mae 3309 – 002 THERMAL ENGINEERING
Solutions to HW # 7

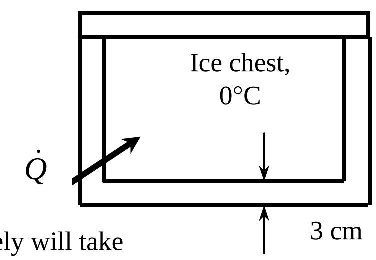
9-42 A styrofoam ice chest is initially filled with 40 kg of ice at 0°C. The time it takes for the ice in the chest to melt completely is to be determined.

Assumptions **1** Steady operating conditions exist. **2** The inner and outer surface temperatures of the ice chest remain constant at 0°C and 8°C, respectively, at all times. **3** Thermal properties of the chest are constant. **4** Heat transfer from the base of the ice chest is negligible.

Properties The thermal conductivity of the styrofoam is given to be k = 0.033 W/m·°C. The heat of fusion of ice at 0°C is 333.7 kJ/kg.

Analysis Disregarding any heat loss through the bottom of the ice chest and using the average thicknesses, the total heat transfer area becomes

$$A = (40-3)(40-3) + 4\times(40-3)(30-3) = 5365\ \text{cm}^2 = 0.5365\ \text{m}^2$$



The rate of heat transfer to the ice chest becomes

$$\dot{Q} = kA\frac{\Delta T}{L} = (0.033\ \text{W/m}\cdot°\text{C})(0.5365\ \text{m}^2)\frac{(8-0)°\text{C}}{0.03\ \text{m}} = 4.72\ \text{W}$$

The total amount of heat needed to melt the ice completely is

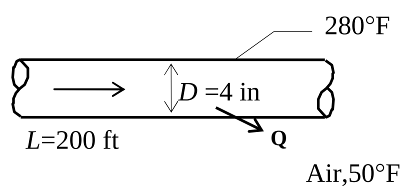
$$Q = mh_{if} = (28\ \text{kg})(333.7\ \text{kJ/kg}) = 9344\ \text{kJ}$$

Then transferring this much heat to the cooler to melt the ice completely will take

$$\Delta t = \frac{Q}{\dot{Q}} = \frac{9344{,}000\ \text{J}}{4.72\ \text{J/s}} = 1.98\times10^6\ \text{s} = \mathbf{22.9\ days}$$

9-45E A 200-ft long section of a steam pipe passes through an open space at a specified temperature. The rate of heat loss from the steam pipe and the annual cost of this energy lost are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Heat transfer by radiation is disregarded. **3** The convection heat transfer coefficient is constant and uniform over the surface.



Analysis (*a*) The rate of heat loss from the steam pipe is

$$A_s = \pi DL = \pi(4/12\ \text{ft})(200\ \text{ft}) = 209.4\ \text{ft}^2$$

$$\dot{Q}_{\text{pipe}} = hA_s(T_s - T_{\text{air}}) = (6\ \text{Btu/h}\cdot\text{ft}^2\cdot°\text{F})(209.4\ \text{ft}^2)(280-50)°\text{F}$$
$$= \mathbf{289{,}000\ Btu/h}$$

(*b*) The amount of heat loss per year is

$$Q = \dot{Q}\Delta t = (289{,}000\ \text{Btu/h})(365\times24\ \text{h/yr}) = 2.531\times10^9\ \text{Btu/yr}$$

The amount of gas consumption per year in the furnace that has an efficiency of 86% is

$$\text{Annual Energy Loss} = \frac{2.531\times10^9\ \text{Btu/yr}}{0.86}\left(\frac{1\ \text{therm}}{100{,}000\ \text{Btu}}\right) = 29{,}435\ \text{therms/yr}$$

Then the annual cost of the energy lost becomes

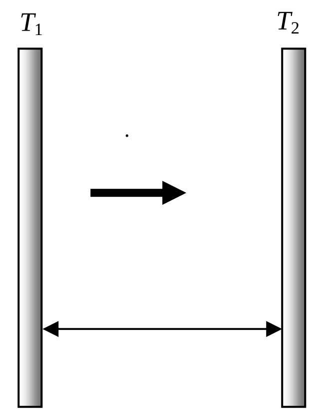
$$\text{Energy cost} = (\text{Annual energy loss})(\text{Unit cost of energy})$$
$$= (29{,}435\ \text{therms/yr})(\$1.10/\text{therm}) = \mathbf{\$32{,}380/yr}$$

9-61 Two large plates at specified temperatures are held parallel to each other. The rate of heat transfer between the plates is to be determined for the cases of still air, evacuation, regular insulation, and super insulation between the plates.

