°C}$$

$$\nu = 1.896\times10^{-5} \text{ m}^2\text{/s}$$

$$\Pr = 0.7202$$

$$\beta = \frac{1}{T_f} = \frac{1}{(60+273)\text{K}} = 0.003003 \text{ K}^{-1}$$



Analysis The characteristic length in this case is the outer diameter of the pipe, $L_c = D = 0.005$ m. Then,

$$Ra = \frac{g\beta(T_s - T_\infty)D^3}{\nu^2}\Pr = \frac{(9.81 \text{ m/s}^2)(0.003003 \text{ K}^{-1})(100-20 \text{ K})(0.005 \text{ m})^3}{(1.896\times10^{-5} \text{ m}^2\text{/s})^2}(0.7202) = 590.2$$

$$Nu = \left\{0.6 + \frac{0.387Ra^{1/6}}{\left[1+\left(0.559/\Pr\right)^{9/16}\right]^{8/27}}\right\}^2 = \left\{0.6 + \frac{0.387(590.2)^{1/6}}{\left[1+\left(0.559/0.7202\right)^{9/16}\right]^{8/27}}\right\}^2 = 2.346$$

$$h = \frac{k}{D}Nu = \frac{0.02808 \text{ W/m.°C}}{0.005 \text{ m}}(2.346) = 13.17 \text{ W/m}^2\text{.°C}$$

$$A_s = \pi DL = \pi(0.005 \text{ m})(4 \text{ m}) = 0.06283 \text{ m}^2$$

$$\dot{Q} = hA_s(T_s - T_\infty)$$

$$(60 \text{ V})(1.5 \text{ A}) = (13.17 \text{ W/m}^2\text{.°C})(0.06283 \text{ m}^2)(T_s - 20)\text{°C}$$

$$T_s = 128.8\text{°C}$$

which is not close to the assumed value of 100°C. Repeating calculations for an assumed surface temperature of 120°C, $[T_f = (T_s+T_\infty)/2 = (120+20)/2 = 70°C]$

$$k = 0.02881 \text{ W/m.°C}$$

$$\nu = 1.995\times10^{-5} \text{ m}^2\text{/s}$$

$$\Pr = 0.7177$$

$$\beta = \frac{1}{T_f} = \frac{1}{(70+273)\text{K}} = 0.002915 \text{ K}^{-1}$$

$$Ra = \frac{g\beta(T_s - T_\infty)D^3}{\nu^2}\Pr = \frac{(9.81 \text{ m/s}^2)(0.002915 \text{ K}^{-1})(120-20 \text{ K})(0.005 \text{ m})^3}{(1.995\times10^{-5} \text{ m}^2\text{/s})^2}(0.7177) = 644.6$$

$$Nu = \left\{0.6 + \frac{0.387Ra^{1/6}}{\left[1+\left(0.559/\Pr\right)^{9/16}\right]^{8/27}}\right\}^2 = \left\{0.6 + \frac{0.387(644.6)^{1/6}}{\left[1+\left(0.559/0.7177\right)^{9/16}\right]^{8/27}}\right\}^2 = 2.387$$

$$h = \frac{k}{D}Nu = \frac{0.02881 \text{ W/m.°C}}{0.005 \text{ m}}(2.387) = 13.76 \text{ W/m}^2\text{.°C}$$

$$\dot{Q} = hA_s(T_s - T_\infty)$$

$$(60 \text{ V})(1.5A) = (13.76 \text{ W/m}^2\text{.°C})(0.06283 \text{ m}^2)(T_s - 20)\text{°C}$$

$$T_s = \mathbf{124.1°C}$$

which is sufficiently close to the assumed value of 120°C.

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14-24 A cylindrical resistance heater is placed horizontally in a fluid. The outer surface temperature of the resistance wire is to be determined for two different fluids.

Assumptions **1** Steady operating conditions exist. **2** Air is an ideal gas with constant properties. **3** The local atmospheric pressure is 1 atm. **4** Any heat transfer by radiation is ignored. **5** Properties are evaluated at 500°C for air and 40°C for water.

