

Solutions Manual for

Heat and Mass Transfer: Fundamentals & Applications

6th Edition

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McGraw-Hill Education, 2020

Chapter 1

INTRODUCTION AND BASIC CONCEPTS

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Thermodynamics and Heat Transfer

1-1C Thermodynamics deals with the amount of heat transfer as a system undergoes a process from one equilibrium state to another. Heat transfer, on the other hand, deals with the rate of heat transfer as well as the temperature distribution within the system at a specified time.

1-2C (a) The driving force for heat transfer is the temperature difference. (b) The driving force for electric current flow is the electric potential difference (voltage). (a) The driving force for fluid flow is the pressure difference.

1-3C The *rating* problems deal with the determination of the *heat transfer rate* for an existing system at a specified temperature difference. The *sizing* problems deal with the determination of the *size* of a system in order to transfer heat at a *specified rate* for a *specified temperature difference*.

1-4C The experimental approach (testing and taking measurements) has the advantage of dealing with the actual physical system, and getting a physical value within the limits of experimental error. However, this approach is expensive, time consuming, and often impractical. The analytical approach (analysis or calculations) has the advantage that it is fast and inexpensive, but the results obtained are subject to the accuracy of the assumptions and idealizations made in the analysis.

1-5C Modeling makes it possible to predict the course of an event before it actually occurs, or to study various aspects of an event mathematically without actually running expensive and time-consuming experiments. When preparing a mathematical model, all the variables that affect the phenomena are identified, reasonable assumptions and approximations are made, and the interdependence of these variables are studied. The relevant physical laws and principles are invoked, and the problem is formulated mathematically. Finally, the problem is solved using an appropriate approach, and the results are interpreted.

1-6C The right choice between a crude and complex model is usually the *simplest* model which yields *adequate* results.

Preparing very accurate but complex models is not necessarily a better choice since such models are not much use to an analyst if they are very difficult and time consuming to solve. At the minimum, the model should reflect the essential features of the physical problem it represents.

1-7C Warmer. Because energy is added to the room air in the form of electrical work.

1-8C Warmer. If we take the room that contains the refrigerator as our system, we will see that electrical work is supplied to this room to run the refrigerator, which is eventually dissipated to the room as waste heat.

1-9C The claim is false. The heater of a house supplies the energy that the house is losing, which is proportional to the temperature difference between the indoors and the outdoors. A turned off heater consumes no energy. The heat lost from a house to the outdoors during the warming up period is less than the heat lost from a house that is already at the temperature that the thermostat is set because of the larger cumulative temperature difference in the latter case. For best practice, the heater should be turned off when no one is at home during day (at subfreezing temperatures, the heater should be kept on at a low temperature to avoid freezing of water in pipes). Also, the thermostat should be lowered during bedtime to minimize the temperature difference between the indoors and the outdoors at night and thus the amount of heat that the heater needs to supply to the house.

1-10C No. The thermostat tells an air conditioner (or heater) at what interior temperature to stop. The air conditioner will cool the house at the same rate no matter what the thermostat setting is. So, it is best to set the thermostat at a comfortable temperature and then leave it alone. Setting the thermostat too low a home owner risks wasting energy and money (and comfort) by forgetting it at the set low temperature.

1-11C No. Since there is no temperature drop of water, the heater will never kick into make up for the heat loss. Therefore, it will not waste any energy during times of no use, and there is no need to use a timer. But if the family were on a time-of-use tariff, it would be possible to save money (but not energy) by turning on the heater when the rate was lowest at night and off during peak periods when rate is the highest.

1-12C For the constant pressure case. This is because the heat transfer to an ideal gas is $mc_p\Delta T$ at constant pressure and $mc_v\Delta T$ at constant volume, and c_p is always greater than c_v .

1-13C The rate of heat transfer per unit surface area is called heat flux $\dot{q}$. It is related to the rate of heat transfer by $\dot{Q} = \int_A \dot{q} dA$.

1-14C Energy can be transferred by heat and work to a close system. An energy transfer is heat transfer when its driving force is temperature difference.

1-15E A logic chip in a computer dissipates 3 W of power. The amount heat dissipated in 8 h and the heat flux on the surface of the chip are to be determined.

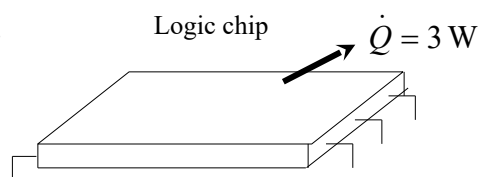
Assumptions Heat transfer from the surface is uniform.

Analysis (a) The amount of heat the chip dissipates during an 8-hour period is

$$Q = \dot{Q} \Delta t = (3 \text{ W})(8 \text{ h}) = 24 \text{ Wh} = 0.024 \text{ kWh}$$

(b) The heat flux on the surface of the chip is

$$\dot{q} = \frac{\dot{Q}}{A} = \frac{3 \text{ W}}{0.08 \text{ in}^2} = 37.5 \text{ W/in}^2$$



1-16 The filament of a 150 W incandescent lamp is 5 cm long and has a diameter of 0.5 mm. The heat flux on the surface of the filament, the heat flux on the surface of the glass bulb, and the annual electricity cost of the bulb are to be determined.

Assumptions Heat transfer from the surface of the filament and the bulb of the lamp is uniform.

Analysis (a) The heat transfer surface area and the heat flux on the surface of the filament are

$$A_s = \pi DL = \pi(0.05 \text{ cm})(5 \text{ cm}) = 0.785 \text{ cm}^2$$

$$\dot{q}_s = \frac{\dot{Q}}{A_s} = \frac{150 \text{ W}}{0.785 \text{ cm}^2} = 191 \text{ W/cm}^2 = 1.91 \times 10^6 \text{ W/m}^2$$

(b) The heat flux on the surface of glass bulb is

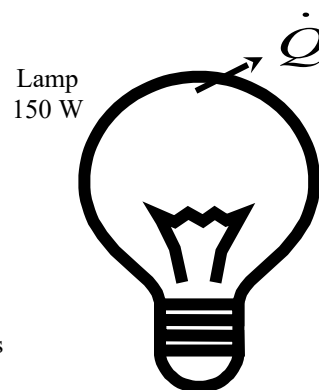
$$A_s = \pi D^2 = \pi(8 \text{ cm})^2 = 201.1 \text{ cm}^2$$

$$\dot{q}_s = \frac{\dot{Q}}{A_s} = \frac{150 \text{ W}}{201.1 \text{ cm}^2} = 0.75 \text{ W/cm}^2 = 7500 \text{ W/m}^2$$

(c) The amount and cost of electrical energy consumed during a one-year period is

$$\text{Electricity Consumption} = \dot{Q} \Delta t = (0.15 \text{ kW})(365 \times 8 \text{ h/yr}) = 438 \text{ kWh/yr}$$

$$\text{Annual Cost} = (438 \text{ kWh/yr})(\$0.08/\text{kWh}) = \$35.04/\text{yr}$$



1-17 An aluminum ball is to be heated from 80°C to 200°C. The amount of heat that needs to be transferred to the aluminum ball is to be determined.

Assumptions The properties of the aluminum ball are constant.

Properties The average density and specific heat of aluminum are given to be $\rho = 2700 \text{ kg/m}^3$ and $c_p = 0.90 \text{ kJ/kg}\cdot^\circ\text{C}$.

Analysis The amount of energy added to the ball is simply the change in its internal energy, and is determined from

$$E_{\text{transfer}} = \Delta U = mc_p(T_2 - T_1)$$

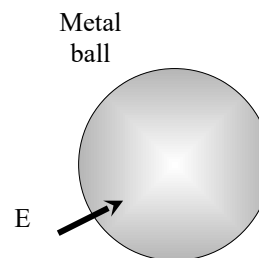
where

$$m = \rho V = \frac{\pi}{6} \rho D^3 = \frac{\pi}{6} (2700 \text{ kg/m}^3)(0.15 \text{ m})^3 = 4.77 \text{ kg}$$

Substituting,

$$E_{\text{transfer}} = (4.77 \text{ kg})(0.90 \text{ kJ/kg}\cdot^\circ\text{C})(200 - 80)^\circ\text{C} = 515 \text{ kJ}$$

Therefore, 515 kJ of energy (heat or work such as electrical energy) needs to be transferred to the aluminum ball to heat it to 200°C.



1-18E A water heater is initially filled with water at 50°F. The amount of energy that needs to be transferred to the water to raise its temperature to 120°F is to be determined.

Assumptions 1 Water is an incompressible substance with constant specific. 2 No water flows in or out of the tank during heating.

Properties The density and specific heat of water at 85°F from Table A-9E are:

$\rho = 62.17 \text{ lbm/ft}^3$ and $c_p = 0.999 \text{ Btu/lbm}\cdot\text{R}$.

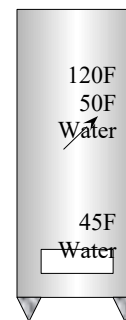
Analysis The mass of water in the tank is

$$m = \rho V = (62.17 \text{ lbm/ft}^3)(60 \text{ gal}) \left(\frac{1 \text{ ft}^3}{7.48 \text{ gal}} \right) = 498.7 \text{ lbm}$$

Then, the amount of heat that must be transferred to the water in the tank as it is heated from 50 to 120°F is determined to be

$$Q = mc_p(T_2 - T_1) = (498.7 \text{ lbm})(0.999 \text{ Btu/lbm}\cdot^\circ\text{F})(120 - 50)^\circ\text{F} = 34,874 \text{ Btu}$$

Discussion Referring to Table A-9E the density and specific heat of water at 50°F are: $\rho = 62.41 \text{ lbm/ft}^3$ and $c_p = 1.000 \text{ Btu/lbm}\cdot\text{R}$ and at 120°F are: $\rho = 61.71 \text{ lbm/ft}^3$ and $c_p = 0.999 \text{ Btu/lbm}\cdot\text{R}$. We evaluated the water properties at an average temperature of 85°F. However, we could have assumed constant properties and evaluated properties at the initial temperature of 50°F or final temperature of 120°F without loss of accuracy.



1-19 An electrically heated house maintained at 22°C experiences infiltration losses at a rate of 0.7 ACH. The amount of energy loss from the house due to infiltration per day and its cost are to be determined.

Assumptions 1 Air as an ideal gas with a constant specific heats at room temperature. 2 The volume occupied by the furniture and other belongings is negligible. 3 The house is maintained at a constant temperature and pressure at all times. 4 The infiltrating air exfiltrates at the indoors temperature of 22°C.

Properties The specific heat of air at room temperature is $c_p = 1.007 \text{ kJ/kg}\cdot^\circ\text{C}$.

Analysis The volume of the air in the house is

$$V = (\text{floor space})(\text{height}) = (200 \text{ m}^2)(3 \text{ m}) = 600 \text{ m}^3$$

Noting that the infiltration rate is 0.7 ACH (air changes per hour) and thus the air in the house is completely replaced by the outdoor air $0.7 \times 24 = 16.8$ times per day, the mass flow rate of air through the house due to infiltration is

$$\dot{m}_{\text{air}} = \frac{P_o \dot{V}_{\text{air}}}{RT_o} = \frac{P_o (\text{ACH} \times V_{\text{house}})}{RT_o}$$

$$\dot{m}_{\text{air}} = \frac{(89.6 \text{ kPa})(16.8 \times 600 \text{ m}^3/\text{day})}{(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(5 + 273.15 \text{ K})} = 11,314 \text{ kg/day}$$

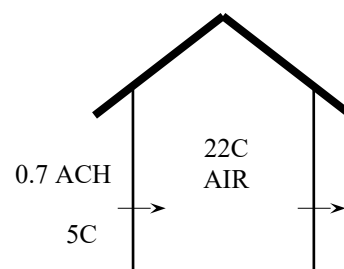
Noting that outdoor air enters at 5°C and leaves at 22°C, the energy loss of this house per day is

$$\dot{Q}_{\text{infiltration}} = \dot{m}_{\text{air}} c_p (T_{\text{indoors}} - T_{\text{outdoors}})$$

$$\dot{Q}_{\text{infiltration}} = (11,314 \text{ kg/day})(1.007 \text{ kJ/kg}\cdot^\circ\text{C})(22 - 5)^\circ\text{C} = 193,681 \text{ kJ/day} = 53.8 \text{ kWh/day}$$

At a unit cost of \$0.082/kWh, the cost of this electrical energy lost by infiltration is

$$\text{Energy Cost} = (\text{Energy used})(\text{Unit cost of energy}) = (53.8 \text{ kWh/day})(\$0.082/\text{kWh}) = \$4.41/\text{day}$$



1-20  Liquid ethanol is being transported in a pipe where heat is added to the liquid. The volume flow rate that is necessary to keep the ethanol temperature below its flashpoint is to be determined.

Assumptions 1 Steady operating conditions exist. 2 The specific heat and density of ethanol are constant.

Properties The specific heat and density of ethanol are given as 2.44 kJ/kg·K and 789 kg/m³, respectively.



Analysis The rate of heat added to the ethanol being transported in the pipe is

$$\dot{Q} = \dot{m} c_p (T_{out} - T_{in})$$

or

$$\dot{Q} = \dot{V} \rho c_p (T_{out} - T_{in})$$

For the ethanol in the pipe to be below its flashpoint, it is necessary to keep T_{out} below 16.6°C. Thus, the volume flow rate should be

$$\dot{V} > \frac{\dot{Q}}{\rho c_p (T_{out} - T_{in})} = \frac{20 \text{ kJ/s}}{(789 \text{ kg/m}^3)(2.44 \text{ kJ/kg} \cdot \text{K})(16.6 - 10) \text{ K}}$$

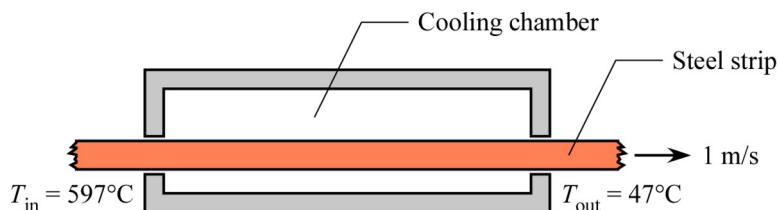
$$\dot{V} > 0.00157 \text{ m}^3/\text{s}$$

Discussion To maintain the ethanol in the pipe well below its flashpoint, it is more desirable to have a much higher flow rate than 0.00157 m³/s.

1-21  A 2 mm thick by 3 cm wide AISI 1010 carbon steel strip is cooled in a chamber from 597 to 47°C to avoid instantaneous thermal burn upon contact with skin tissue. The amount of heat rate to be removed from the steel strip is to be determined.

Assumptions 1 Steady operating conditions exist. 2 The stainless steel sheet has constant specific heat and density. 3 Changes in potential and kinetic energy are negligible.

Properties For AISI 1010 carbon steel, the specific heat of AISI 1010 steel at $(597 + 47)^\circ\text{C} / 2 = 322^\circ\text{C} = 595\text{ K}$ is 682 J/kg·K (by interpolation from Table A-3), and the density is given as 7832 kg/m³.



Analysis The mass of the steel strip being conveyed enters and exits the chamber at a rate of

$$\dot{m} = \rho V_{wt}$$

The rate of heat being removed from the steel strip in the chamber is given as

$$\begin{aligned}\dot{Q}_{\text{removed}} &= \dot{m} c_p (T_{\text{in}} - T_{\text{out}}) \\ &= \rho V_{wt} c_p (T_{\text{in}} - T_{\text{out}}) \\ &= (7832 \text{ kg/m}^3)(1 \text{ m/s})(0.030 \text{ m})(0.002 \text{ m})(682 \text{ J/kg}\cdot\text{K})(597 - 47) \text{ K} \\ &= 176 \text{ kW}\end{aligned}$$

Discussion By slowing down the conveyance speed of the steel strip would reduce the amount of heat rate needed to be removed from the steel strip in the cooling chamber. Since slowing the conveyance speed allows more time for the steel strip to cool.

1-22 Liquid water is to be heated in an electric teapot. The heating time is to be determined.

Assumptions 1 Heat loss from the teapot is negligible. 2 Constant properties can be used for both the teapot and the water.

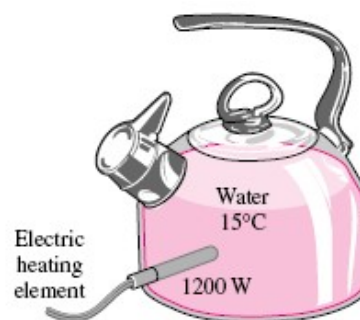
Properties The average specific heats are given to be 0.7 kJ/kg·K for the teapot and 4.18 kJ/kg·K for water.

Analysis We take the teapot and the water in it as the system, which is a closed system (fixed mass). The energy balance in this case can be expressed as

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer to system by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc. energies}} = \underbrace{\Delta U_{\text{system}}}_{\text{Change in internal energy}} = \underbrace{\Delta U_{\text{water}}}_{\text{Change in internal energy of water}} + \underbrace{\Delta U_{\text{teapot}}}_{\text{Change in internal energy of teapot}}$$

Then the amount of energy needed to raise the temperature of water and the teapot from 15°C to 95°C is

$$\begin{aligned}E_{\text{in}} &= (mc \Delta T)_{\text{water}} + (mc \Delta T)_{\text{teapot}} \\ &= (1.2 \text{ kg})(4.18 \text{ kJ/kg}\cdot^\circ\text{C})(95 - 15)^\circ\text{C} + (0.5 \text{ kg})(0.7 \text{ kJ/kg}\cdot^\circ\text{C})(95 - 15)^\circ\text{C} \\ &= 429.3 \text{ kJ}\end{aligned}$$



The 1200-W electric heating unit will supply energy at a rate of 1.2 kW or 1.2 kJ per second. Therefore, the time needed for this heater to supply 429.3 kJ of heat is determined from

$$\Delta t = \frac{\text{Total energy transferred}}{\text{Rate of energy transfer}} = \frac{E_{\text{in}}}{E_{\text{transfer}}} = \frac{429.3 \text{ kJ}}{1.2 \text{ kJ/s}} = 358 \text{ s} = 6.0 \text{ min}$$

Discussion In reality, it will take more than 6 minutes to accomplish this heating process since some heat loss is inevitable during heating. Also, the specific heat units kJ/kg · °C and kJ/kg · K are equivalent, and can be interchanged.

1-23  A water heater uses 100 kW to heat 60 gallon (0.2271 m^3) of liquid water initially at 20°C . Determine the heating duration such that the water exiting the heater would be in compliance with the ASME Boiler and Pressure Vessel Code (ASME BPVC.IV-2015) service restrictions.

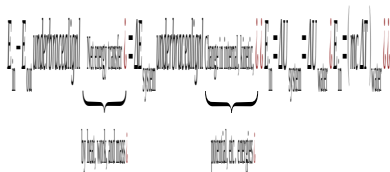
Assumptions **1** Heating of the heater material is negligible (i.e. 100 kW is for heating the water only). **2** Constant properties are used for the water. **3** No water flowing out of the heater during the heating.

Properties The average density and specific heat of water are given to be 970 kg/m^3 and $4.18 \text{ kJ/kg}\cdot\text{K}$, respectively.

Analysis The mass of the water in the heater is

$$m = \rho V = (970 \text{ kg/m}^3)(0.2271 \text{ m}^3) = 220.29 \text{ kg}$$

The energy balance in this case can be expressed as



In terms of heat transfer rate

$$\dot{Q} = \frac{E_{\text{in}}}{\Delta t} = \frac{(mc \Delta T)_{\text{water}}}{\Delta t}$$

Solving for the heating duration from 20°C to 120°C ,

$$\Delta t = \frac{(mc)_{\text{water}}(T_2 - T_1)}{\dot{Q}}$$

$$\Delta t = \frac{(220.29 \text{ kg})(4.18 \text{ kJ/kg}\cdot^\circ\text{C})(100^\circ\text{C})}{100 \text{ kJ/s}} = 920.8 \text{ s} = 15.3 \text{ min}$$

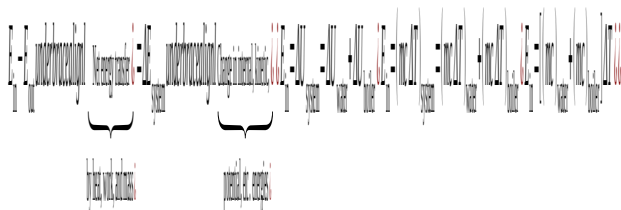
Discussion It takes about 15 minutes at 100 kW to heat 60 gallons of liquid water from 20°C to the ASME Boiler and Pressure Vessel Code service restrictions temperature of 120°C . If the heating duration is more than 15.3 minutes, then the final temperature of the water that would exit the heater would be higher than 120°C , which exceeds the code restrictions.

1-24 C&S A boiler (10 kg) is used to heat 20 gallon (0.07571 m³) of liquid water with 50 kW for 30 minutes. Determine whether this operating condition would be in compliance with the ASME Boiler and Pressure Vessel Code (ASME BPVC.IV-2015) service restrictions.

Assumptions 1 Heat loss from the boiler is negligible. 2 Constant properties are used for both the boiler and the water. 3 The raise in temperature for the boiler and the water is equal. 4 No water flowing out of the boiler during the heating.

Properties The average specific heats are given to be 0.48 kJ/kg·K for the boiler material and 4.18 kJ/kg·K for the water. The average density of the water is 850 kg/m³.

Analysis We take the boiler and the water in it as a closed system. The energy balance in this case can be expressed as



Solving for the raise in temperature

$$\Delta T = \frac{E_{in}}{[(\rho V c)_{water} + (mc)_{boiler}]}$$

$$\Delta T = \frac{(50 \text{ kJ/s})(30 \times 60 \text{ s})}{[(850 \text{ kg/m}^3)(0.07571 \text{ m}^3)(4.18 \text{ kJ/kg} \cdot ^\circ\text{C}) + (10 \text{ kg})(0.48 \text{ kJ/kg} \cdot ^\circ\text{C})]} = 329^\circ\text{C}$$

The final temperature is

$$T_2 = T_1 + \Delta T = 15^\circ\text{C} + 329^\circ\text{C} = 344^\circ\text{C} > 120^\circ\text{C}$$

Discussion The final temperature of the water after 30 minutes of heating at 50 kW is 224°C greater than the ASME Boiler and Pressure Vessel Code service restrictions of 120°C. Thus, the operating condition would not be in compliance with the code. A temperature control mechanism should be implemented to ensure that the water exiting the boiler stays below 120°C.

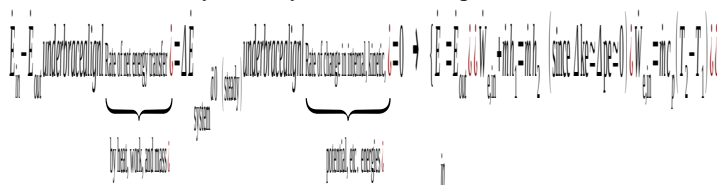
1-25 Water is heated in an insulated tube by an electric resistance heater. The mass flow rate of water through the heater is to be determined.

Assumptions 1 Water is an incompressible substance with a constant specific heat. 2 The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. 3 Heat loss from the insulated tube is negligible.

Properties The specific heat of water at room temperature is $c_p = 4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$.

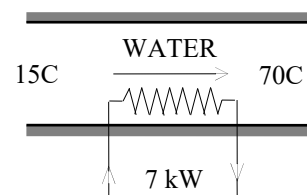
Analysis We take the tube as the system. This is a *control volume* since mass crosses the system boundary during the process. We observe that this is a steady-flow process since there is no change with time at any point and thus

$\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$, there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$, and the tube is insulated. The energy balance for this steady-flow system can be expressed in the rate form as



Thus,

$$\dot{m} = \frac{\dot{W}_{e,in}}{c_p(T_2 - T_1)} = \frac{7 \text{ kJ/s}}{(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(70 - 15)^\circ\text{C}} = 0.0304 \text{ kg/s}$$



1-26 It is observed that the air temperature in a room heated by electric baseboard heaters remains constant even though the heater operates continuously when the heat losses from the room amount to 7000 kJ/h. The power rating of the heater is to be determined.

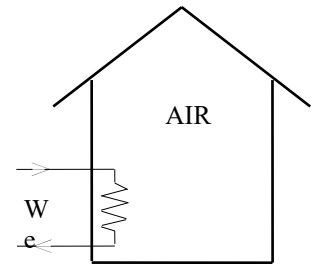
Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa. **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** The temperature of the room remains constant during this process.