Assumptions **1** Steady operating conditions exist since the plate temperatures remain constant. **2** Heat transfer is one-dimensional since the plates are large. **3** The surfaces are black and thus ε = 1. **4** There are no convection currents in the air space between the plates.

Properties The thermal conductivities are k = 0.00015 W/m·°C for super insulation, k = 0.01979 W/m·°C at -50°C (Table A-22) for air, and k = 0.036 W/m·°C for fiberglass insulation.

Analysis (*a*) Disregarding any natural convection currents, the rates of conduction and radiation heat transfer



$$\dot{Q}_{\text{cond}} = kA\frac{T_1 - T_2}{L} = (0.01979 \text{ W/m}^2 \cdot °\text{C})(1 \text{ m}^2)\frac{(290-150) \text{ K}}{0.02 \text{ m}} = 139 \text{ W}$$

$$\dot{Q}_{\text{rad}} = \varepsilon\sigma A_s (T_1{}^4 - T_2{}^4)$$
$$= 1(5.67\times10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1\text{m}^2)\left[(290 \text{ K})^4 - (150 \text{ K})^4\right] = 372 \text{ W}$$

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{cond}} + \dot{Q}_{\text{rad}} = 139 + 372 = \mathbf{511\ W}$$

(*b*) When the air space between the plates is evacuated, there will be radiation heat transfer only. Therefore,

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{rad}} = \mathbf{372\ W}$$

(*c*) In this case there will be conduction heat transfer through the fiberglass insulation only,

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{cond}} = kA\frac{T_1 - T_2}{L} = (0.036 \text{ W/m}\cdot{}^\text{o}\text{ C})(1 \text{ m}^2)\frac{(290-150) \text{ K}}{0.02 \text{ m}} = \mathbf{252\ W}$$

(*d*) In the case of superinsulation, the rate of heat transfer will be

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{cond}} = kA\frac{T_1 - T_2}{L} = (0.00015 \text{ W/m}\cdot°\text{C})(1 \text{ m}^2)\frac{(290-150) \text{ K}}{0.02 \text{ m}} = \mathbf{1.05\ W}$$

Discussion Note that superinsulators are very effective in reducing heat transfer between to surfaces.

9-77 The glass cover of a flat plate solar collector with specified inner and outer surface temperatures is considered. The fraction of heat lost from the glass cover by radiation is to be determined.

Assumptions **1** Steady operating conditions exist since the surface temperatures of the glass remain constant at the specified values. **2** Thermal properties of the glass are constant.

Properties The thermal conductivity of the glass is given to be k = 0.7 W/m·°C.

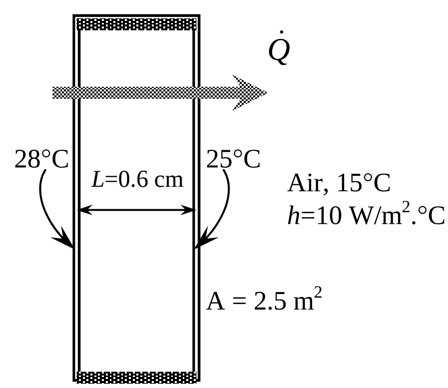
Analysis Under steady conditions, the rate of heat transfer through the glass by conduction is

$$\dot{Q}_{\text{cond}} = kA\frac{\Delta T}{L} = (0.7 \text{ W/m}\cdot°\text{C})(2.5 \text{ m}^2)\frac{(28-25)°\text{C}}{0.006 \text{ m}} = 875 \text{ W}$$

The rate of heat transfer from the glass by convection is

$$\dot{Q}_{\text{conv}} = hA\Delta T = (10 \text{ W/m}^2 \cdot °\text{C})(2.5 \text{ m}^2)(25-15)°\text{C} = 250 \text{ W}$$

Under steady conditions, the heat transferred through the cover by conduction should be transferred from the outer surface by convection and radiation. That is,



$$\dot{Q}_{\text{rad}} = \dot{Q}_{\text{cond}} - \dot{Q}_{\text{conv}} = 875 - 250 = 625 \text{ W}$$