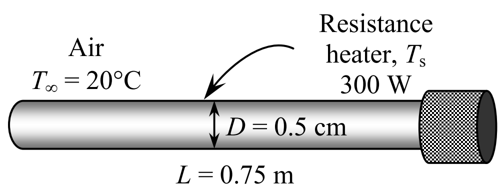
Properties The properties of air at 1 atm and 500°C are (Table A-22)

$$k = 0.05572 \text{ W/m.°C}$$

$$\nu = 7.804 \times 10^{-5} \text{ m}^2/\text{s}$$

$$\text{Pr} = 0.6986,$$

$$\beta = \frac{1}{T_f} = \frac{1}{(500+273)\text{K}} = 0.001294 \text{ K}^{-1}$$



The properties of water at 40°C are (Table A-15)

$$k = 0.631 \text{ W/m.°C}, \quad \nu = \mu / \rho = 0.6582 \times 10^{-6} \text{ m}^2/\text{s}$$

$$\text{Pr} = 4.32, \quad \beta = 0.000377 \text{ K}^{-1}$$

Analysis (*a*) The solution of this problem requires a trial-and-error approach since the determination of the Rayleigh number and thus the Nusselt number depends on the surface temperature which is unknown. We start the solution process by "guessing" the surface temperature to be 1200°C for the calculation of *h*. We will check the accuracy of this guess later and repeat the calculations if necessary. The characteristic length in this case is the outer diameter of the wire, $L_c = D = 0.005$ m. Then,

$$Ra = \frac{g\beta(T_s - T_\infty)D^3}{\nu^2}\text{Pr} = \frac{(9.81 \text{ m/s}^2)(0.001294 \text{ K}^{-1})(1200-20)\text{°C}(0.005 \text{ m})^3}{(7.804 \times 10^{-5} \text{ m}^2/\text{s})^2}(0.6986) = 214.7$$

$$Nu = \left\{0.6 + \frac{0.387 Ra^{1/6}}{\left[1 + (0.559/\text{Pr})^{9/16}\right]^{8/27}}\right\}^2 = \left\{0.6 + \frac{0.387(214.7)^{1/6}}{\left[1 + (0.559/0.6986)^{9/16}\right]^{8/27}}\right\}^2 = 1.919$$

$$h = \frac{k}{D}Nu = \frac{0.05572 \text{ W/m.°C}}{0.005 \text{ m}}(1.919) = 21.38 \text{ W/m}^2\text{.°C}$$

$$A_s = \pi D L = \pi(0.005 \text{ m})(0.75 \text{ m}) = 0.01178 \text{ m}^2$$

and

$$\dot{Q} = hA_s(T_s - T_\infty) \rightarrow 300 \text{ W} = (21.38 \text{ W/m}^2\text{.°C})(0.01178 \text{ m}^2)(T_s - 20)\text{°C} \rightarrow T_s = \mathbf{1211°C}$$

which is sufficiently close to the assumed value of 1200°C used in the evaluation of *h*, and thus it is not necessary to repeat calculations.

(*b*) For the case of water, we "guess" the surface temperature to be 40°C. The characteristic length in this case is the outer diameter of the wire, $L_c = D = 0.005$ m. Then,

$$Ra = \frac{g\beta(T_s - T_\infty)D^3}{\nu^2}\text{Pr} = \frac{(9.81 \text{ m/s}^2)(0.000377 \text{ K}^{-1})(40-20 \text{ K})(0.005 \text{ m})^3}{(0.6582 \times 10^{-6} \text{ m}^2/\text{s})^2}(4.32) = 92{,}197$$

$$Nu = \left\{0.6 + \frac{0.387 Ra^{1/6}}{\left[1 + (0.559/\text{Pr})^{9/16}\right]^{8/27}}\right\}^2 = \left\{0.6 + \frac{0.387(92{,}197)^{1/6}}{\left[1 + (0.559/4.32)^{9/16}\right]^{8/27}}\right\}^2 = 8.986$$

$$h = \frac{k}{D}Nu = \frac{0.631 \text{ W/m.°C}}{0.005 \text{ m}}(8.986) = 1134 \text{ W/m}^2\text{.°C}$$

and $\dot{Q} = hA_s(T_s - T_\infty) \longrightarrow 300 \text{ W} = (1134 \text{ W/m}^2\text{.°C})(0.01178 \text{ m}^2)(T_s - 20)\text{°C} \longrightarrow T_s = \mathbf{42.5°C}$

which is sufficiently close to the assumed value of 40°C in the evaluation of the properties and *h*. The film temperature in this case is $(T_s + T_\infty)/2 = (42.5+20)/2 = 31.3$°C, which is close to the value of 40°C used in the evaluation of the properties.