Analysis We take the room as the system. The energy balance in this case reduces to

$$\underbrace{\dot{Q}_{\text{in}}}_{\text{by heat, work, and mass}} - \underbrace{\dot{Q}_{\text{out}}}_{\text{potential, KE, and mass}} = \dot{U}_{\text{system}} + \dot{E}_{\text{out}} - \dot{E}_{\text{in}}$$

since $\Delta U = mc_v \Delta T = 0$ for isothermal processes of ideal gases. Thus,

$$\dot{W}_{e,\text{in}} = \dot{Q}_{\text{out}} = 7000 \text{ kJ/h} \left(\frac{1 \text{ kW}}{3600 \text{ kJ/h}} \right) = 1.94 \text{ kW}$$



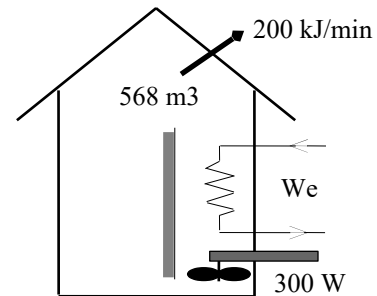
1-27 A room is heated by an electrical resistance heater placed in a short duct in the room in 15 min while the room is losing heat to the outside, and a 300-W fan circulates the air steadily through the heater duct. The power rating of the electric heater and the temperature rise of air in the duct are to be determined.

Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa . **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats at room temperature can be used for air. This assumption results in negligible error in heating and air-conditioning applications. **3** Heat loss from the duct is negligible. **4** The house is air-tight and thus no air is leaking in or out of the room.

Properties The gas constant of air is $R = 0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}$ (Table A-1). Also, $c_p = 1.007\text{ kJ/kg}\cdot\text{K}$ for air at room temperature (Table A-15) and $c_v = c_p - R = 0.720\text{ kJ/kg}\cdot\text{K}$.

Analysis (a) We first take the air in the room as the system. This is a constant volume *closed system* since no mass crosses the system boundary. The energy balance for the room can be expressed as

$$\underbrace{\dot{Q}_{\text{in}} - \dot{Q}_{\text{out}}}_{\text{heat, net, added}} = \underbrace{\dot{W}_{\text{fan, in}} - \dot{W}_{\text{fan, out}}}_{\text{potential, net, changes}} + \underbrace{\dot{W}_{\text{e, in}} - \dot{Q}_{\text{loss}}}_{\text{heat, net, added}} + \underbrace{\dot{W}_{\text{e, out}} - \dot{Q}_{\text{loss}}}_{\text{heat, net, added}} + \underbrace{\dot{W}_{\text{e, in}} - \dot{Q}_{\text{loss}}}_{\text{heat, net, added}} + \underbrace{\dot{W}_{\text{e, out}} - \dot{Q}_{\text{loss}}}_{\text{heat, net, added}}$$



The total mass of air in the room is

$$V = 5 \times 6 \times 8\text{ m}^3 = 240\text{ m}^3$$

$$m = \frac{P_1 V}{RT_1} = \frac{(98\text{ kPa})(240\text{ m}^3)}{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(288\text{ K})} = 284.6\text{ kg}$$

Then the power rating of the electric heater is determined to be

$$\dot{W}_{\text{e, in}} = \dot{Q}_{\text{out}} - \dot{W}_{\text{fan, in}} + mc_v(T_2 - T_1)/\Delta t = (200/60\text{ kJ/s}) - (0.3\text{ kJ/s}) + (284.6\text{ kg})(0.720\text{ kJ/kg}\cdot^{\circ}\text{C})(25 - 15^{\circ}\text{C})/(18 \times 60\text{ s}) = 4.93\text{ kW}$$

(b) The temperature rise that the air experiences each time it passes through the heater is determined by applying the energy balance to the duct,

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{W}_{\text{e, in}} + \dot{W}_{\text{fan, in}} + \dot{m}h_1 = \dot{Q}_{\text{out}} + \dot{m}h_2 \quad (\text{since } \Delta ke \cong \Delta pe \cong 0)$$

$$\dot{W}_{\text{e, in}} + \dot{W}_{\text{fan, in}} = \dot{m}\Delta h = \dot{m}c_p\Delta T$$

Thus,

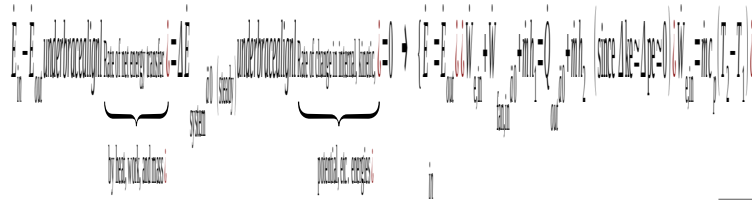
$$\Delta T = \frac{\dot{W}_{\text{e, in}} + \dot{W}_{\text{fan, in}}}{\dot{m}c_p} = \frac{(4.93 + 0.3)\text{ kJ/s}}{(50/60\text{ kg/s})(1.007\text{ kJ/kg}\cdot\text{K})} = 6.2^{\circ}\text{C}$$

1-28 Air is moved through the resistance heaters in a 1200-W hair dryer by a fan. The volume flow rate of air at the inlet and the velocity of the air at the exit are to be determined.

Assumptions **1** Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -141°C and 3.77 MPa . **2** The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. **3** Constant specific heats at room temperature can be used for air. **4** The power consumed by the fan and the heat losses through the walls of the hair dryer are negligible.

Properties The gas constant of air is $R = 0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K}$ (Table A-1). Also, $c_p = 1.007\text{ kJ/kg}\cdot\text{K}$ for air at room temperature (Table A-15).

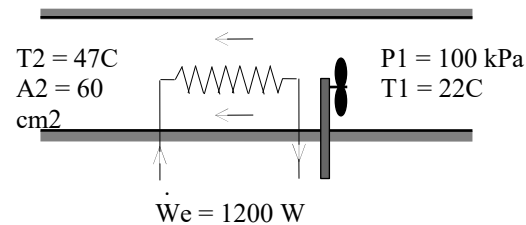
Analysis (a) We take the hair dryer as the system. This is a *control volume* since mass crosses the system boundary during the process. We observe that this is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$, and there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$. The energy balance for this steady-flow system can be expressed in the rate form as



Thus,

$$\dot{m} = \frac{\dot{W}_{e,\text{in}}}{c_p(T_2 - T_1)}$$

$$= \frac{1.2\text{ kJ/s}}{(1.007\text{ kJ/kg}\cdot^{\circ}\text{C})(47 - 22)^{\circ}\text{C}} = 0.04767\text{ kg/s}$$



Then,

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(295\text{ K})}{100\text{ kPa}} = 0.8467\text{ m}^3/\text{kg}$$

$$\dot{V}_1 = \dot{m}v_1 = (0.04767\text{ kg/s})(0.8467\text{ m}^3/\text{kg}) = 0.0404\text{ m}^3/\text{s}$$

(b) The exit velocity of air is determined from the conservation of mass equation,

$$v_2 = \frac{RT_2}{P_2} = \frac{(0.287\text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(320\text{ K})}{100\text{ kPa}} = 0.9184\text{ m}^3/\text{kg}$$

$$\dot{m} = \frac{1}{v_2} A_2 V_2 \rightarrow V_2 = \frac{\dot{m}v_2}{A_2} = \frac{(0.04767\text{ kg/s})(0.9184\text{ m}^3/\text{kg})}{60 \times 10^{-4}\text{ m}^2} = 7.30\text{ m/s}$$

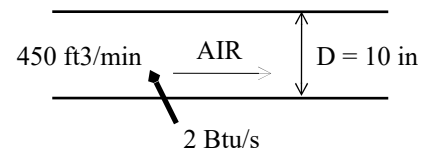
1-29E Air gains heat as it flows through the duct of an air-conditioning system. The velocity of the air at the duct inlet and the temperature of the air at the exit are to be determined.

Assumptions 1 Air is an ideal gas since it is at a high temperature and low pressure relative to its critical point values of -222°F and 548 psia . 2 The kinetic and potential energy changes are negligible, $\Delta ke \cong \Delta pe \cong 0$. 3 Constant specific heats at room temperature can be used for air. This assumption results in negligible error in heating and air-conditioning applications.

Properties The gas constant of air is $R = 0.3704\text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R}$ (Table A-1E). Also, $c_p = 0.240\text{ Btu}/\text{lbm}\cdot\text{R}$ for air at room temperature (Table A-15E).

Analysis We take the air-conditioning duct as the system. This is a *control volume* since mass crosses the system boundary during the process. We *observe* that this is a steady-flow process since there is no change with time at any point and thus $\Delta m_{\text{CV}} = 0$ and $\Delta E_{\text{CV}} = 0$, there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$, and heat is lost from the system. The energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{\text{in}} - \dot{E}_{\text{out}}}_{\text{by heat, work, and mass}} = \underbrace{\dot{E}_{\text{out}} - \dot{E}_{\text{in}}}_{\text{potential, etc. energies}} = 0$$



(a) The inlet velocity of air through the duct is determined from

$$V_1 = \frac{\dot{V}_1}{A_1} = \frac{\dot{V}_1}{\pi r^2} = \frac{450\text{ ft}^3/\text{min}}{\pi (5/12\text{ ft})^2} = 825\text{ ft/min}$$

(b) The mass flow rate of air becomes

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.3704\text{ psia}\cdot\text{ft}^3/\text{lbm}\cdot\text{R})(510\text{ R})}{15\text{ psia}} = 12.6\text{ ft}^3/\text{lbm}$$

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{450\text{ ft}^3/\text{min}}{12.6\text{ ft}^3/\text{lbm}} = 35.7\text{ lbm/min} = 0.595\text{ lbm/s}$$

Then the exit temperature of air is determined to be

$$T_2 = T_1 + \frac{\dot{Q}_{\text{in}}}{\dot{m}c_p} = 50^{\circ}\text{F} + \frac{2\text{ Btu/s}}{(0.595\text{ lbm/s})(0.240\text{ Btu}/\text{lbm}\cdot^{\circ}\text{F})} = 64.0^{\circ}\text{F}$$

1-30  Liquid water entering at 10°C and flowing at 10 g/s (0.01 kg/s) is heated in a circular tube by an electrical heater at 10 kW. Determine whether the water exit temperature would be below 79°C and comply with the ASME Code for Process Piping, and the minimum mass flow rate to keep the exit temperature below 79°C.

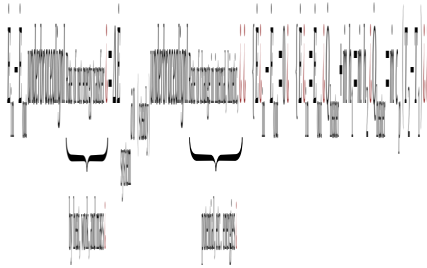
Assumptions 1 Water is an incompressible substance with constant properties. 2 Heat loss from the tube is negligible. 3 Steady operating conditions.

Properties The specific heat of water is given as 4.18 kJ/kg·K.

Analysis The tube is taken as a control volume. For steady state flow, the mass flow rate at the inlet is equal to the mass flow rate at the exit:

$$\dot{m}_1 = \dot{m}_2 = \dot{m}$$

The energy balance for the control volume is



Solving for the exit temperature,

$$T_2 = \frac{\dot{Q}_{\text{heater}}}{\dot{m} c_p} + T_1 = \frac{10 \text{ kJ/s}}{(0.01 \text{ kg/s})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})} + 10^\circ\text{C} = 249^\circ\text{C} > 79^\circ\text{C}$$

Thus, the exit temperature is not in compliance with the ASME Code for Process Piping for PVDC lining.

The minimum mass flow rate needed to keep the water exit temperature from exceeding 79°C is

$$\begin{aligned} \dot{m} &\geq \frac{\dot{Q}_{\text{heater}}}{(T_2 - T_1) c_p} \\ &\geq \frac{10 \text{ kJ/s}}{(79 - 10)^\circ\text{C} (4.18 \text{ kJ/kg} \cdot ^\circ\text{C})} \\ &\geq 0.0347 \text{ kg/s} \end{aligned}$$

The higher the value of mass flow rate, the lower the water exit temperature is achieved.

Discussion If the desire is to have higher exit temperature, then a different thermoplastic lining should be used. Polytetrafluoroethylene (PTFE) lining has a recommended maximum temperature of 260°C by the ASME Code for Process Piping (ASME B31.3-2014, A323).

Heat Transfer Mechanisms

1-31C The thermal conductivity of a material is the rate of heat transfer through a unit thickness of the material per unit area and per unit temperature difference. The thermal conductivity of a material is a measure of how fast heat will be conducted in that material.

1-32C Diamond is a better heat conductor.

1-33C The thermal conductivity of gases is proportional to the square root of absolute temperature. The thermal conductivity of most liquids, however, decreases with increasing temperature, with water being a notable exception.

1-34C Superinsulations are obtained by using layers of highly reflective sheets separated by glass fibers in an evacuated space. Radiation heat transfer between two surfaces is inversely proportional to the number of sheets used and thus heat loss by radiation will be very low by using this highly reflective sheets. At the same time, evacuating the space between the layers forms a vacuum under 0.000001 atm pressure which minimize conduction or convection through the air space between the layers.

1-35C Most ordinary insulations are obtained by mixing fibers, powders, or flakes of insulating materials with air. Heat transfer through such insulations is by conduction through the solid material, and conduction or convection through the air space as well as radiation. Such systems are characterized by apparent thermal conductivity instead of the ordinary thermal conductivity in order to incorporate these convection and radiation effects.

1-36C The mechanisms of heat transfer are conduction, convection and radiation. Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles. Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas which is in motion, and it involves combined effects of conduction and fluid motion. Radiation is energy emitted by matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configurations of the atoms or molecules.

$$\dot{Q}_{\text{cond}} = -kA \frac{dT}{dx}$$

1-37C Conduction is expressed by Fourier's law of conduction as $\dot{Q}_{\text{cond}} = -kA \frac{dT}{dx}$ where dT/dx is the temperature gradient, k is the thermal conductivity, and A is the area which is normal to the direction of heat transfer.

Convection is expressed by Newton's law of cooling as $\dot{Q}_{\text{conv}} = hA_s(T_s - T_\infty)$ where h is the convection heat transfer coefficient, A_s is the surface area through which convection heat transfer takes place, T_s is the surface temperature and T_∞ is the temperature of the fluid sufficiently far from the surface.

Radiation is expressed by Stefan-Boltzman law as $\dot{Q}_{\text{rad}} = \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4)$ where ε is the emissivity of surface, A_s is the surface area, T_s is the surface temperature, T_{surr} is the average surrounding surface temperature and $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ is the Stefan-Boltzman constant.

1-38C Convection involves fluid motion, conduction does not. In a solid we can have only conduction.

1-39C No. It is purely by radiation.

1-40C In forced convection the fluid is forced to move by external means such as a fan, pump, or the wind. The fluid motion in natural convection is due to buoyancy effects only.

1-41C In solids, conduction is due to the combination of the vibrations of the molecules in a lattice and the energy transport by free electrons. In gases and liquids, it is due to the collisions of the molecules during their random motion.

1-42C The parameters that effect the rate of heat conduction through a windowless wall are the geometry and surface area of wall, its thickness, the material of the wall, and the temperature difference across the wall.

1-43C In a typical house, heat loss through the wall with glass window will be larger since the glass is much thinner than a wall, and its thermal conductivity is higher than the average conductivity of a wall.

1-44C The house with the lower rate of heat transfer through the walls will be more energy efficient. Heat conduction is proportional to thermal conductivity (which is 0.72 W/m·°C for brick and 0.17 W/m·°C for wood, Table 1-1) and inversely proportional to thickness. The wood house is more energy efficient since the wood wall is twice as thick but it has about one-fourth the conductivity of brick wall.

1-45C The rate of heat transfer through both walls can be expressed as

$$\begin{aligned}\dot{Q}_{\text{wood}} &= k_{\text{wood}} A \frac{T_1 - T_2}{L_{\text{wood}}} = (0.16 \text{ W/m} \cdot ^\circ\text{C}) A \frac{T_1 - T_2}{0.1 \text{ m}} = 1.6 A (T_1 - T_2) \\ \dot{Q}_{\text{brick}} &= k_{\text{brick}} A \frac{T_1 - T_2}{L_{\text{brick}}} = (0.72 \text{ W/m} \cdot ^\circ\text{C}) A \frac{T_1 - T_2}{0.25 \text{ m}} = 2.88 A (T_1 - T_2)\end{aligned}$$

where thermal conductivities are obtained from Table A-5. Therefore, heat transfer through the brick wall will be larger despite its higher thickness.

1-46C Emissivity is the ratio of the radiation emitted by a surface to the radiation emitted by a blackbody at the same temperature. Absorptivity is the fraction of radiation incident on a surface that is absorbed by the surface. The Kirchhoff's law of radiation states that the emissivity and the absorptivity of a surface are equal at the same temperature and wavelength.

1-47C A blackbody is an idealized body which emits the maximum amount of radiation at a given temperature and which absorbs all the radiation incident on it. Real bodies emit and absorb less radiation than a blackbody at the same temperature.

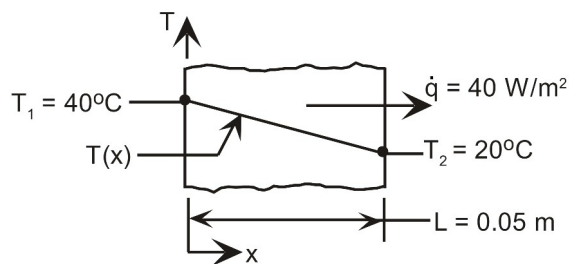
1-48 The thermal conductivity of a wood slab subjected to a given heat flux of 40 W/m^2 with constant left and right surface temperatures of 40°C and 20°C is to be determined.

Assumptions **1** Steady operating conditions exist since the surface temperatures of the wood slab remain constant at the specified values. **2** Heat transfer through the wood slab is one dimensional since the thickness of the slab is small relative to other dimensions. **3** Thermal conductivity of the wood slab is constant.

Analysis The thermal conductivity of the wood slab is determined directly from Fourier's relation to be

$$k = \frac{\dot{q} L}{T_1 - T_2} = \left(40 \frac{\text{W}}{\text{m}^2} \right) \frac{0.05 \text{ m}}{(40 - 20)^\circ\text{C}} = \mathbf{0.10 \text{ W/m}\cdot\text{K}}$$

Discussion Note that the $^\circ\text{C}$ or K temperature units may be used interchangeably when evaluating a temperature difference.



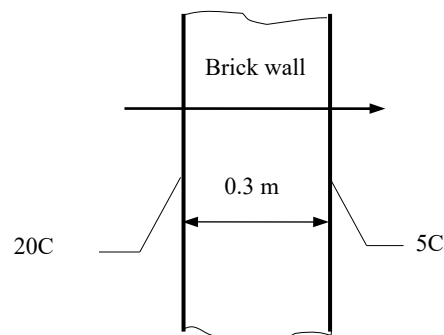
1-49 The inner and outer surfaces of a brick wall are maintained at specified temperatures. The rate of heat transfer through the wall is to be determined.

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

Properties The thermal conductivity of the wall is given to be $k = 0.69 \text{ W/m}\cdot^\circ\text{C}$.

Analysis Under steady conditions, the rate of heat transfer through the wall is

$$\dot{Q}_{\text{cond}} = kA \frac{\Delta T}{L} = (0.69 \text{ W/m}\cdot^\circ\text{C})(4 \times 7 \text{ m}^2) \frac{(20 - 5)^\circ\text{C}}{0.3 \text{ m}} = 966 \text{ W}$$



1-50E The inner and outer glasses of a double pane window with a 0.5-in air space are at specified temperatures. The rate of heat transfer through the window is to be determined

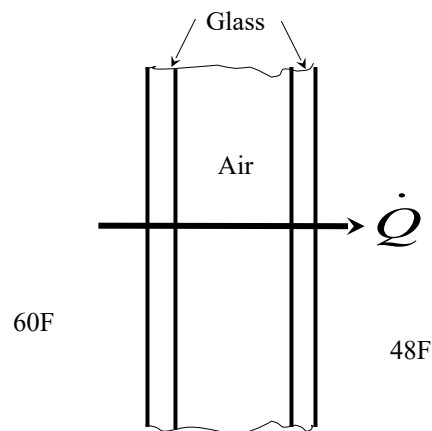
Assumptions **1** Steady operating conditions exist since the surface temperatures of the glass remain constant at the specified values. **2** Heat transfer through the window is one-dimensional. **3** Thermal properties of the air are constant.

Properties The thermal conductivity of air at the average temperature of $(60 + 48)/2 = 54^\circ\text{F}$ is $k = 0.01419 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F}$ (Table A-15E).

Analysis The area of the window and the rate of heat loss through it are

$$A = (4 \text{ ft}) \times (4 \text{ ft}) = 16 \text{ ft}^2$$

$$\dot{Q} = kA \frac{T_1 - T_2}{L} = (0.01419 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F})(16 \text{ ft}^2) \frac{(60 - 48)^\circ\text{F}}{0.25/12 \text{ ft}} = 131 \text{ Btu/h}$$



1-51 The inner and outer surfaces of a window glass are maintained at specified temperatures. The amount of heat transfer through the glass in 5 h 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 $k = 0.78 \text{ W/m}\cdot^\circ\text{C}$.

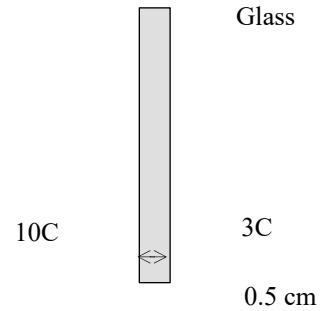
Analysis Under steady conditions, the rate of heat transfer through the glass by conduction is

$$\dot{Q}_{\text{cond}} = kA \frac{\Delta T}{L} = (0.78 \text{ W/m}\cdot^\circ\text{C})(2 \times 2 \text{ m}^2) \frac{(10 - 3)^\circ\text{C}}{0.005 \text{ m}} = 4368 \text{ W}$$

Then the amount of heat transfer over a period of 5 h becomes

$$Q = \dot{Q}_{\text{cond}} \Delta t = (4.368 \text{ kJ/s})(5 \times 3600 \text{ s}) = 78,620 \text{ kJ}$$

If the thickness of the glass doubled to 1 cm, then the amount of heat transfer will go down by half to **39,310 kJ**.





1-52 Prob. 1-51 is reconsidered. The amount of heat loss through the glass as a function of the window glass thickness is to be plotted.

Analysis The problem is solved using EES, and the solution is given below.

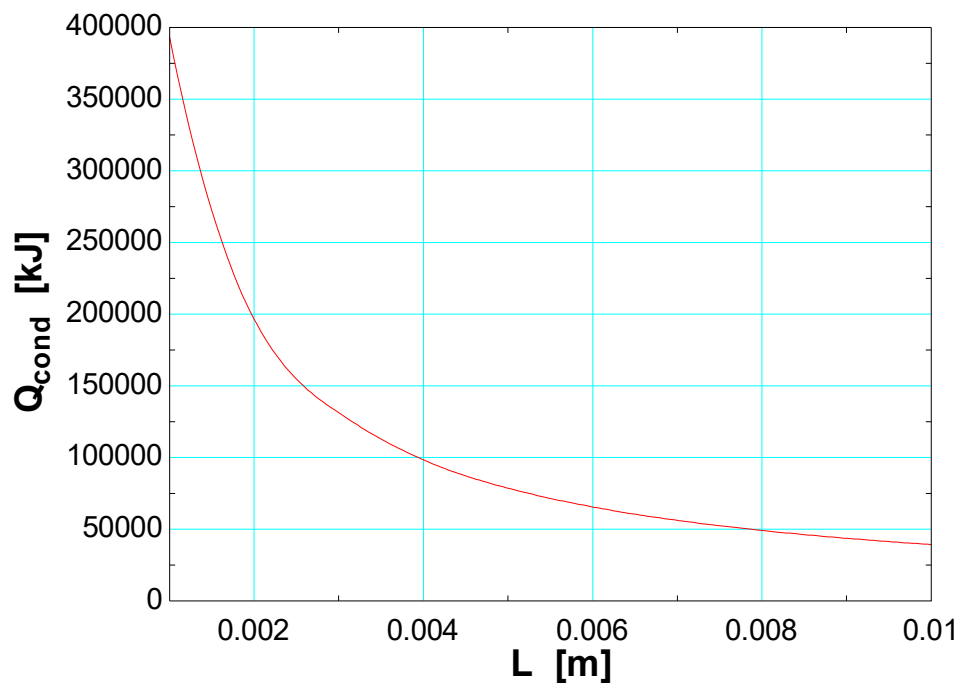
"GIVEN"

L=0.005 [m]
 A=2*2 [m^2]
 T_1=10 [C]
 T_2=3 [C]
 k=0.78 [W/m-C]
 time=5*3600 [s]

"ANALYSIS"

$\dot{Q}_{\text{cond}} = k \cdot A \cdot (T_1 - T_2) / L$
 $Q_{\text{cond}} = \dot{Q}_{\text{cond}} \cdot \text{time} \cdot \text{Convert}(\text{J}, \text{kJ})$

L [m]	Q _{cond} [kJ]
0.001	393120
0.002	196560
0.003	131040
0.004	98280
0.005	78624
0.006	65520
0.007	56160
0.008	49140
0.009	43680
0.01	39312



1-53 Heat is transferred steadily to boiling water in the pan through its bottom. The inner surface temperature of the bottom of the pan is given. The temperature of the outer surface is to be determined.