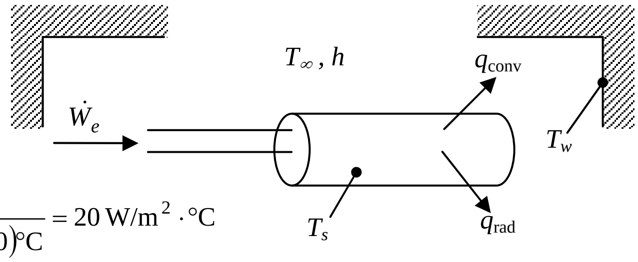
Then the fraction of heat transferred by radiation becomes

$$f = \frac{\dot{Q}_{\text{rad}}}{\dot{Q}_{\text{cond}}} = \frac{625}{875} = \mathbf{0.714} \quad \text{(or 71.4\%)}$$

9-82 An electric heater placed in a room consumes 500 W power when its surfaces are at 120°C. The surface temperature when the heater consumes 700 W is to be determined without and with the consideration of radiation.

Assumptions **1** Steady operating conditions exist. **2** The temperature is uniform over the surface.

Analysis (*a*) Neglecting radiation, the convection heat transfer coefficient is determined from



$$h = \frac{\dot{Q}}{A(T_s - T_\infty)} = \frac{500\text{ W}}{(0.25\text{ m}^2)(120-20)°\text{C}} = 20\text{ W/m}^2\cdot°\text{C}$$

The surface temperature when the heater consumes 700 W is

$$T_s = T_\infty + \frac{\dot{Q}}{hA} = 20°\text{C} + \frac{700\text{ W}}{(20\text{ W/m}^2\cdot°\text{C})(0.25\text{ m}^2)} = \mathbf{160°C}$$

(*b*) Considering radiation, the convection heat transfer coefficient is determined from

$$h = \frac{\dot{Q} - \varepsilon A\sigma(T_s^4 - T_{\text{surr}}^4)}{A(T_s - T_\infty)}$$

$$= \frac{500\text{ W - }(0.75)(0.25\text{ m}^2)(5.67\times10^{-8}\text{ W/m}^2\cdot\text{K}^4)\left[(393\text{ K})^4 - (283\text{ K})^4\right]}{(0.25\text{ m}^2)(120-20)°\text{C}} = 12.58\text{ W/m}^2\cdot°\text{C}$$

Then the surface temperature becomes

$$\dot{Q} = hA(T_s - T_\infty) + \varepsilon A\sigma(T_s^4 - T_{\text{surr}}^4)$$

$$700 = (12.58)(0.25)(T_s - 293) + (0.75)(0.25)(5.67\times10^{-8})\left[T_s^4 - (283\text{ K})^4\right]$$

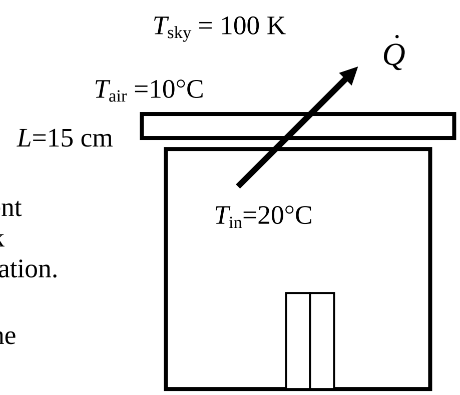
$$T_s = 425.9\text{ K} = \mathbf{152.9°C}$$

Discussion Neglecting radiation changed T_s by more than 7°C, so assumption is not correct in this case.

10-30 The roof of a house with a gas furnace consists of a concrete that is losing heat to the outdoors by radiation and convection. The rate of heat transfer through the roof and the money lost through the roof that night during a 14 hour period are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The emissivity and thermal conductivity of the roof are constant.

Properties The thermal conductivity of the concrete is given to be k = 2 W/m·°C. The emissivity of both surfaces of the roof is given to be 0.9.



Analysis When the surrounding surface temperature is different than the ambient temperature, the thermal resistances network approach becomes cumbersome in problems that involve radiation. Therefore, we will use a different but intuitive approach.