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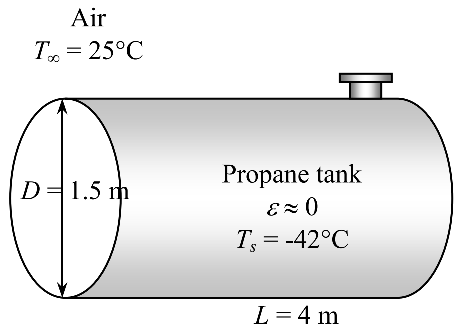
14-45 A cylindrical propane tank is exposed to calm ambient air. The propane is slowly vaporized due to a crack developed at the top of the tank. The time it will take for the tank to empty is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Air is an ideal gas with constant properties. **3** The local atmospheric pressure is 1 atm. **4** Radiation heat transfer is negligible.



Properties The properties of air at 1 atm and the film temperature of $(T_s+T_\infty)/2 = (-42+25)/2 = -8.5°C$ are (Table A-22)

$$k = 0.02299 \text{ W/m.°C}$$
$$\nu = 1.265\times10^{-5} \text{ m}^2\text{/s}$$
$$\text{Pr} = 0.7383$$
$$\beta = \frac{1}{T_f} = \frac{1}{(-8.5+273)\text{K}} = 0.003781 \text{ K}^{-1}$$

Analysis The tank gains heat through its cylindrical surface as well as its circular end surfaces. For convenience, we take the heat transfer coefficient at the end surfaces of the tank to be the same as that of its side surface. (The alternative is to treat the end surfaces as a vertical plate, but this will double the amount of calculations without providing much improvement in accuracy since the area of the end surfaces is much smaller and it is circular in shape rather than being rectangular). The characteristic length in this case is the outer diameter of the tank, $L_c = D = 1.5$ m. Then,

$$Ra = \frac{g\beta(T_\infty - T_s)D^3}{\nu^2}\text{Pr} = \frac{(9.81 \text{ m/s}^2)(0.003781 \text{ K}^{-1})[(25-(-42) \text{ K}](1.5 \text{ m})^3}{(1.265\times10^{-5} \text{ m}^2\text{/s})^2}(0.7383) = 3.869\times10^{10}$$

$$Nu = \left\{0.6 + \frac{0.387Ra^{1/6}}{\left[1+(0.559/\text{Pr})^{9/16}\right]^{8/27}}\right\}^2 = \left\{0.6 + \frac{0.387(3.869\times10^{10})^{1/6}}{\left[1+(0.559/0.7383)^{9/16}\right]^{8/27}}\right\}^2 = 374.1$$

$$h = \frac{k}{D}Nu = \frac{0.02299 \text{ W/m.°C}}{1.5 \text{ m}}(374.1) = 5.733 \text{ W/m}^2\text{.°C}$$
$$A_s = \pi DL + 2\pi D^2/4 = \pi(1.5 \text{ m})(4 \text{ m}) + 2\pi(1.5 \text{ m})^2/4 = 22.38 \text{ m}^2$$

and

$$\dot{Q} = hA_s(T_\infty - T_s) = (5.733 \text{ W/m}^2\text{.°C})(22.38 \text{ m}^2)[(25-(-42)]°C = 8598 \text{ W}$$

The total mass and the rate of evaporation of propane are

$$m = \rho \mathbf{V} = \rho\frac{\pi D^2}{4}L = (581 \text{ kg/m}^3)\frac{\pi(1.5 \text{ m})^2}{4}(4 \text{ m}) = 4107 \text{ kg}$$
$$\dot{m} = \frac{\dot{Q}}{h_{fg}} = \frac{8.598 \text{ kJ/s}}{425 \text{ kJ/kg}} = 0.02023 \text{ kg/s}$$

and it will take

$$\Delta t = \frac{m}{\dot{m}} = \frac{4107 \text{ kg}}{0.02023 \text{ kg/s}} = 202{,}996 \text{ s} = \mathbf{56.4 \text{ hours}}$$

for the propane tank to empty.