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

Properties The thermal conductivity of the aluminum is given to be $k = 237 \text{ W/m}\cdot^\circ\text{C}$.

Analysis The heat transfer area is

$$A = \pi r^2 = \pi (0.075 \text{ m})^2 = 0.0177 \text{ m}^2$$

Under steady conditions, the rate of heat transfer through the bottom of the pan by conduction is

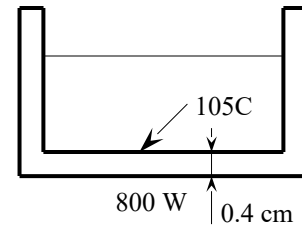
$$\dot{Q} = kA \frac{\Delta T}{L} = kA \frac{T_2 - T_1}{L}$$

Substituting,

$$800 \text{ W} = (237 \text{ W/m}\cdot^\circ\text{C})(0.0177 \text{ m}^2) \frac{T_2 - 105^\circ\text{C}}{0.004 \text{ m}}$$

which gives

$$T_2 = 105.76^\circ\text{C}$$



1-54E The inner and outer surface temperatures of the wall of an electrically heated home during a winter night are measured. The rate of heat loss through the wall that night and its cost are to be determined.

Assumptions 1 Steady operating conditions exist since the surface temperatures of the wall remain constant at the specified values during the entire night. 2 Thermal properties of the wall are constant.

Properties The thermal conductivity of the brick wall is given to be $k = 0.42 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F}$.

Analysis (a) Noting that the heat transfer through the wall is by conduction and the surface area of the wall is

$A = 20 \text{ ft} \times 10 \text{ ft} = 200 \text{ ft}^2$, the steady rate of heat transfer through the wall can be determined from

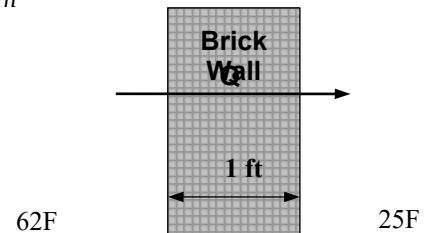
$$\dot{Q} = kA \frac{T_1 - T_2}{L} = (0.42 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F})(200 \text{ ft}^2) \frac{(62 - 25)^\circ\text{F}}{1 \text{ ft}} = 3108 \text{ Btu/h}$$

or 0.911 kW since $1 \text{ kW} = 3412 \text{ Btu/h}$.

(b) The amount of heat lost during an 8 hour period and its cost are

$$Q = \dot{Q} \Delta t = (0.911 \text{ kW})(8 \text{ h}) = 7.288 \text{ kWh}$$

$$\begin{aligned} \text{Cost} &= (\text{Amount of energy})(\text{Unit cost of energy}) \\ &= (7.288 \text{ kWh})(\$0.07/\text{kWh}) \\ &= \$0.51 \end{aligned}$$



Therefore, the cost of the heat loss through the wall to the home owner that night is \$0.51.

1-55 The thermal conductivity of a material is to be determined by ensuring one-dimensional heat conduction, and by measuring temperatures when steady operating conditions are reached.

Assumptions 1 Steady operating conditions exist since the temperature readings do not change with time. **2** Heat losses through the lateral surfaces of the apparatus are negligible since those surfaces are well-insulated, and thus the entire heat generated by the heater is conducted through the samples. **3** The apparatus possesses thermal symmetry.

Analysis The electrical power consumed by the heater and converted to heat is

$$\dot{W}_e = VI = (110 \text{ V})(0.6 \text{ A}) = 66 \text{ W}$$

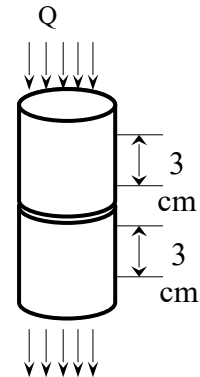
The rate of heat flow through each sample is

$$\dot{Q} = \frac{\dot{W}_e}{2} = \frac{66 \text{ W}}{2} = 33 \text{ W}$$

Then the thermal conductivity of the sample becomes

$$A = \frac{\pi D^2}{4} = \frac{\pi (0.04 \text{ m})^2}{4} = 0.001257 \text{ m}^2$$

$$\dot{Q} = kA \frac{\Delta T}{L} \rightarrow k = \frac{\dot{Q} L}{A \Delta T} = \frac{(33 \text{ W})(0.03 \text{ m})}{(0.001257 \text{ m}^2)(10^\circ \text{C})} = 78.8 \text{ W/m} \cdot ^\circ \text{C}$$



1-56 The thermal conductivity of a material is to be determined by ensuring one-dimensional heat conduction, and by measuring temperatures when steady operating conditions are reached.

Assumptions 1 Steady operating conditions exist since the temperature readings do not change with time. **2** Heat losses through the lateral surfaces of the apparatus are negligible since those surfaces are well-insulated, and thus the entire heat generated by the heater is conducted through the samples. **3** The apparatus possesses thermal symmetry.

Analysis For each sample we have

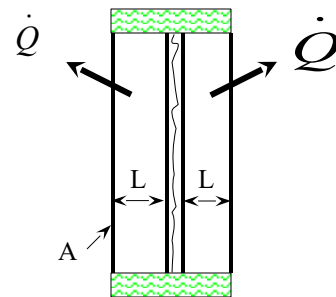
$$\dot{Q} = 25/2 = 12.5 \text{ W}$$

$$A = (0.1 \text{ m})(0.1 \text{ m}) = 0.01 \text{ m}^2$$

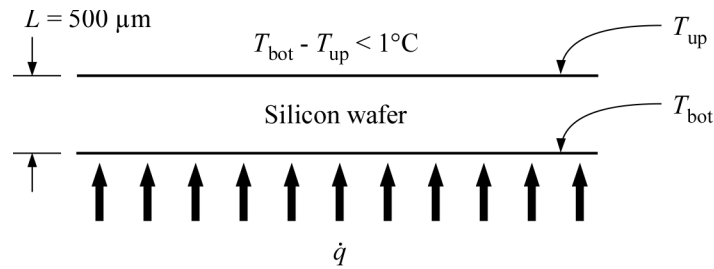
$$\Delta T = 82 - 74 = 8^\circ \text{C}$$

Then the thermal conductivity of the material becomes

$$\dot{Q} = kA \frac{\Delta T}{L} \rightarrow k = \frac{\dot{Q} L}{A \Delta T} = \frac{(12.5 \text{ W})(0.005 \text{ m})}{(0.01 \text{ m}^2)(8^\circ \text{C})} = 0.781 \text{ W/m} \cdot ^\circ \text{C}$$



1-57  To prevent a silicon wafer from warping, the temperature difference across its thickness cannot exceed 1°C . The maximum allowable heat flux on the bottom surface of the wafer is to be determined.



Assumptions **1** Heat conduction is steady and one-dimensional. **2** There is no heat generation. **3** Thermal conductivity is constant.

Properties The thermal conductivity of silicon at 27°C (300 K) is $148 \text{ W/m}\cdot\text{K}$ (Table A-3).

Analysis For steady heat transfer, the Fourier's law of heat conduction can be expressed as

$$\dot{q} = -k \frac{dT}{dx} = -k \frac{T_{\text{up}} - T_{\text{bot}}}{L}$$

Thus, the maximum allowable heat flux so that $T_{\text{bot}} - T_{\text{up}} < 1^\circ\text{C}$ is

$$\dot{q} \leq k \frac{T_{\text{bot}} - T_{\text{up}}}{L} = (148 \text{ W/m}\cdot\text{K}) \frac{1 \text{ K}}{500 \times 10^{-6} \text{ m}}$$

$$\dot{q} \leq 2.96 \times 10^5 \text{ W/m}^2$$

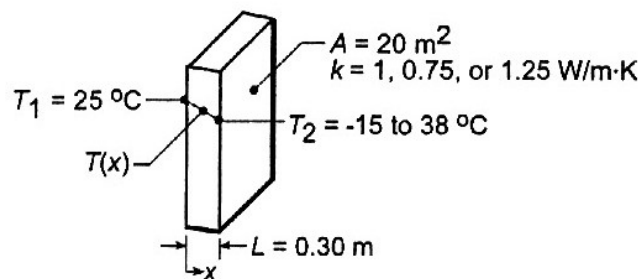
Discussion With the upper surface of the wafer maintained at 27°C , if the bottom surface of the wafer is exposed to a flux greater than $2.96 \times 10^5 \text{ W/m}^2$, the temperature gradient across the wafer thickness could be significant enough to cause warping.

1-58 Heat loss by conduction through a concrete wall as a function of ambient air temperatures ranging from -15 to 38°C is to be determined.

Assumptions 1 One-dimensional conduction. 2 Steady-state conditions exist. 3 Constant thermal conductivity. 4 Outside wall temperature is that of the ambient air.

Properties The thermal conductivity is given to be $k = 0.75$, 1 or $1.25 \text{ W/m}\cdot\text{K}$.

Analysis From Fourier's law, it is evident that the gradient, $dT/dx = -\dot{q}/k$, is a constant, and hence the temperature distribution is linear, if $\dot{q}$ and k are each constant. The heat flux must be constant under one-dimensional, steady-state conditions; and k are each approximately constant if it depends only weakly on temperature. The heat flux and heat rate for the case when the outside wall temperature is $T_2 = -15^\circ\text{C}$



and $k = 1 \text{ W/m}\cdot\text{K}$ are:

$$\dot{q} = -k \frac{dT}{dx} = k \frac{T_1 - T_2}{L} = (1 \text{ W/m}\cdot\text{K}) \frac{25^\circ\text{C} - (-15^\circ\text{C})}{0.30 \text{ m}} = 133.3 \text{ W/m}^2 \quad (1)$$

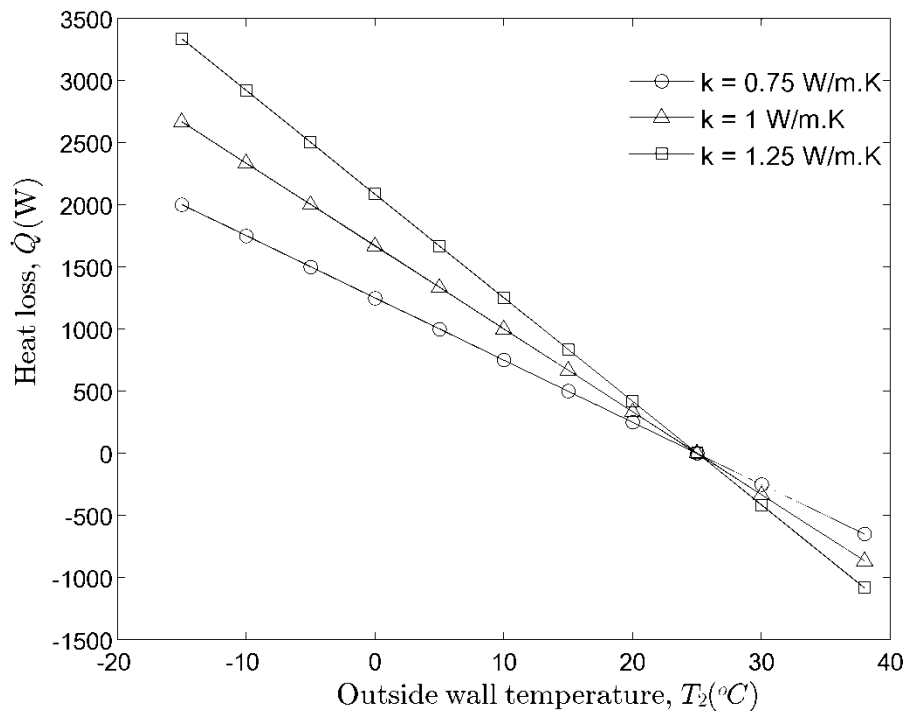
$$\dot{Q} = \dot{q} \cdot A = (133.3 \text{ W/m}^2) \cdot (20 \text{ m}^2) = 2667 \text{ W} \quad (2)$$

Combining Eqs. (1) and (2), the heat rate $\dot{Q}$ can be determined for the range of ambient temperature, $-15 \leq T_2 \leq 38^\circ\text{C}$, with different wall thermal conductivities, k .

Discussion (1) Notice that from the graph, the heat loss curves are linear for all three thermal conductivities. This is true because under steady-state and constant k conditions, the temperature distribution in the wall is linear. (2) As the value of k increases, the slope of the heat loss curve becomes steeper. This shows that for insulating materials (very low k), the heat loss curve would be relatively flat. The magnitude of the heat loss also increases with increasing thermal conductivity. (3) At $T_2 = 25^\circ\text{C}$, all the three heat loss curves intersect at zero; because $T_1 = T_2$ (when the inside and outside temperatures are the same), thus there is no heat conduction through the wall. This shows that heat conduction can only occur when there is temperature difference.

The results for the heat loss $\dot{Q}$ with different thermal conductivities k are tabulated and plotted as follows:

$T_2 [^\circ\text{C}]$	$\dot{Q} [\text{W}]$		
	$k = 0.75 \text{ W/m}\cdot\text{K}$	$k = 1 \text{ W/m}\cdot\text{K}$	$k = 1.25 \text{ W/m}\cdot\text{K}$
-15	2000	2667	3333
-10	1750	2333	2917
-5	1500	2000	2500
0	1250	1667	2083
5	1000	1333	1667
10	750	1000	1250
15	500	666.7	833.3
20	250	333.3	416.7
25	0	0	0
30	-250	-333.3	-416.7
38	-650	-866.7	-1083



1-59 A hollow spherical iron container is filled with iced water at 0°C . The rate of heat gain by the iced water and the rate at which ice melts in the container are to be determined.

Assumptions **1** Steady operating conditions exist since the surface temperatures of the wall remain constant at the specified values. **2** Heat transfer through the shell is one-dimensional. **3** Thermal properties of the iron shell are constant. **4** The inner surface of the shell is at the same temperature as the iced water, 0°C . **5** Treat the spherical shell as a plain wall and use the outer area.

Properties The thermal conductivity of iron is $k = 80.2 \text{ W/m}\cdot^{\circ}\text{C}$ (Table A-3). The heat of fusion of water is given to be 333.7 kJ/kg .

Analysis This spherical shell can be approximated as a plate of thickness 0.4 cm and area

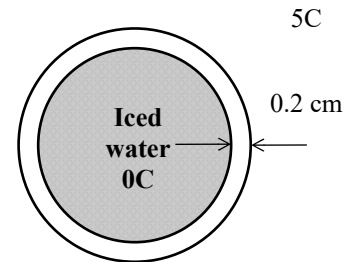
$$A = \pi D^2 = \pi (0.2 \text{ m})^2 = 0.126 \text{ m}^2$$

Then the rate of heat transfer through the shell by conduction is

$$\dot{Q}_{\text{cond}} = kA \frac{\Delta T}{L} = (80.2 \text{ W/m}\cdot^{\circ}\text{C})(0.126 \text{ m}^2) \frac{(5-0)^{\circ}\text{C}}{0.002 \text{ m}} = 25,263 \text{ W} = 25.3 \text{ kW}$$

Considering that it takes 333.7 kJ of energy to melt 1 kg of ice at 0°C , the rate at which ice melts in the container can be determined from

$$\dot{m}_{\text{ice}} = \frac{\dot{Q}}{h_{\text{if}}} = \frac{25.263 \text{ kJ/s}}{333.7 \text{ kJ/kg}} = 0.0757 \text{ kg/s}$$



Discussion We should point out that this result is slightly in error for approximating a curved wall as a plain wall. The error in this case is very small because of the large diameter to thickness ratio. For better accuracy, we could use the inner surface area ($D = 19.6 \text{ cm}$) or the mean surface area ($D = 19.8 \text{ cm}$) in the calculations.



1-60 Prob. 1-59 is reconsidered. The rate at which ice melts as a function of the container thickness is to be plotted.

Analysis The problem is solved using EES, and the solution is given below.

"GIVEN"

$$D=0.2 \text{ [m]}$$

$$L=0.2 \text{ [cm]}$$

$$T_1=0 \text{ [C]}$$

$$T_2=5 \text{ [C]}$$

"PROPERTIES"

$$h_{if}=333.7 \text{ [kJ/kg]}$$

$$k=k_{\text{Iron}, 25}$$

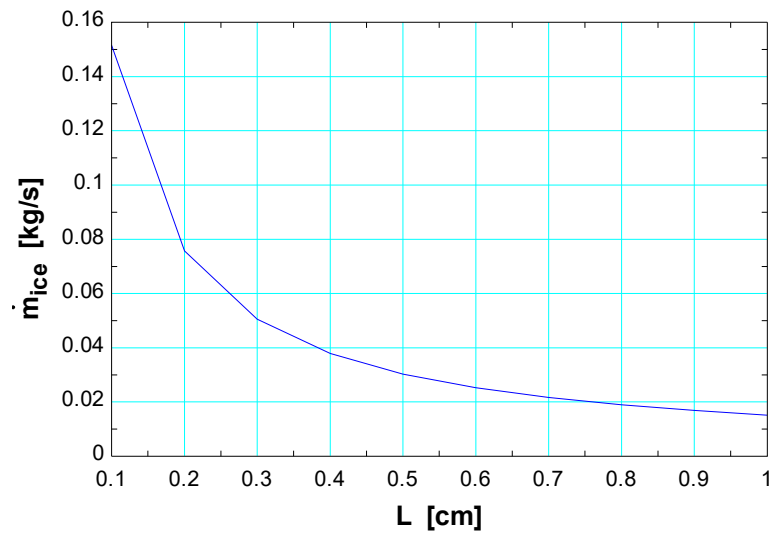
"ANALYSIS"

$$A=\pi \cdot D^2$$

$$Q_{\text{dot_cond}}=k \cdot A \cdot (T_2 - T_1) / (L \cdot \text{Convert}(\text{cm}, \text{m}))$$

$$\dot{m}_{\text{ice}}=(Q_{\text{dot_cond}} \cdot \text{Convert}(\text{W}, \text{kW})) / h_{if}$$

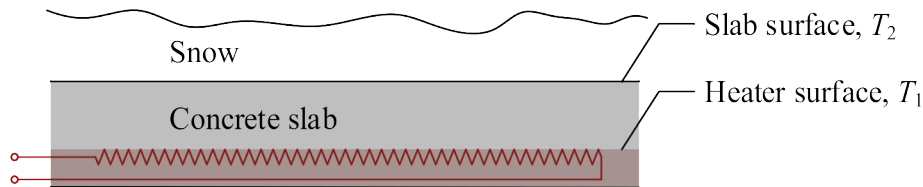
L [cm]	$\dot{m}_{\text{ice}}$ [kg/s]
0.1	0.1515
0.2	0.07574
0.3	0.0505
0.4	0.03787
0.5	0.0303
0.6	0.02525
0.7	0.02164
0.8	0.01894
0.9	0.01683
1	0.01515



1-61  A $5\text{ m} \times 5\text{ m}$ concrete slab with embedded heating cable melts snow at a rate of 0.1 kg/s . The power density (heat flux) for the embedded heater is to be determined whether it is in compliance with the NFPA 70 code. Also, the temperature difference between the heater surface and the slab surface is to be determined whether it exceeds 21°C , as recommended in the ASHRAE Handbook to minimize thermal stress.

Assumptions 1 Steady operating conditions. 2 Slab surface and heater surface temperatures are uniform. 3 Heat transfer through the concrete layer is one-dimensional. 3 Properties of the concrete are constant. 4 The heater heats the surface uniformly.

Properties The thermal conductivity of concrete is given as $1.4\text{ W/m}\cdot\text{K}$. The latent heat of fusion for water is 333.7 kJ/kg (Table A-2).



Analysis The heat rate required for melting snow at 0.1 kg/s is

$$\dot{Q} = \dot{m}_{\text{ice}} h_{if} = (0.1\text{ kg/s})(333700\text{ J/kg}) = 33370\text{ W}$$

For a surface area of $5\text{ m} \times 5\text{ m}$, the power density (heat flux) is

$$\dot{q} = \frac{\dot{Q}}{A_s} = \frac{33370\text{ W}}{25\text{ m}^2} = 1335\text{ W/m}^2 > 1300\text{ W/m}^2$$

To determine the temperature difference between the heater surface (T_1) and the slab surface (T_2), we use the Fourier law of conduction:

$$\dot{q} = k \frac{T_1 - T_2}{L}$$

or

$$T_1 - T_2 = \frac{\dot{q} L}{k} = \frac{(1335\text{ W/m}^2)(0.05\text{ m})}{1.4\text{ W/m}\cdot\text{K}} = 47.7^\circ\text{C} > 21^\circ\text{C}$$

Discussion The power density for the embedded heating cable in the concrete slab slightly exceeds the limit set by the National Electrical Code® (NFPA 70) of 1300 W/m^2 . The temperature difference between the heater surface and the slab surface is about 27°C higher than the recommended value by the 2015 ASHRAE Handbook—HVAC Applications, Chapter 51.

1-62E Using the conversion factors between W and Btu/h, m and ft, and °C and °F, the convection coefficient in SI units is to be expressed in Btu/h·ft²·°F.

Analysis The conversion factors for W and m are straightforward, and are given in conversion tables to be

$$1 \text{ W} = 3.41214 \text{ Btu/h}$$

$$1 \text{ m} = 3.2808 \text{ ft}$$

The proper conversion factor between °C into °F in this case is

$$1^\circ\text{C} = 1.8^\circ\text{F}$$

since the °C in the unit W/m²·°C represents *per °C change in temperature*, and 1°C change in temperature corresponds to a change of 1.8°F. Substituting, we get

$$1 \text{ W/m}^2\cdot^\circ\text{C} = \frac{3.41214 \text{ Btu/h}}{(3.2808 \text{ ft})^2 (1.8^\circ\text{F})} = 0.1761 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$$

which is the desired conversion factor. Therefore, the given convection heat transfer coefficient in English units is

$$h = 14 \text{ W/m}^2\cdot^\circ\text{C} = 14 \times 0.1761 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F} = 2.47 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$$

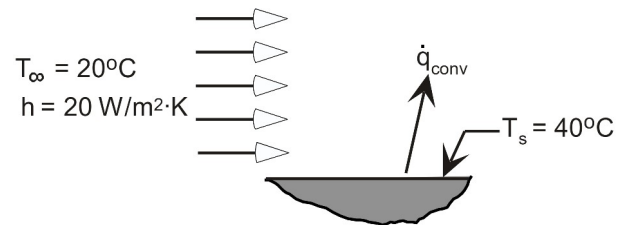
1-63 The heat flux between air with a constant temperature and convection heat transfer coefficient blowing over a pond at a constant temperature is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Convection heat transfer coefficient is uniform. **3** Heat transfer by radiation is negligible. **4** Air temperature and the surface temperature of the pond remain constant.

Analysis From Newton's law of cooling, the heat flux is given as

$$\dot{q}_{\text{conv}} = h (T_s - T_\infty)$$

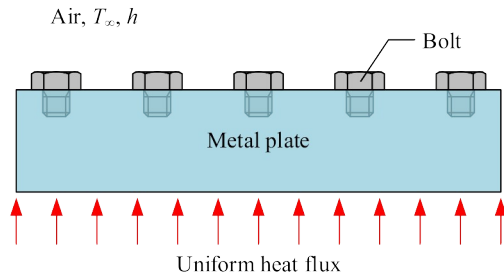
$$\dot{q}_{\text{conv}} = 20 \frac{\text{W}}{\text{m}^2\cdot\text{K}} (40 - 20)^\circ\text{C} = 400 \text{ W/m}^2$$



Discussion (1) Note the direction of heat flow is out of the surface since $T_s > T_\infty$; (2) Recognize why units of K in h and units of °C in $(T_s - T_\infty)$ cancel.

1-64 C&S A series of ASME SA-193 carbon steel bolts are bolted to the upper surface of a metal plate. The upper surface is exposed to convection with the ambient air. The bottom surface is subjected to a uniform heat flux. Determine whether the use of the bolts complies with the ASME Boiler and Pressure Vessel Code, where 260°C is the maximum allowable use temperature.

Assumptions 1 Heat transfer is steady. 2 One dimensional heat conduction through the metal plate. 3 Uniform heat flux on the bottom surface. 4 Uniform surface temperature at the upper plate surface. 5 The temperature of the bolts is equal to the upper surface temperature of the plate.