In steady operation, heat transfer from the room to the roof (by convection and radiation) must be equal to the heat transfer from the roof to the surroundings (by convection and radiation), that must be equal to the heat transfer through the roof by conduction. That is,

$$\dot{Q} = \dot{Q}_{\text{room to roof, conv+rad}} = \dot{Q}_{\text{roof, cond}} = \dot{Q}_{\text{roof to surroundings, conv+rad}}$$

Taking the inner and outer surface temperatures of the roof to be $T_{s,in}$ and $T_{s,out}$, respectively, the quantities above can be expressed as

$$\dot{Q}_{\text{room to roof, conv+rad}} = h_i A(T_{room} - T_{s,in}) + \varepsilon A\sigma(T_{room}{}^4 - T_{s,in}{}^4) = (5\text{ W/m}^2\cdot°\text{C})(300\text{ m}^2)(20 - T_{s,in})°\text{C}$$
$$+ (0.9)(300\text{ m}^2)(5.67\times10^{-8}\text{ W/m}^2\cdot\text{K}^4)\left[(20+273\text{ K})^4 - (T_{s,in}+273\text{ K})^4\right]$$

$$\dot{Q}_{\text{roof, cond}} = kA\frac{T_{s,in} - T_{s,out}}{L} = (2\text{ W/m}\cdot°\text{C})(300\text{ m}^2)\frac{T_{s,in} - T_{s,out}}{0.15\text{ m}}$$

$$\dot{Q}_{\text{roof to surr, conv+rad}} = h_o A(T_{s,out} - T_{surr}) + \varepsilon A\sigma(T_{s,out}{}^4 - T_{surr}{}^4) = (12\text{ W/m}^2\cdot°\text{C})(300\text{ m}^2)(T_{s,out} - 10)°\text{C}$$
$$+ (0.9)(300\text{ m}^2)(5.67\times10^{-8}\text{ W/m}^2\cdot\text{K}^4)\left[(T_{s,out} + 273\text{ K})^4 - (100\text{ K})^4\right]$$

Solving the equations above simultaneously gives

$$\dot{Q} = \mathbf{37{,}440\ W},\ T_{s,in} = \mathbf{7.3°C},\text{ and } T_{s,\text{out}} = -2.1°\text{C}$$

The total amount of natural gas consumption during a 14-hour period is

$$Q_{gas} = \frac{Q_{total}}{0.80} = \frac{\dot{Q}\Delta t}{0.80} = \frac{(37.440\text{ kJ/s})(14\times3600\text{ s})}{0.80}\left(\frac{1\text{ therm}}{105{,}500\text{ kJ}}\right) = 22.36\text{ therms}$$

Finally, the money lost through the roof during that period is

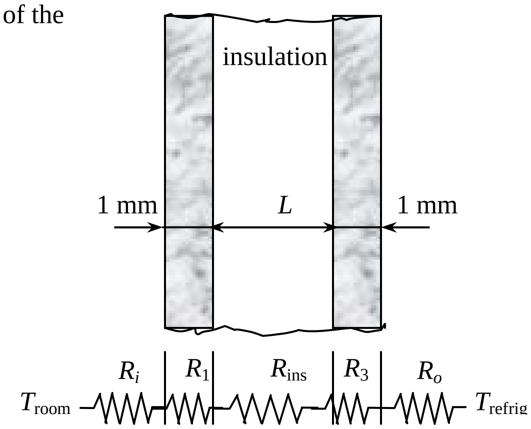
$$\text{Money lost} = (22.36\text{ therms})(\$1.20/\text{therm}) = \mathbf{\$26.8}$$

10-36 The wall of a refrigerator is constructed of fiberglass insulation sandwiched between two layers of sheet metal. The minimum thickness of insulation that needs to be used in the wall in order to avoid condensation on the outer surfaces is to be determined.

Assumptions **1** Heat transfer through the refrigerator walls is steady since the temperatures of the food compartment and the kitchen air remain constant at the specified values. **2** Heat transfer is one-dimensional. **3** Thermal conductivities are constant. **4** Heat transfer coefficients account for the radiation effects.

Properties The thermal conductivities are given to be k = 15.1 W/m·°C for sheet metal and 0.035 W/m·°C for fiberglass insulation.