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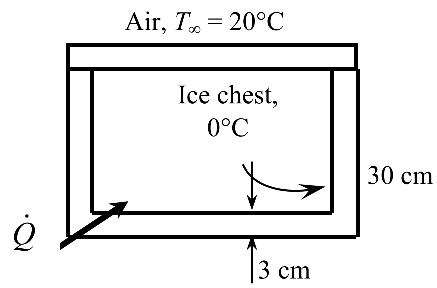
14-82 An ice chest filled with ice at 0°C is exposed to ambient air. The time it will take for the ice in the chest to melt completely is to be determined for natural and forced convection cases.

Assumptions **1** Steady operating conditions exist. **2** Air is an ideal gas with constant properties. **3** Heat transfer from the base of the ice chest is disregarded. **4** Radiation effects are negligible. **5** Heat transfer coefficient is the same for all surfaces considered. **6** The local atmospheric pressure is 1 atm.

Properties The properties of air at 1 atm and the anticipated film temperature of $(T_s+T_\infty)/2 = (15+20)/2 = 17.5°C$ are (Table A-22)

$$k = 0.02495 \text{ W/m.°C}$$
$$\nu = 1.493\times10^{-5} \text{ m}^2/\text{s}$$
$$\Pr = 0.7316$$
$$\beta = \frac{1}{T_f} = \frac{1}{(17.5+273)\text{K}} = 0.003442 \text{ K}^{-1}$$



Analysis The solution of this problem requires a trial-and-error approach since the determination of the Rayleigh number and thus the Nusselt number depends on the surface temperature which is unknown. We start the solution process by "guessing" the surface temperature to be 15°C for the evaluation of the properties and h. We will check the accuracy of this guess later and repeat the calculations if necessary. The characteristic length for the side surfaces is the height of the chest, $L_c = L = 0.3$ m Then,

$$Ra = \frac{g\beta(T_\infty - T_s)L^3}{\nu^2}\Pr = \frac{(9.81 \text{ m/s}^2)(0.003442 \text{ K}^{-1})(20-15 \text{ K})(0.3 \text{ m})^3}{(1.493\times10^{-5} \text{ m}^2/\text{s})^2}(0.7316) = 1.495\times10^7$$

$$Nu = \left\{0.825 + \frac{0.387\text{Ra}^{1/6}}{\left[1+\left(\frac{0.492}{\Pr}\right)^{9/16}\right]^{8/27}}\right\}^2 = \left\{0.825 + \frac{0.387(1.495\times10^7)^{1/6}}{\left[1+\left(\frac{0.492}{0.7316}\right)^{9/16}\right]^{8/27}}\right\}^2 = 35.15$$

$$h = \frac{k}{L}Nu = \frac{0.02495 \text{ W/m.°C}}{0.3 \text{ m}}(35.15) = 2.923 \text{ W/m}^2\text{.°C}$$

The heat transfer coefficient at the top surface can be determined similarly. However, the top surface constitutes only about one-fourth of the heat transfer area, and thus we can use the heat transfer coefficient for the side surfaces for the top surface also for simplicity. The heat transfer surface area is

$$A_s = 4(0.3 \text{ m})(0.4 \text{ m}) + (0.4 \text{ m})(0.4 \text{ m}) = 0.64 \text{ m}^2$$

Then the rate of heat transfer becomes

$$\dot{Q} = \frac{T_\infty - T_{s,i}}{R_{wall} + R_{conv,o}} = \frac{T_\infty - T_{s,i}}{\frac{L}{kA_s} + \frac{1}{hA_s}} = \frac{(20-0)°\text{C}}{\frac{0.03 \text{ m}}{(0.033 \text{ W/m.°C})(0.64 \text{ m}^2)} + \frac{1}{(2.923 \text{ W/m}^2\text{.°C})(0.64 \text{ m}^2)}} = 10.23 \text{ W}$$

The outer surface temperature of the ice chest is determined from Newton's law of cooling to be

$$\dot{Q} = hA_s(T_\infty - T_s) \rightarrow T_s = T_\infty - \frac{\dot{Q}}{hA_s} = 20°\text{C} - \frac{10.23 \text{ W}}{(2.923 \text{ W/m}^2\text{.C})(0.64 \text{ m}^2)} = 14.53°\text{C}$$

which is almost identical to the assumed value of 15°C used in the evaluation of properties and h. Therefore, there is no need to repeat the calculations.