Analysis The uniform heat flux subjected on the bottom plate surface is equal to the heat flux transferred by convection on the upper surface.

$$\dot{q}_0 = \dot{q}_{\text{cond}} = \dot{q}_{\text{conv}} = 5000 \text{ W/m}^2$$

From the Newton's law of cooling, we have

$$\dot{q}_{\text{conv}} = h (T_s - T_\infty)$$

Assuming the temperature of the bolts is equal to the upper surface temperature of the plate,

$$T_{\text{bolt}} = T_s = \frac{\dot{q}_{\text{conv}}}{h} + T_\infty = \frac{5000 \text{ W/m}^2}{10 \text{ W/m}^2 \cdot \text{K}} + 30^\circ\text{C} = 530^\circ\text{C} > 260^\circ\text{C}$$

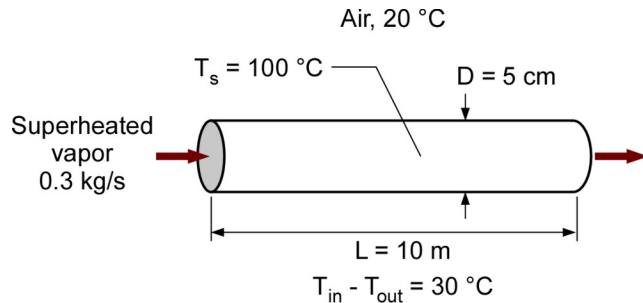
Discussion The temperature of the bolts exceeds the maximum allowable use temperature by 260°C. One way to keep the temperature of the bolts below 260°C is by increasing the convection heat transfer coefficient. Higher convection heat transfer coefficient can be achieved by having forced convection. To keep the upper surface temperature of the plate at 260°C or lower, the convection heat transfer coefficient should be higher than 21.7 W/m²·K.

$$h > \frac{\dot{q}_{\text{conv}}}{T_s - T_\infty} > \frac{5000 \text{ W/m}^2}{(260 - 30) \text{ K}} > 21.7 \text{ W/m}^2 \cdot \text{K}$$

1-65 The convection heat transfer coefficient heat transfer between the surface of a pipe carrying superheated vapor and the surrounding is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat transfer by radiation is not considered. 3 Rate of heat loss from the vapor in the pipe is equal to the heat transfer rate by convection between pipe surface and the surrounding.

Properties The specific heat of vapor is given to be $2190 \text{ J/kg} \cdot ^\circ\text{C}$.



Analysis The surface area of the pipe is

$$A_s = \pi DL = \pi(0.05 \text{ m})(10 \text{ m}) = 1.571 \text{ m}^2$$

The rate of heat loss from the vapor in the pipe can be determined from

$$\begin{aligned} \dot{Q}_{\text{loss}} &= \dot{m} c_p (T_{\text{in}} - T_{\text{out}}) \\ &= (0.3 \text{ kg/s})(2190 \text{ J/kg} \cdot ^\circ\text{C})(30)^\circ\text{C} = 19710 \text{ J/s} \\ &= 19710 \text{ W} \end{aligned}$$

With the rate of heat loss from the vapor in the pipe assumed equal to the heat transfer rate by convection, the heat transfer coefficient can be determined using the Newton's law of cooling:

$$\dot{Q}_{\text{loss}} = \dot{Q}_{\text{conv}} = hA_s(T_s - T_\infty)$$

Rearranging, the heat transfer coefficient is determined to be

$$h = \frac{\dot{Q}_{\text{loss}}}{A_s(T_s - T_\infty)} = \frac{19710 \text{ W}}{(1.571 \text{ m}^2)(100 - 20)^\circ\text{C}} = 157 \text{ W/m}^2 \cdot ^\circ\text{C}$$

Discussion By insulating the pipe surface, heat loss from the vapor in the pipe can be reduced.

1-66  A boiler supplies hot water to a dishwasher through a pipe at 60 g/s. The pipe dimensions are given. The water exits the boiler at 95°C. The pipe section between the boiler and the dishwasher is exposed to convection. The water temperature entering the dishwasher is to be determined whether it meets the ANSI/NSF 3 standard.

Assumptions 1 Constant properties are used for the water. 2 Steady operating conditions. 3 Surface temperature of the pipe is uniform.

Properties The average specific heat of water is given to be 4.20 kJ/kg·K.

Analysis From energy balance, the rate of heat loss from the pipe is equal to the heat transfer rate by convection on the pipe surface:

$$\dot{Q}_{\text{pipe}} = \dot{Q}_{\text{conv}}$$

$$\dot{m} c_p (T_1 - T_2) = h A_s (T_s - T_\infty)$$

Solving for the water temperature entering the dishwasher T_2 , we have

$$T_2 = T_1 - \frac{h A_s}{\dot{m} c_p} (T_s - T_\infty)$$

$$T_2 = 95^\circ\text{C} - \frac{\pi (0.02 \text{ m}) (20 \text{ m}) (100 \text{ W/m}^2 \cdot \text{K})}{(0.06 \text{ kg/s}) (4200 \text{ J/kg} \cdot \text{K})} (50 - 20)^\circ\text{C}$$

$$T_2 = 80^\circ\text{C} < 82^\circ\text{C}$$

Discussion The hot water entering the dishwasher is 2°C lower than the temperature required by the ANSI/NSF 3 standard. To increase the water temperature entering the dishwasher, one or combination of the following steps can be taken: (a) add insulation on the pipe wall to reduce the heat loss from the pipe surface; (b) increase the water mass flow rate; (c) reduce the pipe distance between the boiler and the dishwasher; and (d) increase the water temperature coming out from the boiler.

1-67  Hot liquid flows in a pipe with PVDF lining on the inner surface. The pipe outer surface is subjected to uniform heat flux. The liquid mean temperature and convection heat transfer coefficient are given. Determine whether the surface temperature of the lining complies with the ASME Code for Process Piping.

Assumptions 1 Steady operating conditions. 2 Heat transfer is one-dimensional through the pipe wall. 3 Surface temperature is uniform. 4 Thermal properties are constant.

Analysis The surface energy balance on the PVDF lining is

$$\dot{E}_{\text{in}} = \dot{E}_{\text{out}}$$

$$\dot{Q}_o = \dot{Q}_{\text{conv}}$$

$$\dot{q}_0 A_{s,o} = h A_{s,i} (T_s - T_f)$$

The outer and inner surface areas of the pipe are

$$A_{s,o} = \pi D_o L \quad \text{and} \quad A_{s,i} = \pi D_i L$$

Solving for the lining surface temperature T_s ,

$$\dot{q}_0 (\pi D_o L) = h (\pi D_i L) (T_s - T_f)$$

$$T_s = \frac{\dot{q}_0 D_o}{h D_i} + T_f = \frac{(1200 \text{ W/m}^2) (27 \text{ mm})}{(50 \text{ W/m}^2 \cdot \text{K}) (22 \text{ mm})} + 120^\circ\text{C} = 149.5^\circ\text{C} > 135^\circ\text{C}$$

Discussion The surface temperature of the lining exceeds the maximum temperature recommended by the ASME Process Piping code for PVDF lining. A different thermoplastic lining should be used. Polytetrafluoroethylene (PTFE) lining has a recommended maximum temperature of 260°C by the ASME Code for Process Piping (ASME B31.3-2014, A323), which would meet these conditions.

1-68 An electrical resistor with a uniform temperature of 90 °C is in a room at 20 °C. The heat transfer coefficient by convection is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Radiation heat transfer is negligible. **3** No hot spot exists on the resistor.

Analysis The total heat transfer area of the resistor is

$$A_s = 2(\pi D^2/4) + \pi DL = 2\pi(0.025 \text{ m})^2/4 + \pi(0.025 \text{ m})(0.15 \text{ m}) = 0.01276 \text{ m}^2$$

The electrical energy converted to thermal energy is transferred by convection:

$$\dot{Q}_{\text{conv}} = IV = (5 \text{ A})(6 \text{ V}) = 30 \text{ W}$$

From Newton's law of cooling, the heat transfer by convection is given as

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

Rearranging, the heat transfer coefficient is determined to be

$$h = \frac{\dot{Q}_{\text{conv}}}{A_s(T_s - T_\infty)} = \frac{30 \text{ W}}{(0.01276 \text{ m}^2)(90 - 20)^\circ\text{C}} = 33.6 \text{ W/m}^2 \cdot ^\circ\text{C}$$

Discussion By comparing the magnitude of the heat transfer coefficient determined here with the values presented in Table 1-5, one can conclude that it is likely that forced convection is taking place rather than free convection.

1-69  An electrical cable is covered with polyethylene insulation and is subjected to convection with the ambient air. Determine whether the insulation surface temperature meets the ASTM D1351 standard for polyethylene insulation.

Assumptions **1** Steady operating conditions. **2** Radiation heat transfer is negligible. **3** No hot spot exists on the cable.

Analysis The electrical energy that is converted to thermal energy is determined using the Joule heating relation:

$$\dot{Q} = IV = (1 \text{ A})(30 \text{ V}) = 30 \text{ W}$$

The thermal energy for the joule heating is then transferred through the insulation layer by conduction, and then by convection at the outer surface of the insulation. From the Newton's law of cooling for convection, we have

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

Rearranging the equation and solving for the surface temperature,

$$T_s = \frac{\dot{Q}}{hA_s} + T_\infty = \frac{30 \text{ W}}{(5 \text{ W/m}^2 \cdot \text{K})(0.1 \text{ m}^2)} + 20^\circ\text{C} = 80^\circ\text{C} > 75^\circ\text{C}$$

Discussion With the surface temperature being 5°C higher than the specification of the ASTM D1351 standard for polyethylene insulation that means the temperature at the inner surface of the insulation being in contact with the cable would be higher than 80°C. To solve this problem, we will need to use a larger diameter (or thicker) cable. The electrical resistance decreases with increasing cable thickness, which would reduce joule heating. We can also use a different insulation material with a higher temperature rating. From the ASTM database, the crosslinked polyethylene insulation (ASTM D2655) is rated up to 90°C for normal operation.

1-70  An AISI 316 spherical container is used for storing chemical undergoing exothermic reaction that provide a uniform heat flux to its inner surface. The necessary convection heat transfer coefficient to keep the container's outer surface below 50°C is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Negligible thermal storage for the container. 3 Temperature at the surface remained uniform.

Analysis The heat rate from the chemical reaction provided to the inner surface equal to heat rate removed from the outer surface by convection

$$\dot{Q}_{in} = \dot{Q}_{out}$$

$$\dot{q}_{reaction} A_{s,in} = h A_{s,out} (T_s - T_\infty)$$

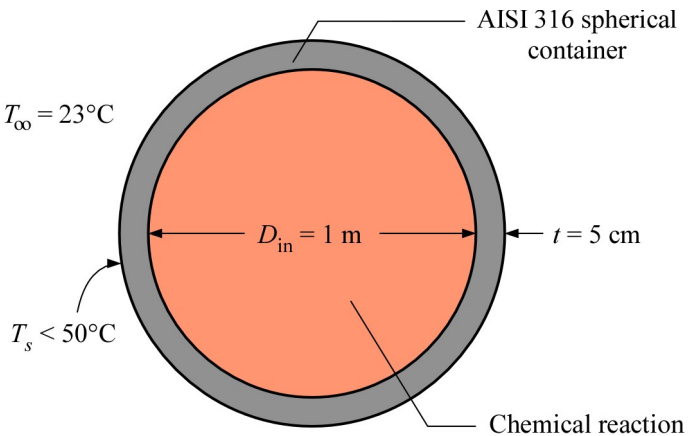
$$\dot{q}_{reaction} (\pi D_{in}^2) = h (\pi D_{out}^2) (T_s - T_\infty) \quad \text{Air, } T_\infty = 23^\circ\text{C}$$

The convection heat transfer coefficient can be determined as

$$h = \frac{\dot{q}_{reaction}}{T_s - T_\infty} \left(\frac{D_{in}}{D_{out}} \right)^2$$

$$\dot{q}_{reaction} = \frac{60000 \text{ W/m}^2}{(50 - 23) \text{ K}} \left(\frac{1 \text{ m}}{1 \text{ m} + 2 \times 0.05 \text{ m}} \right)^2$$

$$\dot{q}_{reaction} = 1840 \text{ W/m}^2 \cdot \text{K}$$



To keep the container's outer surface temperature below 50°C, the convection heat transfer coefficient should be

$$h > 1840 \text{ W/m}^2 \cdot \text{K}$$

Discussion From Table 1-5, the typical values for free convection heat transfer coefficient of gases are between 2–25 W/m²·K. Thus, the required $h > 1840 \text{ W/m}^2 \cdot \text{K}$ is not feasible with free convection of air. To prevent thermal burn, the container's outer surface temperature should be covered with insulation.

1-71 A transistor mounted on a circuit board is cooled by air flowing over it. The transistor case temperature is not to exceed 70°C when the air temperature is 55°C. The amount of power this transistor can dissipate safely is 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. 4 Heat transfer from the base of the transistor is negligible.

Analysis Disregarding the base area, the total heat transfer area of the transistor is

$$A_s = \pi DL + \pi D^2/4$$

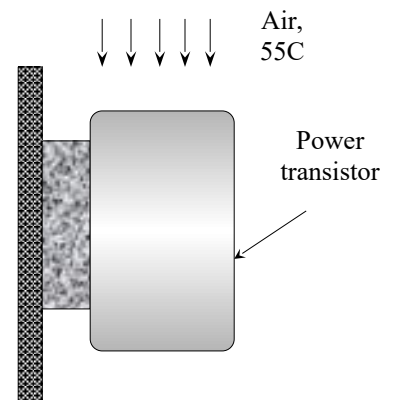
$$\dot{q}_{reaction} = \pi (0.6 \text{ cm})(0.4 \text{ cm}) + \pi (0.6 \text{ cm})^2/4 = 1.037 \text{ cm}^2$$

$$\dot{q}_{reaction} = 1.037 \times 10^{-4} \text{ m}^2$$

Then the rate of heat transfer from the power transistor at specified conditions is

$$\dot{Q} = h A_s (T_s - T_\infty) = (30 \text{ W/m}^2 \cdot ^\circ\text{C})(1.037 \times 10^{-4} \text{ m}^2)(70 - 55)^\circ\text{C} = 0.047 \text{ W}$$

Therefore, the amount of power this transistor can dissipate safely is 0.047 W.



1-72E 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

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

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

$$\dot{Q}_{\text{pipe}} = 289,000 \text{ Btu/h}$$

(b) The amount of heat loss per year is

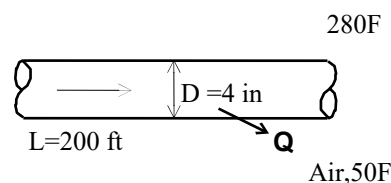
$$Q = \dot{Q} \Delta t = (289,000 \text{ Btu/h})(365 \times 24 \text{ h/yr}) = 2.531 \times 10^9 \text{ Btu/yr}$$

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

$$\text{Annual Energy Loss} = \frac{2.531 \times 10^9 \text{ Btu/yr}}{0.86} \left(\frac{1 \text{ therm}}{100,000 \text{ Btu}} \right) = 29,435 \text{ therms/yr}$$

Then the annual cost of the energy lost becomes

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



1-73 A 4-m diameter spherical tank filled with liquid nitrogen at 1 atm and -196°C is exposed to convection with ambient air. The rate of evaporation of liquid nitrogen in the tank as a result of the heat transfer from the ambient air is 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. 4 The temperature of the thin-shelled spherical tank is nearly equal to the temperature of the nitrogen inside.

Properties The heat of vaporization and density of liquid nitrogen at 1 atm are given to be 198 kJ/kg and 810 kg/m³, respectively.

Analysis The rate of heat transfer to the nitrogen tank is

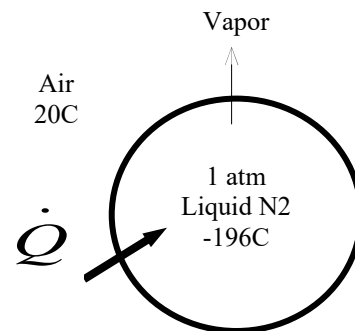
$$A_s = \pi D^2 = \pi (4 \text{ m})^2 = 50.27 \text{ m}^2$$

$$\dot{Q} = hA_s(T_s - T_{\text{air}}) = (25 \text{ W/m}^2 \cdot ^\circ\text{C})(50.27 \text{ m}^2)[20 - (-196)]^\circ\text{C}$$

$$\dot{Q} = 271,430 \text{ W}$$

Then the rate of evaporation of liquid nitrogen in the tank is determined to be

$$\dot{Q} = \dot{m} h_{fg} \rightarrow \dot{m} = \frac{\dot{Q}}{h_{fg}} = \frac{271.430 \text{ kJ/s}}{198 \text{ kJ/kg}} = 1.37 \text{ kg/s}$$



1-74 Power required to maintain the surface temperature of a long, 25 mm diameter cylinder with an imbedded electrical heater for different air velocities.

Assumptions 1 Temperature is uniform over the cylinder surface. 2 Negligible radiation exchange between the cylinder surface and the surroundings. 3 Steady state conditions.

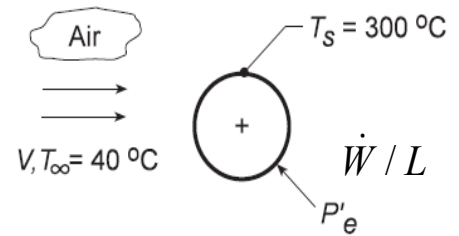
Analysis (a) From an overall energy balance on the cylinder, the power dissipated by the electrical heater is transferred by convection to the air stream. Using Newton's law of cooling on a per unit length basis,

$$\dot{W}/L = h A_s (T_s - T_\infty) = h (\pi D) (T_s - T_\infty)$$

where $\dot{W}/L$ is the electrical power dissipated per unit length of the cylinder. For the $V = 1$ m/s condition, using the data from the table given in the problem statement, find

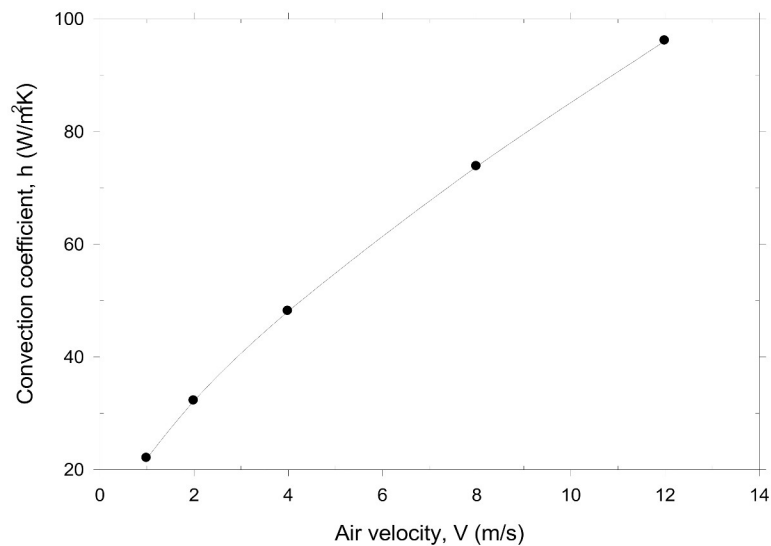
$$h = (\dot{W}/L) / (\pi D) (T_s - T_\infty)$$

$$h = 450 \text{ W/m} / (\pi \times 0.025 \text{ m}) (300 - 40)^\circ\text{C} = 22.0 \text{ W/m}^2\cdot\text{K}$$



Repeating the calculations for the rest of the V values given, find the convection coefficients for the remaining conditions in the table. The results are tabulated and plotted below. Note that h is not linear with respect to the air velocity.

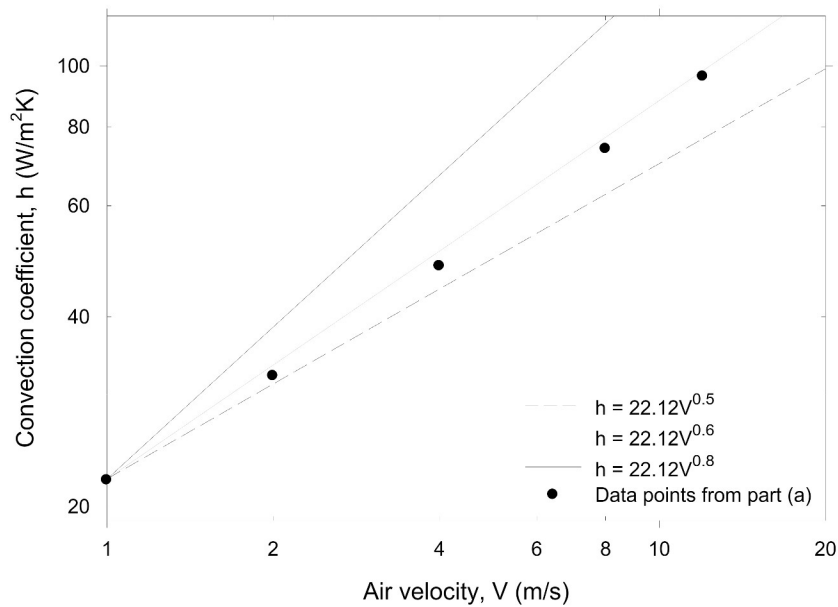
V (m/s)	$\dot{W}/L$ (W/m)	h (W/m ² ·K)
1	450	22.0
2	658	32.2
4	983	48.1
8	1507	73.8
12	1963	96.1



Plot of convection coefficient (h) versus air velocity (V)

(b) To determine the constants C and n , plot h vs. V on log-log coordinates. Choosing $C = 22.12 \text{ W/m}^2\cdot\text{K}(\text{s/m})^n$, assuring a match at $V = 1$, we can readily find the exponent n from the slope of the h vs. V curve. From the trials with $n = 0.8, 0.6$ and 0.5 , we recognize that $n = 0.6$ is a reasonable choice. Hence, the best values of the constants are: **$C = 22.12$** and **$n = 0.6$** . The details of these trials are given in the following table and plot.

$V \text{ (m/s)}$	$\dot{W}/L \text{ (W/m)}$	$h \text{ (W/m}^2\cdot\text{K)}$	$h=22.12V^n \text{ (W/m}^2\cdot\text{K)}$		
			$n = 0.5$	$n = 0.6$	$n = 0.8$
1	450	22.0	22.12	22.12	22.12
2	658	32.2	31.28	33.53	38.51
4	983	48.1	44.24	50.82	67.06
8	1507	73.8	62.56	77.03	116.75
12	1963	96.1	76.63	98.24	161.48



Plots for $h = CV^n$ with $C = 22.12$ and $n = 0.5, 0.6$, and 0.8

Discussion Radiation may not be negligible, depending on the surface emissivity.

1-75 The convection heat transfer coefficient for heat transfer from an electrically heated wire to air is to be determined by measuring temperatures when steady operating conditions are reached and the electric power consumed.

Assumptions 1 Steady operating conditions exist since the temperature readings do not change with time. **2** Radiation heat transfer is negligible.

Analysis In steady operation, the rate of heat loss from the wire equals the rate of heat generation in the wire as a result of resistance heating. That is,

$$\dot{Q} = \dot{E}_{\text{generated}} = VI = (110 \text{ V})(3 \text{ A}) = 330 \text{ W}$$

The surface area of the wire is

$$A_s = \pi DL = \pi(0.002 \text{ m})(1.4 \text{ m}) = 0.00880 \text{ m}^2$$

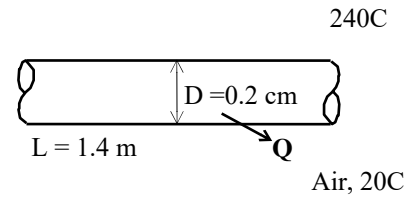
The Newton's law of cooling for convection heat transfer is expressed as

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

Disregarding any heat transfer by radiation, the convection heat transfer coefficient is determined to be

$$h = \frac{\dot{Q}}{A_s(T_s - T_\infty)} = \frac{330 \text{ W}}{(0.00880 \text{ m}^2)(240 - 20)^\circ\text{C}} = 170.5 \text{ W/m}^2 \cdot ^\circ\text{C}$$

Discussion If the temperature of the surrounding surfaces is equal to the air temperature in the room, the value obtained above actually represents the combined convection and radiation heat transfer coefficient.





1-76 Prob. 1-75 is reconsidered. The convection heat transfer coefficient as a function of the wire surface temperature is to be plotted.

Analysis The problem is solved using EES, and the solution is given below.

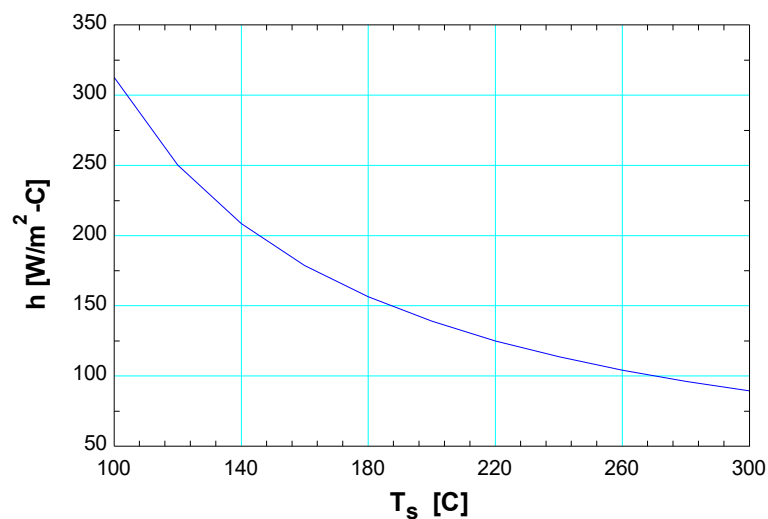
"GIVEN"

L=2.1 [m]
D=0.002 [m]
T_infinity=20 [C]
T_s=180 [C]
V=110 [Volt]
I=3 [Ampere]

"ANALYSIS"

Q_dot=V*I
A=pi*D*L
Q_dot=h*A*(T_s-T_infinity)

T _s [C]	h [W/m ² ·C]
100	312.6
120	250.1
140	208.4
160	178.6
180	156.3
200	138.9
220	125.1
240	113.7
260	104.2
280	96.19
300	89.32



1-77E Using the conversion factors between W and Btu/h, m and ft, and K and R, the Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4$ is to be expressed in the English unit, $\text{Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4$.