Analysis The minimum thickness of insulation can be determined by assuming the outer surface temperature of the refrigerator to be 20°C. In steady operation, the rate of heat transfer through the refrigerator wall is constant, and thus heat transfer between the room and the refrigerated space is equal to the heat transfer between the room and the outer surface of the refrigerator. Considering a unit surface area,



$$\dot{Q} = h_o A(T_{room} - T_{s,out})$$
$$= (9\text{ W/m}^2\cdot°\text{C})(1\text{ m}^2)(25-20)°\text{C} = 45\text{ W}$$

Using the thermal resistance network, heat transfer between the room and the refrigerated space can be expressed as

$$\dot{Q} = \frac{T_{room} - T_{refrig}}{R_{total}}$$

$$\dot{Q}/A = \frac{T_{room} - T_{refrig}}{\frac{1}{h_o} + 2\left(\frac{L}{k}\right)_{metal} + \left(\frac{L}{k}\right)_{insulation} + \frac{1}{h_i}}$$

Substituting,

$$45\text{ W/m}^2 = \frac{(25-3)°\text{C}}{\frac{1}{9\text{ W/m}^2\cdot°\text{C}} + \frac{2\times0.001\text{ m}}{15.1\text{ W/m}^2\cdot°\text{C}} + \frac{L}{0.035\text{ W/m}^2\cdot°\text{C}} + \frac{1}{4\text{ W/m}^2\cdot°\text{C}}}$$

Solv ing for L, the minimum thickness of insulation is determined to be

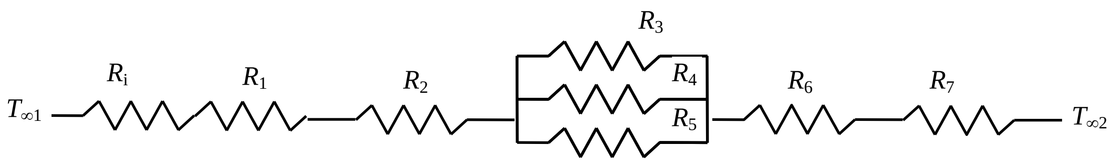
L = 0.0045 m = **0.45 cm**

10-54 A wall consists of horizontal bricks separated by plaster layers. There are also plaster layers on each side of the wall, and a rigid foam on the inner side of the wall. The rate of heat transfer through the wall is to be determined.

Assumptions **1** Heat transfer is steady since there is no indication of change with time. **2** Heat transfer through the wall is one-dimensional. **3** Thermal conductivities are constant. **4** Heat transfer by radiation is disregarded.

Properties The thermal conductivities are given to be k = 0.72 W/m·°C for bricks, k = 0.22 W/m·°C for plaster layers, and k = 0.026 W/m·°C for the rigid foam.

Analysis We consider 1 m deep and 0.33 m high portion of wall which is representative of the entire wall. The thermal resistance network and individual resistances are



$$R_i = R_{conv,1} = \frac{1}{h_1 A} = \frac{1}{(10\ \text{W/m}^2\cdot{}^\circ\text{C})(0.33\times 1\ \text{m}^2)} = 0.303\ {}^\circ\text{C/W}$$

$$R_1 = R_{foam} = \frac{L}{kA} = \frac{0.02\ \text{m}}{(0.026\ \text{W/m}\cdot{}^\circ\text{C})(0.33\times 1\ \text{m}^2)} = 2.33\ {}^\circ\text{C/W}$$

$$R_2 = R_6 = R_{\substack{plaster\\side}} = \frac{L}{kA} = \frac{0.02\ \text{m}}{(0.22\ \text{W/m}\cdot{}^\circ\text{C})(0.33\times 1\ \text{m}^2)} = 0.275\ {}^\circ\text{C/W}$$

$$R_3 = R_5 = R_{\substack{plaster\\center}} = \frac{L}{h_o A} = \frac{0.18\ \text{m}}{(0.22\ \text{W/m}\cdot{}^\circ\text{C})(0.015\times 1\ \text{m}^2)} = 54.55\ {}^\circ\text{C/W}$$

$$R_4 = R_{brick} = \frac{L}{kA} = \frac{0.18\ \text{m}}{(0.72\ \text{W/m}\cdot{}^\circ\text{C})(0.30\times 1\ \text{m}^2)} = 0.833\ {}^\circ\text{C/W}$$