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The rate at which the ice will melt is

$$\dot{Q} = \dot{m}h_{if} \rightarrow \dot{m} = \frac{\dot{Q}}{h_{if}} = \frac{10.23\times10^{-3}\ \text{kJ/s}}{333.7\ \text{kJ/kg}} = 3.066\times10^{-5}\ \text{kg/s}$$

Therefore, the melting of the ice in the chest completely will take

$$m = \dot{m}\Delta t \longrightarrow \Delta t = \frac{m}{\dot{m}} = \frac{30\ \text{kg}}{3.066\times10^{-5}\ \text{kg/s}} = 9.786\times10^{5}\ \text{s} = \mathbf{271.8\ h} = \mathbf{11.3\ days}$$

(b) The temperature drop across the styrofoam will be much greater in this case than that across thermal boundary layer on the surface. Thus we assume outer surface temperature of the styrofoam to be $19\,^\circ\text{C}$. Radiation heat transfer will be neglected. The properties of air at 1 atm and the film temperature of $(T_s+T_\infty)/2 = (19+20)/2 = 19.5°\text{C}$ are (Table A-22)

$$k = 0.0251\ \text{W/m.°C}$$
$$\nu = 1.511\times10^{-5}\ \text{m}^2/\text{s}$$
$$\text{Pr} = 0.7310$$
$$\beta = \frac{1}{T_f} = \frac{1}{(19.5+273)\text{K}} = 0.00342\ \text{K}^{-1}$$

The characteristic length in this case is the width of the chest, $L_c = W$ =0.4 m. Then,

$$\text{Re} = \frac{VW}{\nu} = \frac{(50\times1000/3600\ \text{m/s})(0.4\ \text{m})}{1.511\times10^{-5}\ \text{m}^2/\text{s}} = 367{,}700$$

which is less than critical Reynolds number (5×10^5). Therefore the flow is laminar, and the Nusselt number is determined from

$$Nu = \frac{hW}{k} = 0.664\,\text{Re}^{0.5}\ \text{Pr}^{1/3} = 0.664(367{,}700)^{0.5}(0.7310)^{1/3} = 362.7$$

$$h = \frac{k}{W}Nu = \frac{0.0251\ \text{W/m.°C}}{0.4\ \text{m}}(362.7) = 22.76\ \text{W/m}^2.\text{°C}$$

Then the rate of heat transfer becomes

$$\dot{Q} = \frac{T_\infty - T_{s,i}}{R_{wall} + R_{conv,o}} = \frac{T_\infty - T_{s,i}}{\frac{L}{kA_s} + \frac{1}{hA_s}} = \frac{(20-0)°\text{C}}{\frac{0.03\ \text{m}}{(0.033\ \text{W/m.°C})(0.64\ \text{m}^2)} + \frac{1}{(22.76\ \text{W/m}^2.\text{°C})(0.64\ \text{m}^2)}} = 13.43\ \text{W}$$

The outer surface temperature of the ice chest is determined from Newton's law of cooling to be

$$\dot{Q} = hA_s(T_\infty - T_s) \rightarrow T_s = T_\infty - \frac{\dot{Q}}{hA_s} = 20°\text{C} - \frac{13.43\ \text{W}}{(22.76\ \text{W/m}^2.\text{C})(0.64\ \text{m}^2)} = 19.1°\text{C}$$

which is almost identical to the assumed value of 19°C used in the evaluation of properties and h. Therefore, there is no need to repeat the calculations. Then the rate at which the ice will melt becomes

$$\dot{Q} = \dot{m}h_{if} \rightarrow \dot{m} = \frac{\dot{Q}}{h_{if}} = \frac{13.43\times10^{-3}\ \text{kJ/s}}{333.7\ \text{kJ/kg}} = 4.025\times10^{-5}\ \text{kg/s}$$

Therefore, the melting of the ice in the chest completely will take

$$m = \dot{m}\Delta t \longrightarrow \Delta t = \frac{m}{\dot{m}} = \frac{30}{4.025\times10^{-5}} = 7.454\times10^{5}\ \text{s} = \mathbf{207.05\ h} = \mathbf{8.6\ days}$$

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