Analysis The conversion factors for W, m, and K are given in conversion tables to be

$$1 \text{ W} = 3.41214 \text{ Btu/h}$$

$$1 \text{ m} = 3.2808 \text{ ft}$$

$$1 \text{ K} = 1.8 \text{ R}$$

Substituting gives the Stefan-Boltzmann constant in the desired units,

$$\sigma = 5.67 \text{ W/m}^2 \cdot \text{K}^4 = 5.67 \times \frac{3.41214 \text{ Btu/h}}{(3.2808 \text{ ft})^2 (1.8 \text{ R})^4} = 0.171 \text{ Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4$$

1-78 A spacecraft in space absorbs solar radiation while losing heat to deep space by thermal radiation. The surface temperature of the spacecraft is to be determined when steady conditions are reached.

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

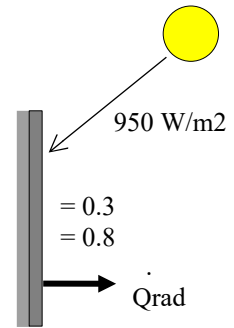
Properties The outer surface of a spacecraft has an emissivity of 0.8 and an absorptivity of 0.3.

Analysis When the heat loss from the outer surface of the spacecraft by radiation equals the solar radiation absorbed, the surface temperature can be determined from

$$\begin{aligned}\dot{Q}_{\text{solar absorbed}} &= \dot{Q}_{\text{rad}} \\ \alpha \dot{Q}_{\text{solar}} &= \varepsilon \sigma A_s (T_s^4 - T_{\text{space}}^4) \\ 0.3 \times A_s \times (950 \text{ W/m}^2) &= 0.8 \times A_s \times (5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4) [T_s^4 - (0 \text{ K})^4]\end{aligned}$$

Canceling the surface area A and solving for T_s gives

$$T_s = 281.5 \text{ K}$$



1-79 A person with a specified surface temperature is subjected to radiation heat transfer in a room at specified wall temperatures. The rate of radiation heat loss from the person is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat transfer by convection is disregarded. 3 The emissivity of the person is constant and uniform over the exposed surface.

Properties The average emissivity of the person is given to be 0.5.

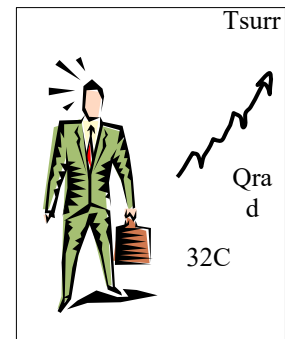
Analysis Noting that the person is completely enclosed by the surrounding surfaces, the net rates of radiation heat transfer from the body to the surrounding walls, ceiling, and the floor in both cases are

(a) $T_{\text{surr}} = 300 \text{ K}$

$$\begin{aligned}\dot{Q}_{\text{rad}} &= \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4) \\ &= (0.5)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1.7 \text{ m}^2)[(32+273)^4 - (300 \text{ K})^4] \text{ K}^4 \\ &= 26.7 \text{ W}\end{aligned}$$

(b) $T_{\text{surr}} = 280 \text{ K}$

$$\begin{aligned}\dot{Q}_{\text{rad}} &= \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4) \\ &= (0.5)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1.7 \text{ m}^2)[(32+273)^4 - (280 \text{ K})^4] \text{ K}^4 \\ &= 121 \text{ W}\end{aligned}$$



Discussion Note that the radiation heat transfer goes up by more than 4 times as the temperature of the surrounding surfaces drops from 300 K to 280 K.

1-80 A sealed electronic box dissipating a total of 100 W of power is placed in a vacuum chamber. If this box is to be cooled by radiation alone and the outer surface temperature of the box is not to exceed 55°C, the temperature the surrounding surfaces must be kept is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat transfer by convection is disregarded. 3 The emissivity of the box is constant and uniform over the exposed surface. 4 Heat transfer from the bottom surface of the box to the stand is negligible.

Properties The emissivity of the outer surface of the box is given to be 0.95.

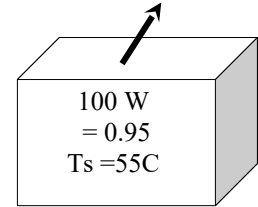
Analysis Disregarding the base area, the total heat transfer area of the electronic box is

$$A_s = (0.4 \text{ m})(0.4 \text{ m}) + 4 \times (0.2 \text{ m})(0.4 \text{ m}) = 0.48 \text{ m}^2$$

The radiation heat transfer from the box can be expressed as

$$\dot{Q}_{\text{rad}} = \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4)$$

$$100 \text{ W} = (0.95)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(0.48 \text{ m}^2) \left[(55 + 273 \text{ K})^4 - T_{\text{surr}}^4 \right]$$



which gives $T_{\text{surr}} = 296.3 \text{ K} = 23.3^\circ\text{C}$. Therefore, the temperature of the surrounding surfaces must be less than 23.3°C.

1-81 One highly polished surface at 1070°C and one heavily oxidized surface are emitting the same amount of energy per unit area. The temperature of the heavily oxidized surface is to be determined.

Assumptions The emissivity of each surface is constant and uniform.

Properties The emissivity of the highly polished surface is $\varepsilon_1 = 0.1$, and the emissivity of heavily oxidized surface is $\varepsilon_2 = 0.78$.

Analysis The rate of energy emitted by radiation is

$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4$$

For both surfaces to emit the same amount energy per unit area

$$(\dot{Q}_{\text{emit}}/A_s)_1 = (\dot{Q}_{\text{emit}}/A_s)_2$$

or

$$\varepsilon_1 T_{s,1}^4 = \varepsilon_2 T_{s,2}^4$$

The temperature of the heavily oxidized surface is

$$T_{s,2} = \left(\frac{\varepsilon_1}{\varepsilon_2} T_{s,1}^4 \right)^{1/4} = \left[\frac{0.1}{0.78} (1070 + 273)^4 \right]^{1/4} \text{ K} = 803.6 \text{ K}$$

Discussion If both surfaces are maintained at the same temperature, then the highly polished surface will emit less energy than the heavily oxidized surface.

1-82 A spherical probe in space absorbs solar radiation while losing heat to deep space by thermal radiation. The incident radiation rate on the probe surface is to be determined.

Assumptions 1 Steady operating conditions exist and surface temperature remains constant. 2 Heat generation is uniform.

Properties The outer surface the probe has an emissivity of 0.9 and an absorptivity of 0.1.

Analysis The rate of heat transfer at the surface of the probe can be expressed as

$$\begin{aligned}\dot{Q}_{\text{gen}} &= \dot{Q}_{\text{rad}} - \dot{Q}_{\text{absorbed}} \\ \dot{e}_{\text{gen}} V &= \varepsilon \sigma A_s (T_s^4 - T_{\text{space}}^4) - \alpha A_s \dot{q}_{\text{solar}} \\ \dot{e}_{\text{gen}} \left(\frac{4}{3} \pi r^3 \right) &= \varepsilon \sigma (4 \pi r^2) (T_s^4 - T_{\text{space}}^4) - \alpha (4 \pi r^2) \dot{q}_{\text{solar}}\end{aligned}$$

Thus, incident radiation rate on the probe surface is

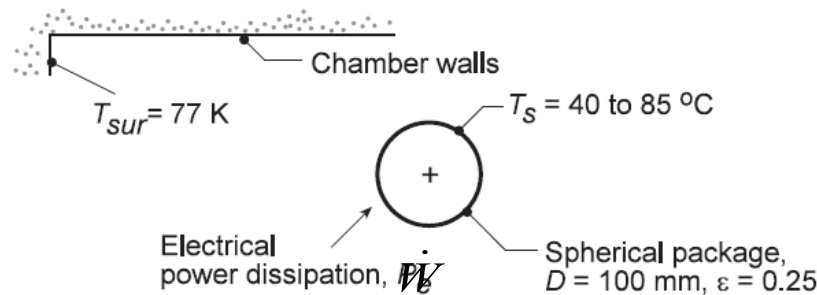
$$\begin{aligned}\dot{q}_{\text{solar}} &= \frac{1}{\alpha} \left[\varepsilon \sigma (T_s^4 - T_{\text{space}}^4) - \frac{r}{3} \dot{e}_{\text{gen}} \right] \\ \dot{q}_{\text{solar}} &= \frac{1}{0.1} \left[(0.9) (5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4) [(-40 + 273)^4 - 0] \right] \text{K}^4 - \frac{(1 \text{ m})(100 \text{ W/m}^3)}{3} \Bigg] = 1171 \text{ W/m}^2\end{aligned}$$

$$\dot{Q}_{\text{solar}} = A_s \dot{q}_{\text{solar}} = (4 \pi r^2) \dot{q}_{\text{solar}} = 4 \pi (1 \text{ m})^2 (1171 \text{ W/m}^2) = 14,715 \text{ W}$$

Discussion By adjusting the emissivity or absorptivity of the probe surface, the amount of incident radiation rate on the surface can be changed.

1-83 Spherical shaped instrumentation package with prescribed surface emissivity within a large laboratory room having walls at 77 K.

Assumptions **1** Uniform surface temperature. **2** Laboratory room walls are large compared to the spherical package. **3** Steady state conditions.



Analysis From an overall energy balance on the package, the internal power dissipation $\dot{W}$ will be transferred by radiation exchange between the package and the laboratory walls. The net rate of radiation between these two surfaces is given by

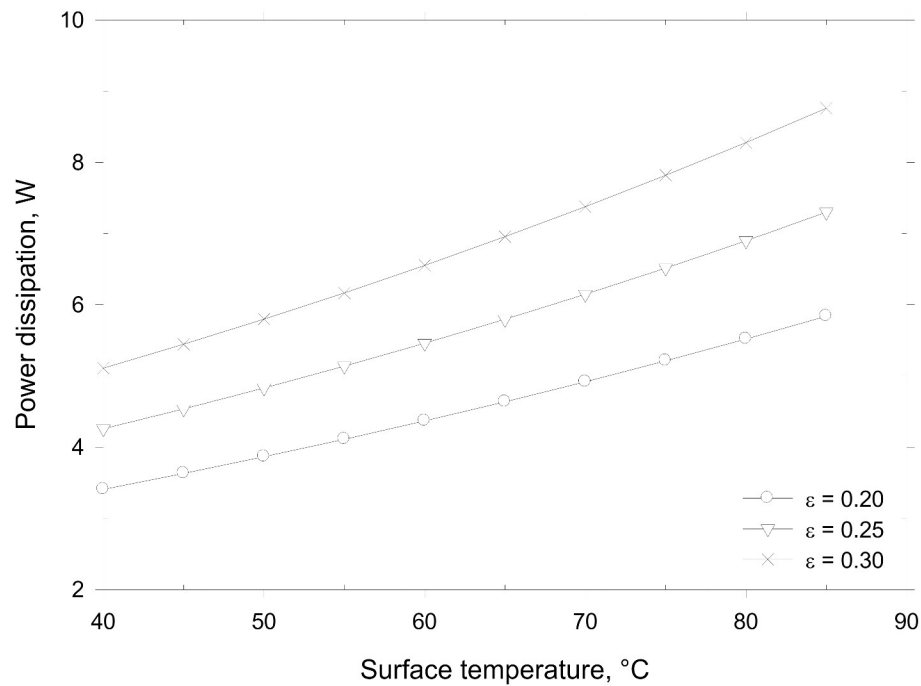
$$\dot{Q}_{rad} = \dot{W} = \varepsilon \sigma A_s (T_s^4 - T_{sur}^4)$$

For the condition when $T_s = 40^\circ\text{C}$, $\varepsilon = 0.25$, with $A_s = \pi D^2$, the power dissipation will be

$$\dot{W} = 0.25 (\pi \times 0.10^2 \text{ m}^2) (5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}) [(40 + 273)^4 - 77^4] \text{ K}^4 = 4.3 \text{ W}$$

Repeating this calculation for the range $40^\circ\text{C} \leq T_s \leq 85^\circ\text{C}$, we can obtain the power dissipation as a function of surface temperature for the $\varepsilon = 0.25$ condition. Similarly, the calculation can be repeated for with 0.2 or 0.3. The details of these trials are given in the following table and plot.

T_s ($^\circ\text{C}$)	$\dot{W}$ (W)		
	$\varepsilon = 0.20$	$\varepsilon = 0.25$	$\varepsilon = 0.30$
40	3.41	4.26	5.11
45	3.63	4.54	5.45
50	3.87	4.83	5.80
55	4.11	5.14	6.17
60	4.37	5.46	6.55
65	4.64	5.80	6.96
70	4.92	6.15	7.38
75	5.21	6.52	7.82
80	5.52	6.90	8.28
85	5.84	7.30	8.76



Family of curves for power dissipation ($\dot{W}$) versus surface temperature (T_s) for different values of emissivity (ε)

Discussion:

(1) As expected, the internal power dissipation increases with increasing emissivity and surface temperature. Because the radiation rate equation is non-linear with respect to temperature, the power dissipation will likewise not be linear with surface temperature.

(2) At a constant surface temperature, the power dissipation is linear with respect to the emissivity. The trends of the $\dot{W}$ versus T_s curves remained similar at different values of emissivity. By increasing the emissivity, the $\dot{W}$ versus T_s curve is shifted higher.

(3) The emissivity of various materials is listed in Tables A-18 and A-19 of the text.

(4) The maximum power dissipation possible if the surface temperature is not to exceed 85 °C is $\dot{W} = 8.76$, where $\varepsilon = 0.30$.

Similarly, the minimum power dissipation possible for the surface temperature range $40^\circ\text{C} \leq T_s \leq 85^\circ\text{C}$ is $\dot{W} = 3.41$ W, where $T_s = 40^\circ\text{C}$ and $\varepsilon = 0.20$. Therefore, the possible range of power dissipation for $40^\circ\text{C} \leq T_s \leq 85^\circ\text{C}$ and $0.2 \leq \varepsilon \leq 0.3$ is $3.41 \leq \dot{W} \leq 8.76$ W.

Simultaneous Heat Transfer Mechanisms

1-84C All three modes of heat transfer cannot occur simultaneously in a medium. A medium may involve two of them simultaneously.

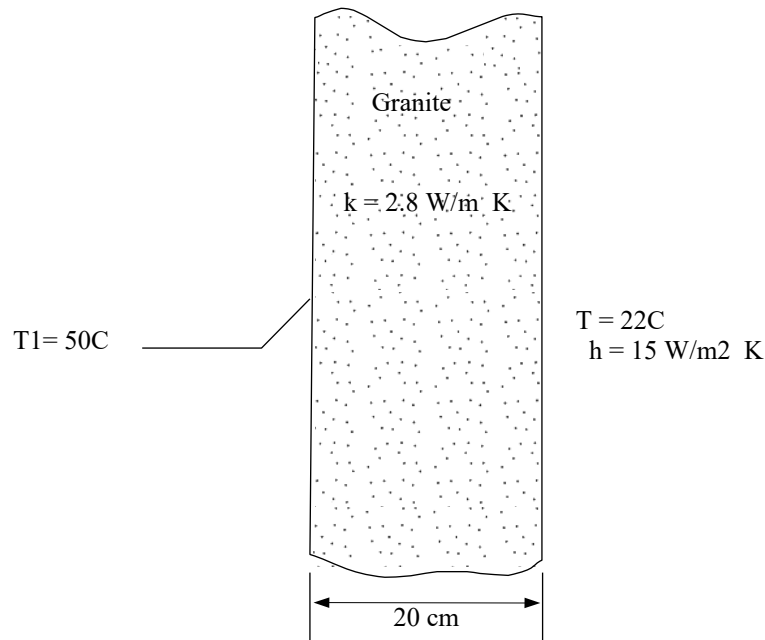
1-85C (a) Conduction and convection: No. (b) Conduction and radiation: Yes. Example: A hot surface on the ceiling. (c) Convection and radiation: Yes. Example: Heat transfer from the human body.

1-86C The human body loses heat by convection, radiation, and evaporation in both summer and winter. In summer, we can keep cool by dressing lightly, staying in cooler environments, turning a fan on, avoiding humid places and direct exposure to the sun. In winter, we can keep warm by dressing heavily, staying in a warmer environment, and avoiding drafts.

1-87C The fan increases the air motion around the body and thus the convection heat transfer coefficient, which increases the rate of heat transfer from the body by convection and evaporation. In rooms with high ceilings, ceiling fans are used in winter to force the warm air at the top downward to increase the air temperature at the body level. This is usually done by forcing the air up which hits the ceiling and moves downward in a gently manner to avoid drafts.

1-88 The right surface of a granite wall is subjected to convection heat transfer while the left surface is maintained as a constant temperature. The right wall surface temperature and the heat flux through the wall are to be determined.

Assumptions **1** Steady operating conditions exist. **2** Heat transfer through the granite wall is one dimensional. **3** Thermal conductivity of the granite wall is constant. **4** Radiation heat transfer is negligible.



Analysis The heat transfer through the wall by conduction is equal to heat transfer to the outer wall surface by convection:

$$\begin{aligned}\dot{q}_{\text{cond}} &= \dot{q}_{\text{conv}} \\ k \frac{T_1 - T_2}{L} &= h(T_2 - T_\infty) \\ T_2 &= \frac{(kT_1/L) + hT_\infty}{(k/L) + h} \\ T_2 &= \frac{(2.8 \text{ W/m} \cdot \text{K})(50^\circ\text{C})/(0.20 \text{ m}) + (15 \text{ W/m}^2 \cdot \text{K})(22^\circ\text{C})}{(2.8 \text{ W/m} \cdot \text{K})/(0.20 \text{ m}) + 15 \text{ W/m}^2 \cdot \text{K}} \\ T_2 &= 35.5^\circ\text{C}\end{aligned}$$

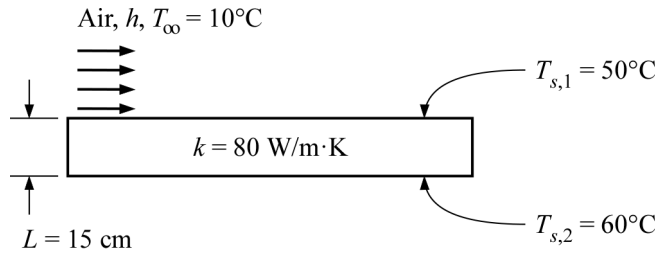
Now that T_2 is known, we can calculate the heat flux. Since the heat transfer through the wall by conduction is equal to heat transfer to the outer wall surface by convection, we may use either the Fourier's law of heat conduction or the Newton's law of cooling to find the heat flux. Using Fourier's law of heat conduction:

$$\dot{q}_{\text{cond}} = k \frac{T_1 - T_2}{L} = (2.8 \text{ W/m} \cdot \text{K}) \frac{(50 - 35.5)^\circ\text{C}}{0.20 \text{ m}} = 203 \text{ W/m}^2$$

Discussion Alternatively using Newton's law of cooling to find the heat flux, we obtain the same result:

$$\dot{q}_{\text{conv}} = h(T_2 - T_\infty) = (15 \text{ W/m}^2 \cdot \text{K})(35.5 - 22) = 203 \text{ W/m}^2$$

1-89 The upper surface of a solid plate is being cooled by air. The air convection heat transfer coefficient at the upper plate surface is to be determined.



Assumptions **1** Steady operating conditions exist. **2** Thermal conductivity of the plate is constant. **3** Heat conduction in solid is one-dimensional. **4** Temperatures at the surfaces remained constant.

Properties The thermal conductivity of the solid plate is given as $k = 80 \text{ W/m}\cdot\text{K}$.

Analysis Applying energy balance on the upper surface of the solid plate

$$\dot{q}_{\text{cond}} = \dot{q}_{\text{conv}}$$

$$k \frac{T_{s,2} - T_{s,1}}{L} = h(T_{s,1} - T_{\infty})$$

The convection heat transfer of the air is

$$h = \frac{k}{L} \frac{T_{s,2} - T_{s,1}}{T_{s,1} - T_{\infty}} = \frac{80 \text{ W/m}\cdot\text{K}}{0.15 \text{ m}} \left(\frac{60 - 50}{50 - 10} \right) = 133 \text{ W/m}^2\cdot\text{K}$$

Discussion A convection heat transfer coefficient of $133 \text{ W/m}^2\cdot\text{K}$ for forced convection of gas is reasonable when compared with the values listed in Table 1-5.

1-90 Air is blown over a hot horizontal plate which is maintained at a constant temperature. The surface also loses heat by radiation. The inside plate temperature is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Heat transfer through the steel plate is one dimensional. **3** Thermal conductivity of the steel plate is constant.

Analysis The heat transfer by conduction through the plate is equal to the sum of convection and radiation heat losses:

$$\dot{Q}_{\text{cond}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}}$$

where

$$\dot{Q}_{\text{conv}} = hA(T_s - T_{\infty}) = (25 \text{ W/m}^2\cdot\text{K})(0.38 \text{ m}^2)(250 - 20) \text{ K} = 2185 \text{ W}$$

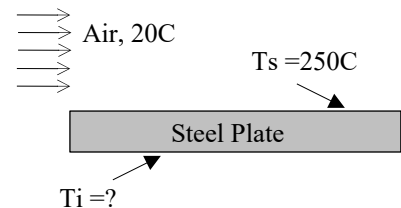
$$\dot{Q}_{\text{rad}} = 300 \text{ W}$$

Then,

$$\dot{Q}_{\text{cond}} = kA \frac{T_i - T_s}{L} = 2185 \text{ W} + 300 \text{ W} = 2485 \text{ W}$$

Solving for the inside plate temperature

$$T_i = T_s + \frac{\dot{Q}_{\text{cond}} L}{kA} = 250^\circ\text{C} + \frac{(2485 \text{ W})(0.02 \text{ m})}{(43 \text{ W/m}\cdot\text{K})(0.38 \text{ m}^2)} = 253^\circ\text{C}$$



Discussion Heat loss by convection is much more dominant than heat loss by radiation. If we had not accounted for the heat loss by radiation in our calculation, the inside plate temperature would be 252.7°C , which is only 0.3°C less than the actual value. In this case we could have neglected the heat loss by radiation.

1-91 For an electronic package with given surface area, power dissipation, surface emissivity and absorptivity to solar radiation and the solar flux, the surface temperature with and without incident solar radiation is to be determined.

Assumptions 1 Steady operating conditions exist.

Analysis Apply conservation of energy (heat balance) to a control volume about the electronic package in rate form

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{E}_{gen} = \dot{E}_{stored} = 0$$

With the solar input, we have

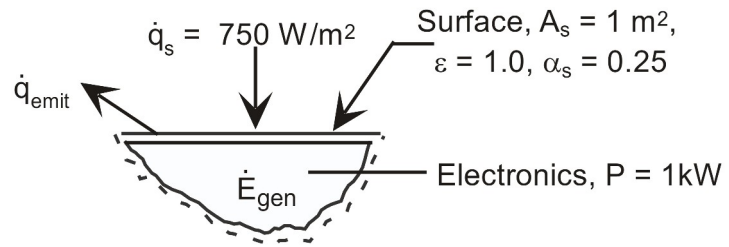
$$\alpha_s A_s \dot{q}_s - A_s \dot{q}_{emit} + P = 0$$

where

$$\dot{q}_{emit} = \epsilon \sigma T_s^4$$

Solving for the surface temperature T_s , we have

$$T_s = \left(\frac{\alpha_s A_s \dot{q}_s + P}{A_s \epsilon \sigma} \right)^{1/4}$$



(a) Surface Temperature in the sun ($\dot{q}_s = 750 \text{ W/m}^2$)

$$T_s = \left[\frac{(0.25)(1 \text{ m}^2)(750 \text{ W/m}^2) + 1000 \text{ W}}{(1 \text{ m}^2)(1.0)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)} \right]^{1/4} = 380.4 \text{ K}$$

(b) Surface Temperature in the shade ($\dot{q}_s = 0$)

$$T_s = \left[\frac{1000 \text{ W}}{(1 \text{ m}^2)(1.0)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)} \right]^{1/4} = 364.4 \text{ K}$$

Discussion In orbit, the space station would be continuously cycling between shade and sunshine, and a steady-state condition would not exist.

1-92 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 $\varepsilon = 1$. **4** There are no convection currents in the air space between the plates.

Properties The thermal conductivities are $k = 0.00015 \text{ W/m}\cdot^\circ\text{C}$ for super insulation, $k = 0.01979 \text{ W/m}\cdot^\circ\text{C}$ at -50°C (Table A-15) for air, and $k = 0.036 \text{ W/m}\cdot^\circ\text{C}$ for fiberglass insulation (Table A-6).