$$R_\text{o} = R_{conv,2} = \frac{1}{h_2 A} = \frac{1}{(20\ \text{W/m}\cdot{}^\circ\text{C})(0.33\times 1\ \text{m}^2)} = 0.152\ {}^\circ\text{C/W}$$

$$\frac{1}{R_{mid}} = \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5} = \frac{1}{54.55} + \frac{1}{0.833} + \frac{1}{54.55} \longrightarrow R_{mid} = 0.81\ {}^\circ\text{C/W}$$

$$R_{total} = R_i + R_1 + 2R_2 + R_{mid} + R_o = 0.303 + 2.33 + 2(0.275) + 0.81 + 0.152 = 4.145\ {}^\circ\text{C/W}$$

The steady rate of heat transfer through the wall per $0.33\ \text{m}^2$ is

$$\dot{Q} = \frac{T_{\infty 1} - T_{\infty 2}}{R_{total}} = \frac{[(22-(-4)]{}^\circ\text{C}}{4.145{}^\circ\text{C/W}} = 6.27\ \text{W}$$

Then steady rate of heat transfer through the entire wall becomes

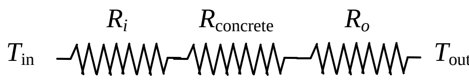
$$\dot{Q}_{total} = (6.27\ \text{W})\frac{(4\times 6)\text{m}^2}{0.33\ \text{m}^2} = \mathbf{456\ W}$$

10-63 A kiln is made of 20 cm thick concrete walls and ceiling. The two ends of the kiln are made of thin sheet metal covered with 2-cm thick styrofoam. For specified indoor and outdoor temperatures, the rate of heat transfer from the kiln is to be determined.

Assumptions **1** Heat transfer is steady since there is no indication of change with time. **2** Heat transfer through the walls and ceiling is one-dimensional. **3** Thermal conductivities are constant. **4** Heat transfer coefficients account for the radiation heat transfer. **5** Heat loss through the floor is negligible. **6** Thermal resistance of sheet metal is negligible.

Properties The thermal conductivities are given to be k = 0.9 W/m·°C for concrete and k = 0.033 W/m·°C for styrofoam insulation.

Analysis In this problem there is a question of which surface area to use. We will use the outer surface area for outer convection resistance, the inner surface area for inner convection resistance, and the average area for the conduction resistance. Or we could use the inner or the outer surface areas in the calculation of all thermal resistances with little loss in accuracy. For top and the two side surfaces:



$$R_i = \frac{1}{h_i A_i} = \frac{1}{(3000\ \text{W/m}^2\cdot°\text{C})[(40\ \text{m})(13-1.2)\ \text{m}]} = 0.0071\times10^{-4}\ °\text{C/W}$$

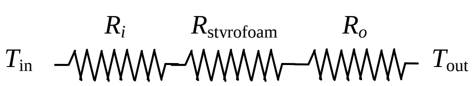
$$R_{concrete} = \frac{L}{kA_{ave}} = \frac{0.2\ \text{m}}{(0.9\ \text{W/m}\cdot°\text{C})[(40\ \text{m})(13-0.6)\ \text{m}]} = 4.480\times10^{-4}\ °\text{C/W}$$

$$R_o = \frac{1}{h_o A_o} = \frac{1}{(25\ \text{W/m}^2\cdot°\text{C})[(40\ \text{m})(13\ \text{m})]} = 0.769\times10^{-4}\ °\text{C/W}$$

$$R_{total} = R_i + R_{concrete} + R_o = (0.0071+4.480+0.769)\times10^{-4} = 5.256\times10^{-4}\ °\text{C/W}$$

and $$\dot{Q}_{top+sides} = \frac{T_{in}-T_{out}}{R_{total}} = \frac{[40-(-4)]°\text{C}}{5.256\times10^{-4}\ °\text{C/W}} = 83{,}700\ \text{W}$$