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

$$\begin{aligned}\dot{Q}_{\text{cond}} &= kA \frac{T_1 - T_2}{L} = (0.01979 \text{ W/m}\cdot^\circ\text{C})(1 \text{ m}^2) \frac{(290 - 150) \text{ K}}{0.02 \text{ m}} = 139 \text{ W} \\ \dot{Q}_{\text{rad}} &= \varepsilon \sigma A_s (T_1^4 - T_2^4) \\ &= 1(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1 \text{ m}^2)[(290 \text{ K})^4 - (150 \text{ K})^4] = 372 \text{ W} \\ \dot{Q}_{\text{total}} &= \dot{Q}_{\text{cond}} + \dot{Q}_{\text{rad}} = 139 + 372 = 511 \text{ W}\end{aligned}$$

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

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

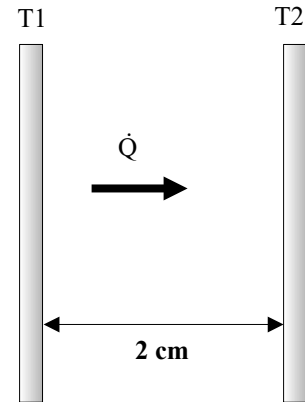
(c) In this case there will be conduction heat transfer through the fiberglass insulation only,

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

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

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

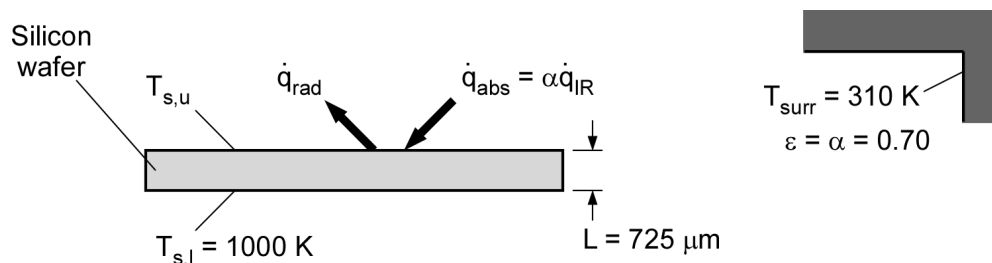
Discussion Note that superinsulators are very effective in reducing heat transfer between to surfaces.



1-93 The upper surface temperature of a silicon wafer undergoing heat treatment in a vacuum chamber by infrared heater is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Radiation heat transfer between upper wafer surface and surroundings is between a small object and a large enclosure. 3 One-dimensional conduction in wafer. 4 The silicon wafer has constant properties. 5 No hot spot exists on the wafer.

Properties The thermal conductivity of silicon at 1000 K is $31.2 \text{ W/m} \cdot \text{K}$ (Table A-3).



Analysis The heat transfer through the thickness of the wafer by conduction is equal to net heat transfer at the upper wafer surface:

$$\begin{aligned}\dot{q}_{\text{cond}} &= \dot{q}_{\text{abs}} - \dot{q}_{\text{rad}} \\ k \frac{T_{s,u} - T_{s,l}}{L} &= \alpha \dot{q}_{\text{IR}} - \epsilon \sigma (T_{s,u}^4 - T_{\text{surr}}^4) \\ (31.2 \text{ W/m} \cdot \text{K}) \frac{(T_{s,u} - 1000) \text{ K}}{(725 \times 10^{-6} \text{ m})} &= (0.70)(200000 \text{ W/m}^2) - (0.70)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(T_{s,u}^4 - 310^4) \text{ K}^4\end{aligned}$$

Copy the following line and paste on a blank EES screen to solve the above equation:

$$31.2*(T_{\text{su}}-1000)/725\text{e-}6=0.70*200000-0.70*5.67\text{e-}8*(T_{\text{su}}^4-310^4)$$

Solving by EES software, the upper surface temperature of silicon wafer is

$$T_{s,u} = 1002 \text{ K}$$

Discussion Excessive temperature difference across the wafer thickness will cause warping in the silicon wafer.

1-94 The total rate of heat transfer from a person by both convection and radiation to the surrounding air and surfaces at specified temperatures is to be determined.

Assumptions 1 Steady operating conditions exist. 2 The person is completely surrounded by the interior surfaces of the room. 3 The surrounding surfaces are at the same temperature as the air in the room. 4 Heat conduction to the floor through the feet is negligible. 5 The convection coefficient is constant and uniform over the entire surface of the person.

Properties The emissivity of a person is given to be $\epsilon = 0.9$.

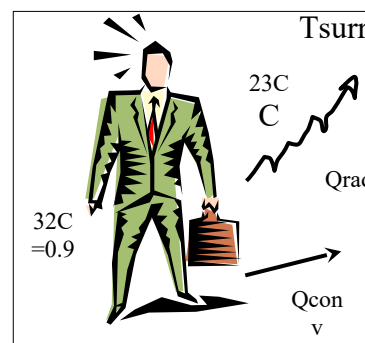
Analysis The person is completely enclosed by the surrounding surfaces, and he or she will lose heat to the surrounding air by convection and to the surrounding surfaces by radiation. The total rate of heat loss from the person is determined from

$$\begin{aligned}\dot{Q}_{\text{rad}} &= \epsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4) = (0.90)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1.7 \text{ m}^2)[(32+273)^4 - (23+273)^4] \text{ K}^4 = 84.8 \text{ W} \\ \dot{Q}_{\text{conv}} &= h A_s \Delta T = (5 \text{ W/m}^2 \cdot \text{K})(1.7 \text{ m}^2)(32-23)^\circ \text{C} = 76.5 \text{ W}\end{aligned}$$

and

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = 84.8 + 76.5 = 161.3 \text{ W}$$

Discussion Note that heat transfer from the person by evaporation, which is of comparable magnitude, is not considered in this problem.



1-95E A spherical ball whose surface is maintained at a temperature of 170°F is suspended in the middle of a room at 70°F. The total rate of heat transfer from the ball is to be determined.

Assumptions 1 Steady operating conditions exist since the ball surface and the surrounding air and surfaces remain at constant temperatures. 2 The thermal properties of the ball and the convection heat transfer coefficient are constant and uniform.

Properties The emissivity of the ball surface is given to be $\varepsilon = 0.8$.

Analysis The heat transfer surface area is

$$A_s = \pi D^2 = \pi (2/12 \text{ ft})^2 = 0.08727 \text{ ft}^2$$

Under steady conditions, the rates of convection and radiation heat transfer are

$$\dot{Q}_{\text{conv}} = h A_s \Delta T = (15 \text{ Btu/h} \cdot \text{ft}^2 \cdot ^\circ\text{F}) (0.08727 \text{ ft}^2) (170 - 70) ^\circ\text{F} = 130.9 \text{ Btu/h}$$

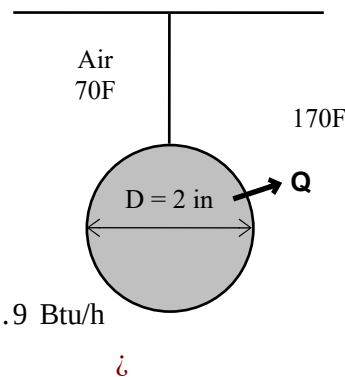
$$\dot{Q}_{\text{rad}} = \varepsilon \sigma A_s (T_s^4 - T_o^4)$$

$$= 0.8 (0.08727 \text{ ft}^2) (5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4) [(170 + 459.67)^4 - (70 + 459.67)^4]$$

Therefore,

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = 130.9 + 9.4 = 140.3 \text{ Btu/h}$$

Discussion Note that heat loss by convection is several times that of heat loss by radiation. The radiation heat loss can further be reduced by coating the ball with a low-emissivity material.



1-96 A 1000-W iron is left on the iron board with its base exposed to the air at 20°C. The temperature of the base of the iron is to be determined in steady operation.

Assumptions 1 Steady operating conditions exist. 2 The thermal properties of the iron base and the convection heat transfer coefficient are constant and uniform. 3 The temperature of the surrounding surfaces is the same as the temperature of the surrounding air.

Properties The emissivity of the base surface is given to be $\varepsilon = 0.6$.

Analysis At steady conditions, the 1000 W energy supplied to the iron will be dissipated to the surroundings by convection and radiation heat transfer.

Therefore,

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = 1000 \text{ W}$$

where

$$\dot{Q}_{\text{conv}} = h A_s \Delta T = (35 \text{ W/m}^2 \cdot \text{K}) (0.02 \text{ m}^2) (T_s - 293 \text{ K}) = 0.7 (T_s - 293 \text{ K})$$

and

$$\dot{Q}_{\text{rad}} = \varepsilon \sigma A_s (T_s^4 - T_o^4) = 0.6 (0.02 \text{ m}^2) (5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4) [T_s^4 - (293 \text{ K})^4]$$

$$= 0.06804 \times 10^{-8} [T_s^4 - (293 \text{ K})^4]$$

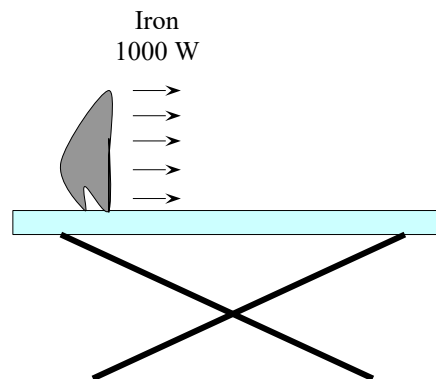
Substituting,

$$1000 \text{ W} = 0.7 (T_s - 293 \text{ K}) + 0.06804 \times 10^{-8} [T_s^4 - (293 \text{ K})^4]$$

Solving by trial and error gives

$$T_s = 947 \text{ K} = 674 ^\circ\text{C}$$

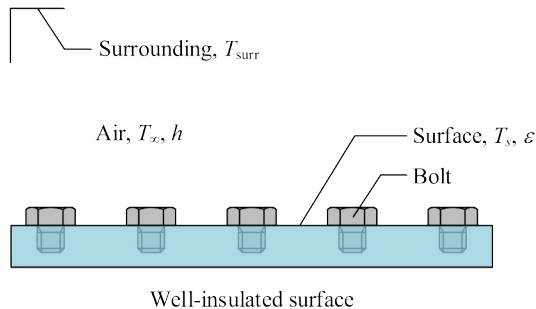
Discussion We note that the iron will dissipate all the energy it receives by convection and radiation when its surface temperature reaches 947 K.



1-97  A series of ASTM B21 naval brass bolts are bolted on the upper surface of a plate. The upper surface is exposed to convection with air and radiation with the surrounding surface. Determine whether the use of the bolts complies with the ASME Code for Process Piping, where 149°C is the maximum use temperature for ASTM B21 bolts.

Assumptions 1 Heat transfer is steady. 2 Kirchhoff's law is applicable. 3 Surrounding surface is treated as blackbody. 4 Uniform surface temperature at the upper plate surface. 5 The temperature of the bolts is equal to the upper plate surface temperature.

Properties The emissivity of the plate and bolts is given as 0.3.



Analysis Since the bottom surface is well-insulated, heat transfer occurs at the upper surface only. From surface energy balance, we have

$$\begin{aligned}\dot{E}_{in} &= \dot{E}_{out} \\ \dot{Q}_{rad} &= \dot{Q}_{conv} \\ \epsilon \sigma A_s (T_{surr}^4 - T_s^4) &= h A_s (T_s - T_\infty)\end{aligned}$$

Assuming the temperature of the bolts is equal to the upper surface temperature of the plate,

$$(0.3)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)[(300+273)^4 - T_s^4] \text{ K}^4 = (5 \text{ W/m}^2 \cdot \text{K})[T_s - (50+273)] \text{ K}$$

Solving for T_s yields

$$T_{bolt} = T_s = 491 \text{ K} = 218^\circ \text{C} > 149^\circ \text{C}$$

Discussion The temperature of the bolts exceeds the maximum use temperature by 149°C. The use of the ASTM B21 bolts under these conditions does not comply with the ASME Code for Process Piping (ASME B31.3-2014). Another type of bolts should be considered for use under these conditions. For example, the ASTM A193 B8M steel bolts have a maximum use temperature of 538°C.

1-98 A spherical tank located outdoors is used to store iced water at 0°C . The rate of heat transfer to the iced water in the tank and the amount of ice at 0°C that melts during a 24-h period are to be determined.

Assumptions **1** Steady operating conditions exist since the surface temperatures of the wall remain constant at the specified values. **2** Thermal properties of the tank and the convection heat transfer coefficient is constant and uniform. **3** The average surrounding surface temperature for radiation exchange is 15°C . **4** The thermal resistance of the tank is negligible, and the entire steel tank is at 0°C .

Properties The heat of fusion of water at atmospheric pressure is $h_{if} = 333.7 \text{ kJ/kg}$. The emissivity of the outer surface of the tank is 0.75.

Analysis (a) The outer surface area of the spherical tank is

$$A_s = \pi D^2 = \pi (3.02 \text{ m})^2 = 28.65 \text{ m}^2$$

Then the rates of heat transfer to the tank by convection and radiation become

$$\dot{Q}_{\text{conv}} = hA_s(T_{\infty} - T_s) = (30 \text{ W/m}^2 \cdot ^{\circ}\text{C})(28.65 \text{ m}^2)(25 - 0)^{\circ}\text{C} = 21,488 \text{ W}$$

$$\dot{Q}_{\text{rad}} = \varepsilon A_s \sigma (T_{\text{surr}}^4 - T_s^4) = (0.75)(28.65 \text{ m}^2)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)[(288 \text{ K})^4 - (273 \text{ K})^4] = 1614 \text{ W}$$

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = 21,488 + 1614 = 23,102 \text{ W} = 23.1 \text{ kW}$$

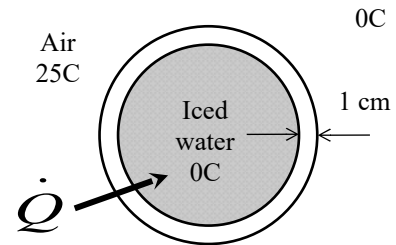
(b) The amount of heat transfer during a 24-hour period is

$$Q = \dot{Q} \Delta t = (23.102 \text{ kJ/s})(24 \times 3600 \text{ s}) = 1,996,000 \text{ kJ}$$

Then the amount of ice that melts during this period becomes

$$Q = m h_{if} \rightarrow m = \frac{Q}{h_{if}} = \frac{1,996,000 \text{ kJ}}{333.7 \text{ kJ/kg}} = 5980 \text{ kg}$$

Discussion The amount of ice that melts can be reduced to a small fraction by insulating the tank.



1-99 A draw batch furnace front is subjected to uniform heat flux on the inside surface, while the outside surface is subjected to convection and radiation heat transfer. The outside surface temperature is to be determined.

Assumptions 1 Heat conduction is steady. 2 One dimensional heat conduction across the furnace front thickness. 3 Uniform heat flux on inside surface.

Properties Emissivity and convective heat transfer coefficient are given to be 0.23 and 12 W/m²·K, respectively.

Analysis The uniform heat flux subjected on the inside surface is equal to the sum of heat fluxes transferred by convection and radiation on the outside surface

$$\dot{q}_0 = h(T_o - T_{\infty}) + \epsilon\sigma(T_o^4 - T_{\text{surr}}^4)$$

$$8000 \text{ W/m}^2 = (12 \text{ W/m}^2 \cdot \text{K})[T_o - (30 + 273)] \text{ K} + (0.23)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)[T_o^4 - (30 + 273)^4] \text{ K}^4$$

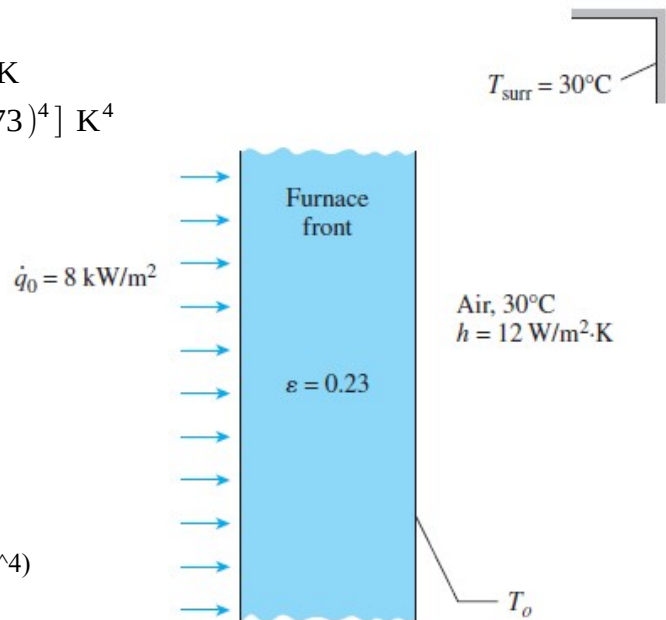
Solving for the outer surface temperature yields

$$T_o = 707 \text{ K} = 434^\circ \text{C}$$

Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
h=12 [W/m^2-K]
q_dot_0=8000 [W/m^2]
T_surr=303 [K]
epsilon=0.23
sigma=5.67e-8 [W/m^2-K^4]
q_dot_0=h*(T_o-T_surr)+epsilon*sigma*(T_o^4-T_surr^4)
```

Discussion By insulating the furnace front, heat loss from the outer surface can be reduced.



1-100 A flat-plate solar absorber is exposed to an incident solar radiation. The efficiency of the solar absorber (the ratio of the usable heat collected by the absorber to the incident solar radiation on the absorber) is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Temperature at the surface remained constant.

Properties The absorber surface has an absorptivity of 0.93 and an emissivity of 0.9.

Analysis The rate of usable heat at the absorber plate can be expressed as

$$\dot{Q}_{\text{usable}} = \dot{Q}_{\text{absorbed}} - \dot{Q}_{\text{rad}} - \dot{Q}_{\text{conv}}$$

$$\dot{Q}_{\text{usable}} = \alpha A_s \dot{q}_{\text{solar}} - \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4) - h A_s (T_s - T_{\infty})$$

Expressed in terms of heat flux, we have

$$\dot{q}_{\text{usable}} = \alpha \dot{q}_{\text{solar}} - \varepsilon \sigma (T_s^4 - T_{\text{surr}}^4) - h (T_s - T_{\infty})$$

$$\dot{q}_{\text{usable}} = (0.93)(800 \text{ W/m}^2) - (0.9)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)[(40+273)^4 - (-5+273)^4] - (7 \text{ W/m}^2 \cdot \text{K})(40-20) \text{ K}$$

$$\dot{q}_{\text{usable}} = 377.5 \text{ W/m}^2$$

Thus, the efficiency of the solar absorber is

$$\eta = \frac{\dot{q}_{\text{usable}}}{\dot{q}_{\text{solar}}} = \frac{377.5 \text{ W/m}^2}{800 \text{ W/m}^2} = 0.472$$

Discussion The efficiency of the solar absorber is influenced by the surrounding and ambient temperatures, as well as the convective heat transfer coefficient. If the weather is particularly windy, thus causing higher level of heat loss via convection, then the efficiency of the solar absorber could be adversely affected.

1-101 A flat-plate solar collector is used to heat water. The temperature rise of the water heated by the net heat rate from the solar collector is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Specific heat of water is constant. 3 Temperature at the surface remained constant. 4 Conduction through the solar absorber is negligible. 5 Heat loss through the sides and back of the absorber is negligible.

Properties The absorber surface has an absorptivity of 0.9 and an emissivity of 0.9. The specific heat of water is given as 4.2 kJ/kg·K.

Analysis The net heat rate absorbed by the solar collector is

$$\dot{Q}_{\text{net}} = \dot{Q}_{\text{absorbed}} - \dot{Q}_{\text{rad}} - \dot{Q}_{\text{conv}}$$

$$\dot{Q}_{\text{net}} = A_s [\alpha \dot{q}_{\text{solar}} - \epsilon \sigma (T_s^4 - T_{\text{surr}}^4) - h(T_s - T_{\infty})]$$

$$\dot{Q}_{\text{net}} = (2 \text{ m}^2) [(0.9)(500 \text{ W/m}^2) - (0.9)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4) [(35 + 273)^4 - (0 + 273)^4] - (5 \text{ W/m}^2 \cdot \text{K})(35 - 25) \text{ K}]$$

$$\dot{Q}_{\text{net}} = 448.4 \text{ W}$$

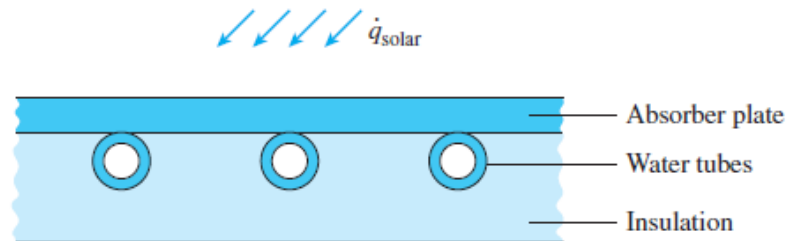
The temperature rise can be determined using

$$\dot{Q}_{\text{net}} = \dot{m} c_p (T_{\text{out}} - T_{\text{in}})$$

Thus,

$$T_{\text{out}} - T_{\text{in}} = \frac{\dot{Q}_{\text{net}}}{\dot{m} c_p} = \frac{448.4 \text{ W}}{(0.005 \text{ kg/s})(4200 \text{ J/kg} \cdot \text{K})} = 21.4^\circ \text{C}$$

Discussion The temperature rise of the water is influenced by the usable net heat rate absorbed by the solar collector and the water flow rate.



1-102  A draw batch furnace front is subjected to uniform heat flux on the inside surface, while the outside surface is subjected to convection and radiation heat transfer. The outside surface temperature is to be determined whether it is below 50°C or not.

Assumptions 1 Heat conduction is steady. 2 One dimensional heat conduction across the furnace front thickness. 3 Uniform heat flux on inside surface.

Properties Emissivity and convective heat transfer coefficient are given to be 0.7 and 15 W/m²·K, respectively.

Analysis The uniform heat flux subjected on the inside surface is equal to the sum of heat fluxes transferred by convection and radiation on the outside surface

$$\dot{q}_0 = h(T_o - T_{\infty}) + \epsilon\sigma(T_o^4 - T_{\text{surr}}^4)$$

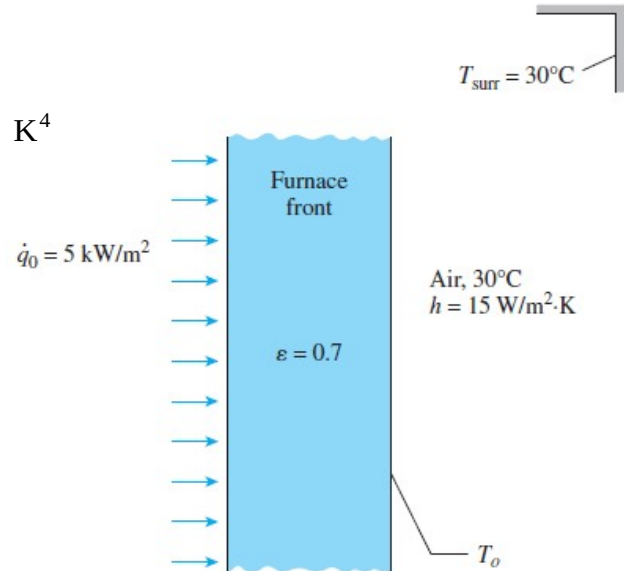
$$5000 \text{ W/m}^2 = (15 \text{ W/m}^2 \cdot \text{K})[T_o - (30 + 273)] \text{ K} \\ + (0.7)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)[T_o^4 - (30 + 273)^4] \text{ K}^4$$

Solving for the outer surface temperature yields

$$T_o = 497 \text{ K} = 224^\circ \text{C} > 50^\circ \text{C}$$

Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
h=15 [W/m^2-K]
q_dot_0=5000 [W/m^2]
T_surr=303 [K]
epsilon=0.7
sigma=5.67e-8 [W/m^2-K^4]
q_dot_0=h*(T_o-T_surr)+epsilon*sigma*(T_o^4-T_surr^4)
```



Discussion Yes, insulation is required on the furnace front surface to avoid thermal burn upon contact with skin.

1-103E A flat plate solar collector is placed horizontally on the roof of a house. The rate of heat loss from the collector by convection and radiation during a calm day are to be determined.

Assumptions 1 Steady operating conditions exist. 2 The emissivity and convection heat transfer coefficient are constant and uniform. 3 The exposed surface, ambient, and sky temperatures remain constant.

Properties The emissivity of the outer surface of the collector is given to be 0.9.

Analysis The exposed surface area of the collector is

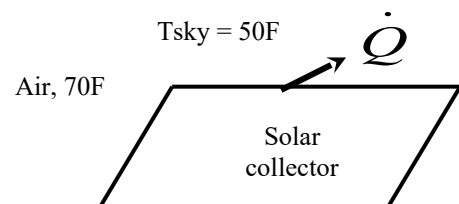
$$A_s = (5 \text{ ft})(15 \text{ ft}) = 75 \text{ ft}^2$$

Noting that the exposed surface temperature of the collector is 100°F, the total rate of heat loss from the collector to the environment by convection and radiation becomes

$$\dot{Q}_{\text{conv}} = hA_s(T_{\infty} - T_s) = (2.5 \text{ Btu/h} \cdot \text{ft}^2 \cdot ^\circ \text{F})(75 \text{ ft}^2)(100 - 70)^\circ \text{F} = 5625 \text{ Btu/h} \\ \dot{Q}_{\text{rad}} = \epsilon A_s \sigma (T_{\text{surr}}^4 - T_s^4) = (0.9)(75 \text{ ft}^2)(0.1714 \times 10^{-8} \text{ Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4)[(100 + 460 \text{ R})^4 - (50 + 460 \text{ R})^4] \\ = 3551 \text{ Btu/h}$$

and

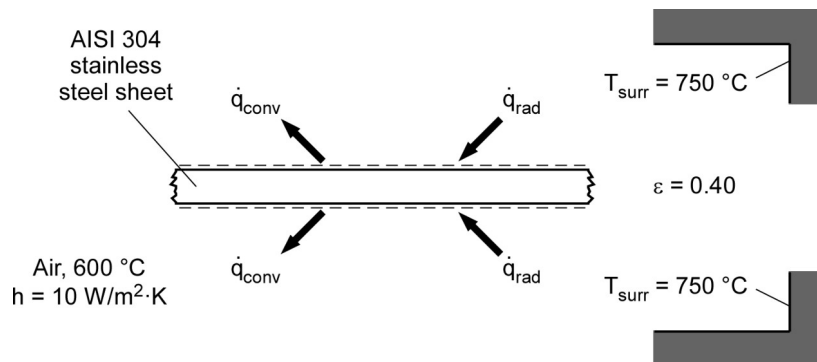
$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = 5625 + 3551 = 9176 \text{ Btu/h}$$



1-104 Temperature of the stainless steel sheet going through an annealing process inside an electrically heated oven is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Temperature of the stainless steel sheet is uniform. **3** Radiation heat transfer between stainless steel sheet and surrounding oven surfaces is between a small object and a large enclosure.

Properties The emissivity of the stainless steel sheet is given to be 0.40.



Analysis The amount of heat transfer by radiation between the sheet and the surrounding oven surfaces is balanced by the convection heat transfer between the sheet and the ambient air:

$$\dot{q}_{\text{rad}} - \dot{q}_{\text{conv}} = 0$$

$$\varepsilon \sigma (T_{\text{surr}}^4 - T_s^4) - h (T_s - T_{\infty}) = 0$$

$$(0.40)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)[(750 + 273)^4 - T_s^4] \text{ K}^4 - (10 \text{ W/m}^2 \cdot \text{K})[T_s - (600 + 273)] \text{ K} = 0$$

Solving the above equation by EES software (Copy the following line and paste on a blank EES screen to verify solution):

$$0.40 \cdot 5.67 \text{e-}8 \cdot ((750 + 273)^4 - T_s^4) - 10 \cdot (T_s - (600 + 273)) = 0$$

The temperature of the stainless steel sheet is

$$T_s = 1009 \text{ K} = 736 \text{ °C}$$

Discussion Note that the energy balance equation involving radiation heat transfer used for solving the stainless steel sheet temperature must be used with absolute temperature.

1-105 The roof of a house with a gas furnace consists of a 15-cm thick 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 $k = 2 \text{ W/m}\cdot^\circ\text{C}$. The emissivity of the outer surface of the roof is given to be 0.9.

Analysis In steady operation, heat transfer from the outer surface of the roof to the surroundings by convection and radiation must be equal to the heat transfer through the roof by conduction. That is,

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

The inner surface temperature of the roof is given to be $T_{s,\text{in}} = 15^\circ\text{C}$. Letting $T_{s,\text{out}}$ denote the outer surface temperatures of the roof, the energy balance above can be expressed as

$$\dot{Q} = kA \frac{T_{s,\text{in}} - T_{s,\text{out}}}{L} = h_o A (T_{s,\text{out}} - T_{\text{surr}}) + \varepsilon A \sigma (T_{s,\text{out}}^4 - T_{\text{surr}}^4)$$

$$\dot{Q} = (2 \text{ W/m}\cdot^\circ\text{C})(300 \text{ m}^2) \frac{15^\circ\text{C} - T_{s,\text{out}}}{0.15 \text{ m}}$$

$$= (15 \text{ W/m}^2\cdot^\circ\text{C})(300 \text{ m}^2)(T_{s,\text{out}} - 10)^\circ\text{C} + (0.9)(300 \text{ m}^2)(5.67 \times 10^{-8} \text{ W/m}^2\cdot\text{K}^4)[(T_{s,\text{out}} + 273 \text{ K})^4 - (255 \text{ K})^4]$$

Solving the equations above using an equation solver (or by trial and error) gives

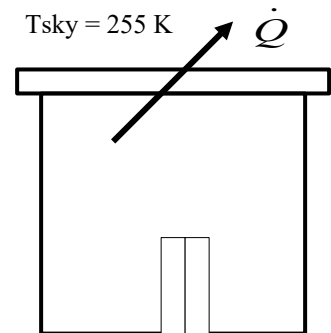
$$\dot{Q} = 25,450 \text{ W and } T_{s,\text{out}} = 8.64^\circ\text{C}$$

Then the amount of natural gas consumption during a 16-hour period is

$$E_{\text{gas}} = \frac{Q_{\text{total}}}{0.85} = \frac{\dot{Q} \Delta t}{0.85} = \frac{(25.450 \text{ kJ/s})(14 \times 3600 \text{ s})}{0.85} \left(\frac{1 \text{ therm}}{105,500 \text{ kJ}} \right) = 14.3 \text{ therms}$$

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

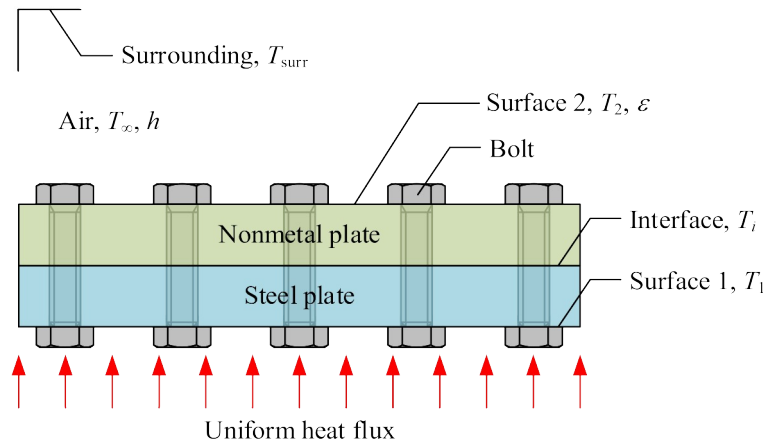
$$\text{Money lost} = (14.3 \text{ therms})(\$0.60/\text{therm}) = \$8.58$$



1-106  A nonmetal plate and an ASME SA-240 stainless steel plate are bolted together by ASTM B21 naval brass bolts. The bottom surface is subjected to uniform heat flux. The top surface is exposed to convection and radiation heat transfer. Determine whether the ASME Boiler and Pressure Vessel Code and the ASME Code for Process Piping are being complied.

Assumptions 1 Heat transfer is steady. 2 One dimensional heat conduction through the plates. 3 Uniform heat flux on bottom surface. 4 Uniform surface temperatures. 5 No contact resistance at the interface.

Properties The thermal conductivities for the steel plate is given as $k_1 = 15 \text{ W/m}\cdot\text{K}$ and for the nonmetal plate as $k_2 = 0.05 \text{ W/m}\cdot\text{K}$.



Analysis The uniform heat flux subjected on the bottom plate surface is transferred by conduction through the plates, and by convection and radiation on the top surface:

$$\dot{q}_0 = \dot{q}_{\text{cond},1} = 200 \text{ W/m}^2$$

$$\dot{q}_0 = \dot{q}_{\text{cond},1} = \dot{q}_{\text{cond},2}$$

$$\dot{q}_0 = \dot{q}_{\text{cond},2} = \dot{q}_{\text{conv}} + \dot{q}_{\text{rad}}$$

where

$$\dot{q}_{\text{cond},1} = k_1 \frac{T_1 - T_i}{L}, \quad \dot{q}_{\text{cond},2} = k_2 \frac{T_i - T_2}{L}, \quad \dot{q}_{\text{conv}} = h(T_2 - T_\infty), \quad \dot{q}_{\text{rad}} = \epsilon \sigma (T_2^4 - T_{\text{surr}}^4)$$

Combining the equations to solve for T_1 , T_2 , and T_i , we have

$$200 \text{ W/m}^2 = k_1 \frac{T_1 - T_i}{L} \quad (1)$$

$$200 \text{ W/m}^2 = k_2 \frac{T_i - T_2}{L} \quad (2)$$

$$200 \text{ W/m}^2 = h(T_2 - T_\infty) + \epsilon \sigma (T_2^4 - T_{\text{surr}}^4) \quad (3)$$

Solving for the top surface temperature T_2 using Eq. (3), yields

$$200 \text{ W/m}^2 = (5 \text{ W/m}^2\cdot\text{K})(T_2 - 20) \text{ K} + (0.3)(5.67 \times 10^{-8} \text{ W/m}^2\cdot\text{K}^4)[(T_2 + 273)^4 - (30 + 273)^4] \text{ K}^4$$

$$\rightarrow T_2 = 51.13^\circ\text{C}$$

Solving for the interface temperature T_i using Eq. (2), yields

$$200 \text{ W/m}^2 = (0.05 \text{ W/m}\cdot\text{K}) \frac{T_i - 51.13^\circ\text{C}}{0.038 \text{ m}} \rightarrow T_i = 203.1^\circ\text{C}$$

Solving for the bottom surface temperature T_1 using Eq. (1), yields

$$200 \text{ W/m}^2 = (15 \text{ W/m}\cdot\text{K}) \frac{T_1 - 203.1^\circ\text{C}}{0.038 \text{ m}} \rightarrow T_1 = 203.6^\circ\text{C}$$

Discussion The ASME SA-240 stainless steel plate has an average temperature of 203.6°C , which complies with the ASME Boiler and Pressure Vessel Code (ASME BPVC.IV-2015, HF-300) which requires a temperature of less than 260°C . However, the ASTM B21 naval brass bolts are used in a steel plate that its temperature exceeds the maximum use temperature of 149°C required by the ASME Code for Process Piping (ASME B31.3-2014). Another type of bolts should be

considered for use under these conditions. For example, the ASTM A193 B8M steel bolts have a maximum use temperature of 538°C (ASME B31.3-2014).

1-107 The outer surface of a wall is exposed to solar radiation. The effective thermal conductivity of the wall is to be determined.

Assumptions 1 Steady operating conditions exist. 2 The heat transfer coefficient is constant and uniform over the surface.

Properties Both the solar absorptivity and emissivity of the wall surface are given to be 0.8.

Analysis The heat transfer through the wall by conduction is equal to net heat transfer to the outer wall surface:

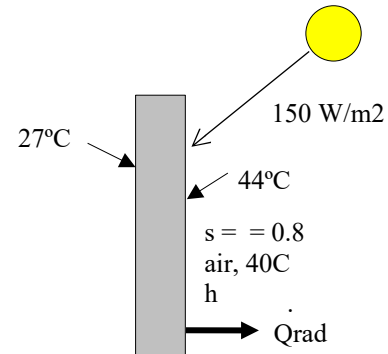
$$\dot{q}_{\text{cond}} = \dot{q}_{\text{conv}} + \dot{q}_{\text{rad}} + \dot{q}_{\text{solar}}$$

$$k \frac{T_2 - T_1}{L} = h(T_o - T_2) + \varepsilon \sigma (T_{\text{surr}}^4 - T_2^4) + \alpha_s q_{\text{solar}}$$

$$k \frac{(44 - 27)^\circ\text{C}}{0.25 \text{ m}} = (8 \text{ W/m}^2 \cdot ^\circ\text{C})(40 - 44)^\circ\text{C} + (0.8)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)[(40 + 273 \text{ K})^4 - (44 + 273 \text{ K})^4] + (0.8)(150 \text{ W/m}^2)$$

Solving for k gives

$$k = 0.961 \text{ W/m} \cdot ^\circ\text{C}$$



Solving Engineering Problems

1-108C (a) Despite the convenience and capability the engineering software packages offer, they are still just tools, and they will not replace the traditional engineering courses. They will simply cause a shift in emphasis in the course material from mathematics to physics. (b) They are of great value in engineering practice, however, as engineers today rely on software packages for solving large and complex problems in a short time, and perform optimization studies efficiently.

1-109  We are to determine a positive real root of the following equation using EES: $3.5x^3 - 10x^{0.5} - 3x = -4$.

Analysis Using EES software, copy the following lines and paste on a blank EES screen to verify the solution:

$$3.5*x^3-10*x^{0.5}-3*x = -4$$

Answer: $x = 1.554$

Discussion To obtain the solution in EES, click on the icon that looks like a calculator, or Calculate-Solve.

1-110  We are to solve a system of 2 equations and 2 unknowns using EES.

Analysis Using EES software, copy the following lines and paste on a blank EES screen to verify the solution:

$$x^3-y^2=10.5$$

$$3*x*y+y=4.6$$

Answers: $x = 2.215$, $y = 0.6018$

Discussion To obtain the solution in EES, click on the icon that looks like a calculator, or Calculate-Solve.

1-111  We are to solve a system of 3 equations with 3 unknowns using EES.

Analysis Using EES software, copy the following lines and paste on a blank EES screen to verify the solution:

$$2*x-y+z=5$$

$$3*x^2+2*y=z+2$$

$$x*y+2*z=8$$

Answers: $x = 1.141$, $y = 0.8159$, $z = 3.535$.

Discussion To obtain the solution in EES, click on the icon that looks like a calculator, or Calculate-Solve.

1-112  We are to solve a system of 3 equations with 3 unknowns using EES.

Analysis Using EES software, copy the following lines and paste on a blank EES screen to verify the solution:

$$x^2*y-z=1.5$$

$$x-3*y^{0.5}+x*z=-2$$

$$x+y-z=4.2$$

Answers: $x = 0.9149$, $y = 10.95$, $z = 7.665$

Discussion To obtain the solution in EES, click on the icon that looks like a calculator, or Calculate-Solve.

Special Topic: Thermal Comfort

1-113C The metabolism refers to the burning of foods such as carbohydrates, fat, and protein in order to perform the necessary bodily functions. The metabolic rate for an average man ranges from 108 W while reading, writing, typing, or listening to a lecture in a classroom in a seated position to 1250 W at age 20 (730 at age 70) during strenuous exercise. The corresponding rates for women are about 30 percent lower. Maximum metabolic rates of trained athletes can exceed 2000 W. We are interested in metabolic rate of the occupants of a building when we deal with heating and air conditioning because the metabolic rate represents the rate at which a body generates heat and dissipates it to the room. This body heat contributes to the heating in winter, but it adds to the cooling load of the building in summer.

1-114C The metabolic rate is proportional to the size of the body, and the metabolic rate of women, in general, is lower than that of men because of their smaller size. Clothing serves as insulation, and the thicker the clothing, the lower the environmental temperature that feels comfortable.

1-115C Asymmetric thermal radiation is caused by the *cold surfaces* of large windows, uninsulated walls, or cold products on one side, and the *warm surfaces* of gas or electric radiant heating panels on the walls or ceiling, solar heated masonry walls or ceilings on the other. Asymmetric radiation causes discomfort by exposing different sides of the body to surfaces at different temperatures and thus to different rates of heat loss or gain by radiation. A person whose left side is exposed to a cold window, for example, will feel like heat is being drained from that side of his or her body.

1-116C (a) Draft causes undesired local cooling of the human body by exposing parts of the body to high heat transfer coefficients. (b) Direct contact with *cold floor surfaces* causes localized discomfort in the feet by excessive heat loss by conduction, dropping the temperature of the bottom of the feet to uncomfortable levels.

1-117C Stratification is the formation of vertical still air layers in a room at different temperatures, with highest temperatures occurring near the ceiling. It is likely to occur at places with high ceilings. It causes discomfort by exposing the head and the feet to different temperatures. This effect can be prevented or minimized by using destratification fans (ceiling fans running in reverse).

1-118C It is necessary to ventilate buildings to provide adequate fresh air and to get rid of excess carbon dioxide, contaminants, odors, and humidity. Ventilation increases the energy consumption for heating in winter by replacing the warm indoors air by the colder outdoors air. Ventilation also increases the energy consumption for cooling in summer by replacing the cold indoors air by the warm outdoors air. It is not a good idea to keep the bathroom fans on all the time since they will waste energy by expelling conditioned air (warm in winter and cool in summer) by the unconditioned outdoor air.

Review Problems

1-119 The windows of a house in Atlanta are of double door type with wood frames and metal spacers. The average rate of heat loss through the windows in winter is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat losses associated with the infiltration of air through the cracks/openings are not considered.

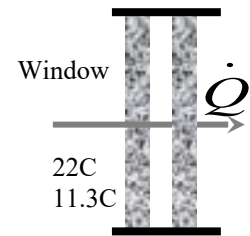
Analysis The rate of heat transfer through the window can be determined from

$$\dot{Q}_{\text{window, avg}} = U_{\text{overall}} A_{\text{window}} (T_i - T_o)$$

where T_i and T_o are the indoor and outdoor air temperatures, respectively, U_{overall} is the U -factor (the overall heat transfer coefficient) of the window, and A_{window} is the window area. Substituting,

$$\dot{Q}_{\text{window, avg}} = (2.5 \text{ W/m}^2 \cdot ^\circ\text{C})(20 \text{ m}^2)(22 - 11.3)^\circ\text{C} = 535 \text{ W}$$

Discussion This is the “average” rate of heat transfer through the window in winter in the absence of any infiltration.



1-120 The range of U -factors for windows are given. The range for the rate of heat loss through the window of a house is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Heat losses associated with the infiltration of air through the cracks/openings are not considered.

Analysis The rate of heat transfer through the window can be determined from

$$\dot{Q}_{\text{window}} = U_{\text{overall}} A_{\text{window}} (T_i - T_o)$$

where T_i and T_o are the indoor and outdoor air temperatures, respectively, U_{overall} is the U -factor (the overall heat transfer coefficient) of the window, and A_{window} is the window area. Substituting,

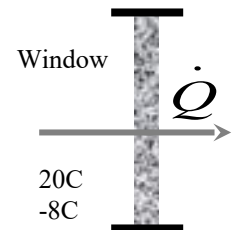
$$\dot{Q}_{\text{window, max}} = (6.25 \text{ W/m}^2 \cdot ^\circ\text{C})(1.2 \times 1.8 \text{ m}^2)[20 - (-8)]^\circ\text{C} = 378 \text{ W}$$

Maximum heat loss:

$$\dot{Q}_{\text{window, min}} = (1.25 \text{ W/m}^2 \cdot ^\circ\text{C})(1.2 \times 1.8 \text{ m}^2)[20 - (-8)]^\circ\text{C} = 76 \text{ W}$$

Minimum heat loss:

Discussion Note that the rate of heat loss through windows of identical size may differ by a factor of 5, depending on how the windows are constructed.



1-121 A room is to be heated by 1 ton of hot water contained in a tank placed in the room. The minimum initial temperature of the water is to be determined if it is to meet the heating requirements of this room for a 24-h period.

Assumptions 1 Water is an incompressible substance with constant specific heats. 2 Air is an ideal gas with constant specific heats. 3 The energy stored in the container itself is negligible relative to the energy stored in water. 4 The room is maintained at 20°C at all times. 5 The hot water is to meet the heating requirements of this room for a 24-h period.

Properties The specific heat of water at room temperature is $c = 4.18 \text{ kJ/kg} \cdot ^\circ\text{C}$ (Table A-9).

Analysis Heat loss from the room during a 24-h period is

$$Q_{\text{loss}} = (10,000 \text{ kJ/h})(24 \text{ h}) = 240,000 \text{ kJ}$$

Taking the contents of the room, including the water, as our system, the energy balance can be written as

$$\underbrace{E_{\text{in}} - E_{\text{out}}}_{\text{Net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{\text{system}}}_{\text{Change in internal, kinetic, potential, etc. energies}} \rightarrow -Q_{\text{out}} = \Delta U = (\Delta U)_{\text{water}} + (\Delta U)_{\text{air}}$$

or

$$-Q_{\text{out}} = [mc(T_2 - T_1)]_{\text{water}}$$

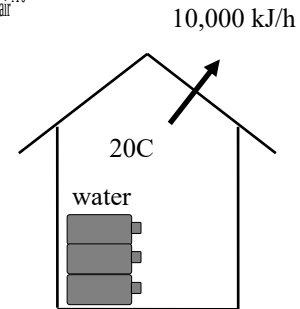
Substituting,

$$-240,000 \text{ kJ} = (1000 \text{ kg})(4.18 \text{ kJ/kg} \cdot ^\circ\text{C})(20 - T_1)$$

It gives

$$T_1 = 77.4^\circ\text{C}$$

where T_1 is the temperature of the water when it is first brought into the room.



1-122 Engine valves are to be heated in a heat treatment section. The amount of heat transfer, the average rate of heat transfer, the average heat flux, and the number of valves that can be heat treated daily are to be determined.

Assumptions Constant properties given in the problem can be used.

Properties The average specific heat and density of valves are given to be $c_p = 440 \text{ J/kg} \cdot ^\circ\text{C}$ and $\rho = 7840 \text{ kg/m}^3$.

Analysis (a) The amount of heat transferred to the valve is simply the change in its internal energy, and is determined from

$$Q = \Delta U = mc_p(T_2 - T_1) \\ \dot{Q} (0.0788 \text{ kg})(0.440 \text{ kJ/kg} \cdot ^\circ\text{C})(800 - 40)^\circ\text{C} = 26.35 \text{ kJ}$$

(b) The average rate of heat transfer can be determined from

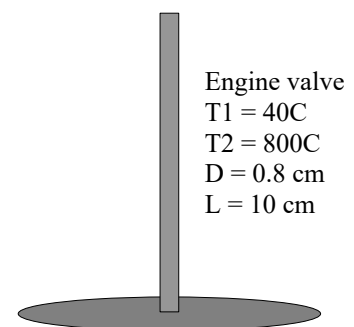
$$\dot{Q}_{\text{avg}} = \frac{Q}{\Delta t} = \frac{26.35 \text{ kJ}}{5 \times 60 \text{ s}} = 0.0878 \text{ kW} = 87.8 \text{ W}$$

(c) The average heat flux is determined from

$$\dot{q}_{\text{ave}} = \frac{\dot{Q}_{\text{avg}}}{A_s} = \frac{\dot{Q}_{\text{avg}}}{2\pi DL} = \frac{87.8 \text{ W}}{2\pi(0.008 \text{ m})(0.1 \text{ m})} = 1.75 \times 10^4 \text{ W/m}^2$$

(d) The number of valves that can be heat treated daily is

$$\text{Number of valves} = \frac{(10 \times 60 \text{ min})(25 \text{ valves})}{5 \text{ min}} = 3000 \text{ valves}$$



1-123 A cylindrical resistor on a circuit board dissipates 0.8 W of power. The amount of heat dissipated in 24 h, the heat flux, and the fraction of heat dissipated from the top and bottom surfaces are to be determined.

Assumptions Heat is transferred uniformly from all surfaces.

Analysis (a) The amount of heat this resistor dissipates during a 24-hour period is

$$Q = \dot{Q} \Delta t = (0.8 \text{ W})(24 \text{ h}) = 19.2 \text{ Wh} = 69.1 \text{ kJ} \quad (\text{since } 1 \text{ Wh} = 3600 \text{ Ws} = 3.6 \text{ kJ})$$

(b) The heat flux on the surface of the resistor is

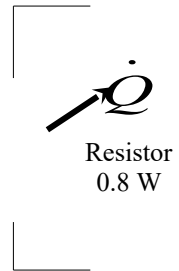
$$A_s = 2 \frac{\pi D^2}{4} + \pi DL = 2 \frac{\pi (0.4 \text{ cm})^2}{4} + \pi (0.4 \text{ cm})(2 \text{ cm}) = 0.251 + 2.513 = 2.764 \text{ cm}^2$$

$$\dot{q}_s = \frac{\dot{Q}}{A_s} = \frac{0.80 \text{ W}}{2.764 \text{ cm}^2} = 0.289 \text{ W/cm}^2$$

(c) Assuming the heat transfer coefficient to be uniform, heat transfer is proportional to the surface area. Then the fraction of heat dissipated from the top and bottom surfaces of the resistor becomes

$$\frac{Q_{\text{top-base}}}{Q_{\text{total}}} = \frac{A_{\text{top-base}}}{A_{\text{total}}} = \frac{0.251}{2.764} = 0.091 \quad \text{or } (9.1\%)$$

Discussion Heat transfer from the top and bottom surfaces is small relative to that transferred from the side surface.