Heat loss through the end surface of the kiln with styrofoam:



$$R_i = \frac{1}{h_i A_i} = \frac{1}{(3000\ \text{W/m}^2\cdot°\text{C})[(4-0.4)(5-0.4)\ \text{m}^2]} = 0.201\times10^{-4}\ °\text{C/W}$$

$$R_{styrofoam} = \frac{L}{kA_{ave}} = \frac{0.02\ \text{m}}{(0.033\ \text{W/m}\cdot°\text{C})[(4-0.2)(5-0.2)\ \text{m}^2]} = 0.0332\ °\text{C/W}$$

$$R_o = \frac{1}{h_o A_o} = \frac{1}{(25\ \text{W/m}^2\cdot°\text{C})[4\times5\ \text{m}^2]} = 0.0020\ °\text{C/W}$$

$$R_{total} = R_i + R_{styrpfoam} + R_o = 0.201\times10^{-4} + 0.0332 + 0.0020 = 0.0352\ °\text{C/W}$$

and $$\dot{Q}_{end\ surface} = \frac{T_{in}-T_{out}}{R_{total}} = \frac{[40-(-4)]°\text{C}}{0.0352\ °\text{C/W}} = 1250\ \text{W}$$

Then the total rate of heat transfer from the kiln becomes

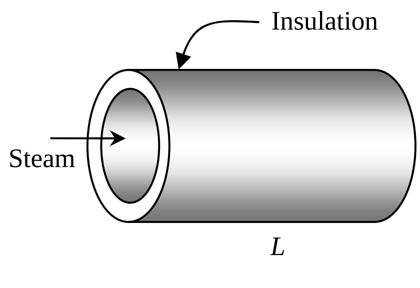
$$\dot{Q}_{total} = \dot{Q}_{top+sides} + 2\dot{Q}_{side} = 83{,}700 + 2\times1250 = \mathbf{86{,}200\ W}$$

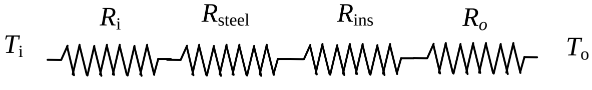
10-70 Steam flows in a steel pipe, which is insulated by gypsum plaster. The rate of heat transfer from the steam and the temperature on the outside surface of the insulation are be determined.

Assumptions **1** Heat transfer is steady since there is no indication of any change with time. **2** Heat transfer is one-dimensional since there is thermal symmetry about the centerline and no variation in the axial direction. **3** Thermal conductivities are constant. **4** The thermal contact resistance at the interface is negligible.

Properties (a) The thermal conductivities of steel and gypsum plaster are given to be 50 and 0.5 W/m·°C, respectively.

Analysis The thermal resistances are





$$R_i = \frac{1}{h_i A_i} = \frac{1}{(800\text{ W/m}^2\cdot{}^\circ\text{C})\pi(0.06\text{ m})(20\text{ m})} = 0.0003316^\circ\text{C/W}$$

$$R_{\text{steel}} = \frac{\ln(D_2/D_1)}{2\pi k_{\text{steel}}L} = \frac{\ln(8/6)}{2\pi(50\text{ W/m}\cdot{}^\circ\text{C})(20\text{ m})} = 0.0000458^\circ\text{C/W}$$

$$R_{\text{ins}} = \frac{\ln(D_3/D_2)}{2\pi k_{\text{ins}}L} = \frac{\ln(16/8)}{2\pi(0.5\text{ W/m}\cdot{}^\circ\text{C})(20\text{ m})} = 0.011032^\circ\text{C/W}$$

$$R_o = \frac{1}{h_o A_o} = \frac{1}{(200\text{ W/m}^2\cdot{}^\circ\text{C})\pi(0.16\text{ m})(20\text{ m})} = 0.0004974^\circ\text{C/W}$$

The total thermal resistance and the rate of heat transfer are

$$R_{\text{total}} = R_i + R_{\text{steel}} + R_{\text{ins}} + R_o = 0.0003316 + 0.0000458 + 0.011032 + 0.0004974 = 0.011907^\circ\text{C/W}$$

$$\dot{Q} = \frac{T_i - T_o}{R_{\text{total}}} = \frac{(200-10)^\circ\text{C}}{0.011907\text{ m}^2\cdot\text{C/W}} = \mathbf{15{,}957\ W}$$

(b) The temperature at the outer surface of the insulation is determined from

$$\dot{Q} = \frac{T_s - T_o}{R_o} \longrightarrow 15{,}957\text{ W} = \frac{(T_s - 10)^\circ\text{C}}{0.0004974\text{ m}^2\cdot{}^\circ\text{C/W}} \longrightarrow T_s = \mathbf{17.9^\circ C}$$