1-124 The heat generated in the circuitry on the surface of a 3-W silicon chip is conducted to the ceramic substrate. The temperature difference across the chip in steady operation is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Thermal properties of the chip are constant.

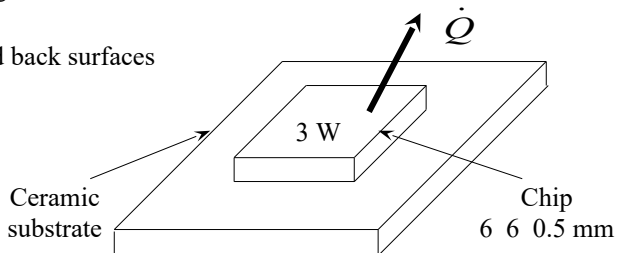
Properties The thermal conductivity of the silicon chip is given to be $k = 130 \text{ W/m}\cdot^\circ\text{C}$.

Analysis The temperature difference between the front and back surfaces of the chip is

$$A = (0.006 \text{ m})(0.006 \text{ m}) = 0.000036 \text{ m}^2$$

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

$$\Delta T = \frac{\dot{Q}L}{kA} = \frac{(3 \text{ W})(0.0005 \text{ m})}{(130 \text{ W/m}\cdot^\circ\text{C})(0.000036 \text{ m}^2)} = 0.32^\circ\text{C}$$



1-125 A circuit board houses 80 closely spaced logic chips on one side, each dissipating 0.06 W. All the heat generated in the chips is conducted across the circuit board. The temperature difference between the two sides of the circuit board is to be determined.

Assumptions 1 Steady operating conditions exist. 2 Thermal properties of the board are constant. 3 All the heat generated in the chips is conducted across the circuit board.

Properties The effective thermal conductivity of the board is given to be $k = 16 \text{ W/m}\cdot^\circ\text{C}$.

Analysis The total rate of heat dissipated by the chips is

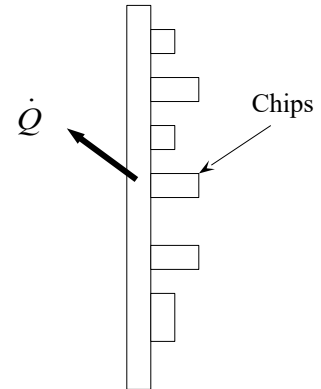
$$\dot{Q} = 80 \times (0.06 \text{ W}) = 4.8 \text{ W}$$

Then the temperature difference between the front and back surfaces of the board is

$$A = (0.12 \text{ m})(0.18 \text{ m}) = 0.0216 \text{ m}^2$$

$$\dot{Q} = kA \frac{\Delta T}{L} \rightarrow \Delta T = \frac{\dot{Q}L}{kA} = \frac{(4.8 \text{ W})(0.003 \text{ m})}{(16 \text{ W/m}\cdot^\circ\text{C})(0.0216 \text{ m}^2)} = 0.042^\circ\text{C}$$

Discussion Note that the circuit board is nearly isothermal.



1-126 An electric resistance heating element is immersed in water initially at 20°C . The time it will take for this heater to raise the water temperature to 80°C as well as the convection heat transfer coefficients at the beginning and at the end of the heating process are to be determined.

Assumptions 1 Steady operating conditions exist and thus the rate of heat loss from the wire equals the rate of heat generation in the wire as a result of resistance heating. 2 Thermal properties of water are constant. 3 Heat losses from the water in the tank are negligible.

Properties The specific heat of water at room temperature is $c = 4.18 \text{ kJ/kg}\cdot^\circ\text{C}$ (Table A-9).

$$\dot{Q} = \dot{E}_{\text{generated}} = 800 \text{ W}$$

Analysis When steady operating conditions are reached, we have $\dot{Q} = \dot{E}_{\text{generated}} = 800 \text{ W}$. This is also equal to the rate of heat gain by water. Noting that this is the only mechanism of energy transfer, the time it takes to raise the water temperature from 20°C to 80°C is determined to be

$$\begin{aligned} Q_{\text{in}} &= mc(T_2 - T_1) \\ \dot{Q}_{\text{in}} \Delta t &= mc(T_2 - T_1) \\ \Delta t &= \frac{mc(T_2 - T_1)}{\dot{Q}_{\text{in}}} = \frac{(75 \text{ kg})(4180 \text{ J/kg}\cdot^\circ\text{C})(80 - 20)^\circ\text{C}}{800 \text{ J/s}} = 23,510 \text{ s} = 6.53 \text{ h} \end{aligned}$$

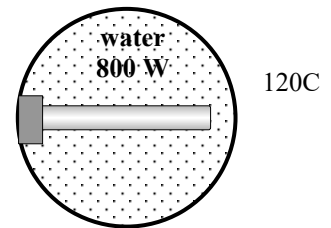
The surface area of the wire is

$$A_s = \pi DL = \pi(0.005 \text{ m})(0.4 \text{ m}) = 0.00628 \text{ m}^2$$

The Newton's law of cooling for convection heat transfer is expressed as $\dot{Q} = hA_s(T_s - T_\infty)$. Disregarding any heat transfer by radiation and thus assuming all the heat loss from the wire to occur by convection, the convection heat transfer coefficients at the beginning and at the end of the process are determined to be

$$\begin{aligned} h_1 &= \frac{\dot{Q}}{A_s(T_s - T_{\infty 1})} = \frac{800 \text{ W}}{(0.00628 \text{ m}^2)(120 - 20)^\circ\text{C}} = 1274 \text{ W/m}^2\cdot^\circ\text{C} \\ h_2 &= \frac{\dot{Q}}{A_s(T_s - T_{\infty 2})} = \frac{800 \text{ W}}{(0.00628 \text{ m}^2)(120 - 80)^\circ\text{C}} = 3185 \text{ W/m}^2\cdot^\circ\text{C} \end{aligned}$$

Discussion Note that a larger heat transfer coefficient is needed to dissipate heat through a smaller temperature difference for a specified heat transfer rate.



1-127 A standing man is subjected to high winds and thus high convection coefficients. The rate of heat loss from this man by convection in still air at 20°C, in windy air, and the wind chill temperature are to be determined.

Assumptions **1** A standing man can be modeled as a 30-cm diameter, 170-cm long vertical cylinder with both the top and bottom surfaces insulated. **2** The exposed surface temperature of the person and the convection heat transfer coefficient is constant and uniform. **3** Heat loss by radiation is negligible.

Analysis The heat transfer surface area of the person is

$$A_s = \pi DL = \pi(0.3 \text{ m})(1.70 \text{ m}) = 1.60 \text{ m}^2$$

The rate of heat loss from this man by convection in still air is

$$\dot{Q}_{\text{still air}} = hA_s\Delta T = (15 \text{ W/m}^2\cdot^\circ\text{C})(1.60 \text{ m}^2)(34 - 20)^\circ\text{C} = \mathbf{336 \text{ W}}$$

In windy air it would be

$$\dot{Q}_{\text{windy air}} = hA_s\Delta T = (30 \text{ W/m}^2\cdot^\circ\text{C})(1.60 \text{ m}^2)(34 - 20)^\circ\text{C} = \mathbf{672 \text{ W}}$$

To lose heat at this rate in still air, the air temperature must be

$$672 \text{ W} = (hA_s\Delta T)_{\text{still air}} = (15 \text{ W/m}^2\cdot^\circ\text{C})(1.60 \text{ m}^2)(34 - T_{\text{effective}})^\circ\text{C}$$

which gives

$$T_{\text{effective}} = \mathbf{6^\circ\text{C}}$$

That is, the windy air at 20°C feels as cold as still air at 6°C as a result of the wind-chill effect.



Windy weather

1-128 The surface temperature of an engine block that generates 50 kW of power output is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Temperature inside the engine compartment is uniform. **3** Heat transfer by radiation is not considered.

Analysis With a net engine efficiency of 35%, which means 65% of the generated power output are heat loss by convection:

$$\dot{Q}_{\text{conv}} = \dot{W}_{\text{out}}(1 - \eta) = (50 \text{ kW})(1 - 0.35) = 32.5 \text{ kW}$$

From Newton's law of cooling, the heat transfer by convection is given as

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

Rearranging, the engine block surface temperature is

$$T_s = \frac{\dot{Q}_{\text{conv}}}{hA_s} + T_\infty = \frac{32.5 \times 10^3 \text{ W}}{(50 \text{ W/m}^2\cdot^\circ\text{C})(0.95 \text{ m}^2)} + 157^\circ\text{C} = \mathbf{841^\circ\text{C}}$$

Discussion Due to the complex geometry of the engine block, hot spots are likely to occur with temperatures much higher than 841 °C.

1-129 Electric power required to maintain the surface temperature of an electrical wire submerged in boiling water at 115°C.

Assumptions **1** Steady operating conditions exist. **2** Convection heat transfer coefficient is uniform. **3** Heat transfer by radiation is negligible. **4** Heat losses from the boiler are negligible.

Analysis From an overall energy balance on the electrical wire, the power dissipated by the wire is transferred by convection to the water. Using Newton's law of cooling,

$$\dot{Q}_{conv} = h A_s (T_s - T_\infty)$$

where the surface area of the wire is

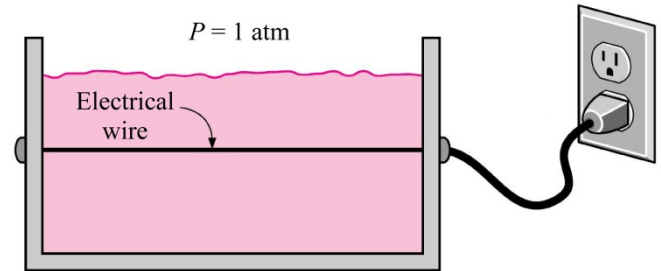
$$A_s = \pi DL = \pi (1 \times 10^{-3}) (15 \times 10^{-2}) = 4.712 \times 10^{-4} \text{ m}^2$$

The heat transfer by convection with $h = 51,250 \text{ W/m}^2\cdot\text{K}$ (average of the upper and lower values of the convection heat transfer coefficients given in Table 1-5) is

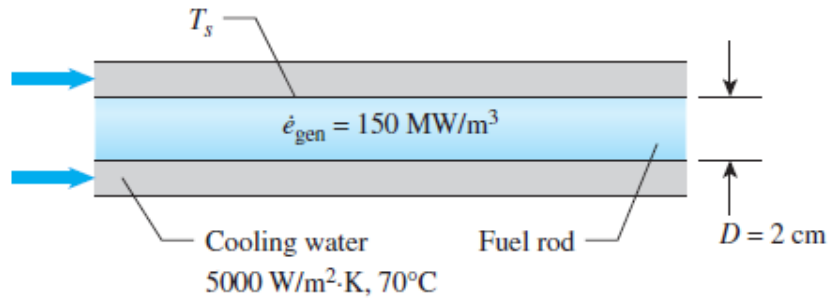
$$\dot{Q}_{conv} = h A_s (T_s - T_\infty) = (51,250 \text{ W/m}^2\cdot\text{K}) (4.712 \times 10^{-4} \text{ m}^2) (115 - 100) \text{ K} = \mathbf{362.2 \text{ W}}$$

This is equal to the electric power that must be supplied to maintain the surface temperature of the wire at 115°C.

Discussion If we had used the two extreme values of the convection heat transfer coefficient for boiling and condensation given in Table 1-5, the required electric power would range from 17.7 W (for $h = 2500 \text{ W/m}^2\cdot\text{K}$) to 706.8 W (for $h = 100,000 \text{ W/m}^2\cdot\text{K}$).



1-130 A cylindrical fuel rod is cooled by water flowing through its encased concentric tube. The surface temperature of the fuel rod is to be determined.



Assumptions **1** Steady operating conditions exist. **2** Heat generation in the fuel rod is uniform.

Analysis The total heat transfer area of the fuel rod is

$$A_s = \pi DL$$

The heat transfer rate from the fuel rod is equal to the rate of heat generation multiplied by the fuel rod volume

$$\dot{Q} = \dot{e}_{gen} (\pi D^2 L / 4)$$

The rate of heat removal from the fuel rod by the cooling water is

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

$$\dot{e}_{gen} (\pi D^2 L / 4) = h \pi DL (T_s - T_\infty)$$

Thus,

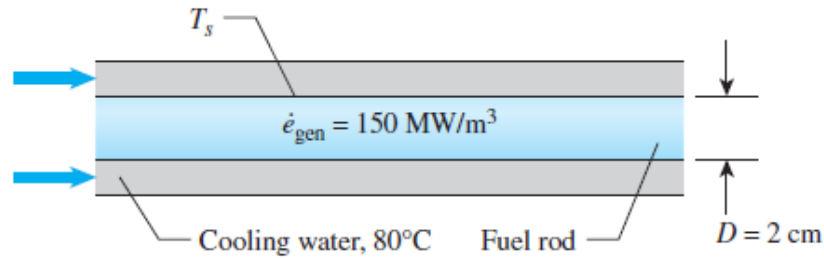
The surface temperature of the fuel rod is

$$T_s = T_\infty + \frac{D \dot{e}_{gen}}{4h}$$

$$T_s = 70^\circ\text{C} + \frac{(0.02 \text{ m})(150 \times 10^6 \text{ W/m}^3)}{4(5000 \text{ W/m}^2 \cdot \text{K})} = 220^\circ\text{C}$$

Discussion A convection heat transfer coefficient of 5000 W/m²·K for forced convection of liquid is reasonable when compared with the values listed in Table 1-5.

1-131 **PtD** A cylindrical fuel rod is cooled by water flowing through its encased concentric tube. The surface temperature of the fuel rod must be maintained below 300°C and the convection heat transfer coefficient is to be determined.



Assumptions 1 Steady operating conditions exist. 2 Heat generation in the fuel rod is uniform.

Analysis The total heat transfer area of the fuel rod is

$$A_s = \pi DL$$

The heat transfer rate from the fuel rod is equal to the rate of heat generation multiply the fuel rod volume

$$\dot{Q} = \dot{e}_{gen} (\pi D^2 L / 4)$$

The heat transfer rate removed from the fuel rod by the cooling water is

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

Thus,

$$\dot{e}_{gen} (\pi D^2 L / 4) = h \pi DL (T_s - T_\infty)$$

The convection heat transfer coefficient can be determined as

$$h = \frac{D \dot{e}_{gen}}{4 (T_s - T_\infty)}$$

$$= \frac{(0.02 \text{ m})(150 \times 10^6 \text{ W/m}^3)}{4 (300 - 80) \text{ K}}$$

$$= 3410 \text{ W/m}^2 \cdot \text{K}$$

To maintained the fuel rod surface temperature below 300°C, the convection heat transfer coefficient should be

$$h > 3410 \text{ W/m}^2 \cdot \text{K}$$

Discussion For the fuel rod surface temperature to be kept below 300°C, the cooling water convection heat transfer coefficient should be higher than 3410 W/m²·K. Higher value of convection heat transfer coefficient can be achieved by increasing the flow rate of cooling water.

1-132 The rate of radiation heat transfer between a person and the surrounding surfaces at specified temperatures is to be determined in summer and in winter.

Assumptions 1 Steady operating conditions exist. 2 Heat transfer by convection is not considered. 3 The person is completely surrounded by the interior surfaces of the room. 4 The surrounding surfaces are at a uniform temperature.

Properties The emissivity of a person is given to be $\varepsilon = 0.95$

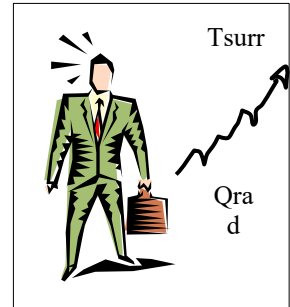
Analysis Noting that the person is completely enclosed by the surrounding surfaces, the net rates of radiation heat transfer from the body to the surrounding walls, ceiling, and the floor in both cases are:

(a) Summer: $T_{\text{surr}} = 23 + 273 = 296$

$$\begin{aligned}\dot{Q}_{\text{rad}} &= \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4) \\ &= (0.95)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1.6 \text{ m}^2)[(32 + 273)^4 - (296 \text{ K})^4] \\ &= 84.2 \text{ W}\end{aligned}$$

(b) Winter: $T_{\text{surr}} = 12 + 273 = 285 \text{ K}$

$$\begin{aligned}\dot{Q}_{\text{rad}} &= \varepsilon \sigma A_s (T_s^4 - T_{\text{surr}}^4) \\ &= (0.95)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1.6 \text{ m}^2)[(32 + 273)^4 - (285 \text{ K})^4] \\ &= 177.2 \text{ W}\end{aligned}$$



Discussion Note that the radiation heat transfer from the person more than doubles in winter.

1-133 The base surface of a cubical furnace is surrounded by black surfaces at a specified temperature. The net rate of radiation heat transfer to the base surface from the top and side surfaces is to be determined.

Assumptions 1 Steady operating conditions exist. 2 The top and side surfaces of the furnace closely approximate black surfaces. 3 The properties of the surfaces are constant.

Properties The emissivity of the base surface is $\varepsilon = 0.7$.

Analysis The base surface is completely surrounded by the top and side surfaces. Then using the radiation relation for a surface completely surrounded by another large (or black) surface, the net rate of radiation heat transfer from the top and side surfaces to the base is determined to be

$$\begin{aligned}\dot{Q}_{\text{rad,base}} &= \varepsilon A \sigma (T_{\text{base}}^4 - T_{\text{surr}}^4) \\ &= (0.7)(3 \times 3 \text{ m}^2)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)[(1200 \text{ K})^4 - (800 \text{ K})^4] \\ &= 594,400 \text{ W} = 594 \text{ kW}\end{aligned}$$

Black furnace
1200 K

Base, 800 K

1-134 The power required to maintain the soldering iron tip at 400 °C is to be determined.

Assumptions **1** Steady operating conditions exist since the tip surface and the surrounding air temperatures remain constant. **2** The thermal properties of the tip and the convection heat transfer coefficient are constant and uniform. **3** The surrounding surfaces are at the same temperature as the air.

Properties The emissivity of the tip is given to be 0.80.

Analysis The total heat transfer area of the soldering iron tip is

$$A_s = \pi D^2/4 + \pi DL$$

$$= \pi (0.0025 \text{ m})^2/4 + \pi (0.0025 \text{ m})(0.02 \text{ m})$$

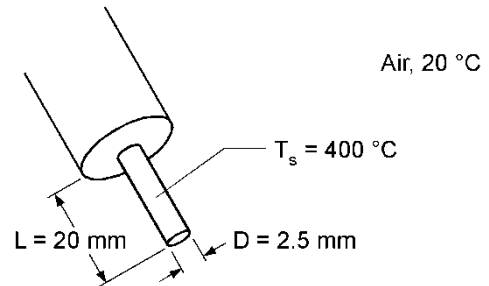
$$= 1.62 \times 10^{-4} \text{ m}^2$$

The rate of heat transfer by convection is

$$\dot{Q}_{\text{conv}} = hA_s(T_{\text{tip}} - T_{\infty})$$

$$= (25 \text{ W/m}^2 \cdot ^\circ\text{C})(1.62 \times 10^{-4} \text{ m}^2)(400 - 20)^\circ\text{C}$$

$$= 1.54 \text{ W}$$



The rate of heat transfer by radiation is

$$\dot{Q}_{\text{rad}} = \epsilon \sigma A_s (T_{\text{tip}}^4 - T_{\text{surr}}^4)$$

$$= (0.80)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)(1.62 \times 10^{-4} \text{ m}^2)[(400 + 273)^4 - (20 + 273)^4] \text{ K}^4$$

$$= 1.45 \text{ W}$$

Thus, the power required is equal to the total rate of heat transfer from the tip by both convection and radiation:

$$\dot{Q}_{\text{total}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} = 1.54 \text{ W} + 1.45 \text{ W} = 2.99 \text{ W}$$

Discussion If the soldering iron tip is highly polished with an emissivity of 0.05, the power required to maintain the tip at 400 °C will reduce to 1.63 W, or by 45.5%.

1-135 The backside of the thin metal plate is insulated and the front side is exposed to solar radiation. The surface temperature of the plate is to be determined when it stabilizes.

Assumptions **1** Steady operating conditions exist. **2** Heat transfer through the insulated side of the plate is negligible. **3** The heat transfer coefficient is constant and uniform over the plate. **4** Radiation heat transfer is negligible.

Properties The solar absorptivity of the plate is given to be $\alpha = 0.7$.

Analysis When the heat loss from the plate by convection equals the solar radiation absorbed, the surface temperature of the plate can be determined from

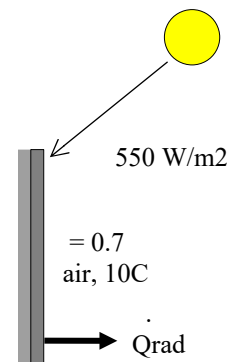
$$\dot{Q}_{\text{solar absorbed}} = \dot{Q}_{\text{conv}}$$

$$\alpha \dot{Q}_{\text{solar}} = hA_s(T_s - T_o)$$

$$0.7 \times A \times 550 \text{ W/m}^2 = (25 \text{ W/m}^2 \cdot ^\circ\text{C}) A_s (T_s - 10)$$

Canceling the surface area A_s and solving for T_s gives

$$T_s = 25.4^\circ\text{C}$$



1-136 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 $k = 0.7 \text{ W/m}\cdot^\circ\text{C}$.

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

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

The rate of heat transfer from the glass by convection is

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

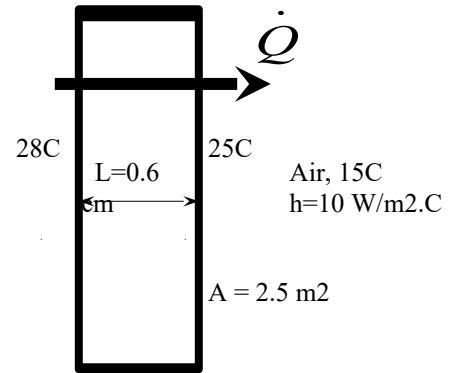
Under steady conditions, the heat transferred through the cover by conduction should be transferred from the outer surface by convection and radiation. That is,

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

Then the fraction of heat transferred by radiation becomes

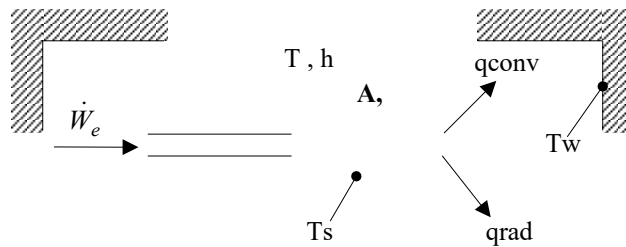
$$f = \frac{\dot{Q}_{\text{rad}}}{\dot{Q}_{\text{cond}}} = \frac{625}{875} = 0.714$$

(or 71.4%)



1-137 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

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

The surface temperature when the heater consumes 700 W is

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

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

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

$$= \frac{500 \text{ W} - (0.75)(0.25 \text{ m}^2)(5.67 \times 10^{-8} \text{ W/m}^2 \cdot \text{K}^4)[(393 \text{ K})^4 - (283 \text{ K})^4]}{(0.25 \text{ m}^2)(120 - 20)^\circ\text{C}}$$

$$= 12.58 \text{ W/m}^2 \cdot ^\circ\text{C}$$

Then the surface temperature becomes

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

$$700 = (12.58)(0.25)(T_s - 293) + (0.75)(0.25)(5.67 \times 10^{-8})[T_s^4 - (283 \text{ K})^4]$$

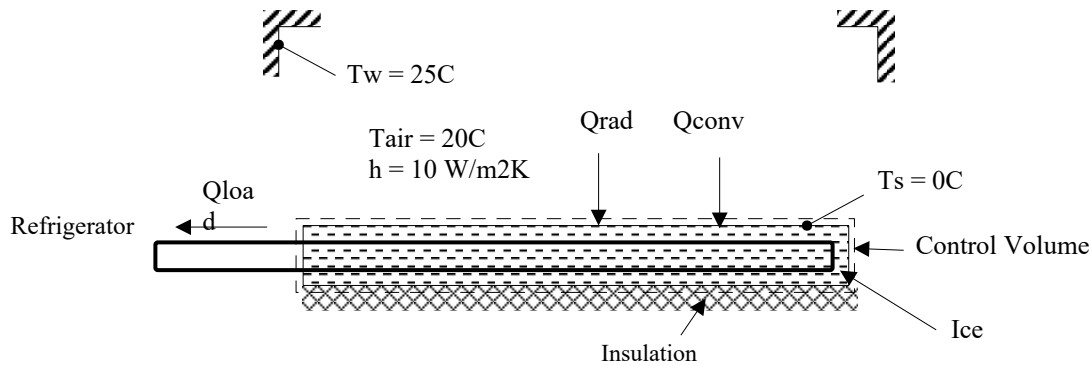
$$T_s = 425.9 \text{ K} = 152.9^\circ\text{C}$$

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

1-138 An ice skating rink is located in a room is considered. The refrigeration load of the system and the time it takes to melt 3 mm of ice are to be determined.

Assumptions 1 Steady operating conditions exist in part (a). 2 The surface is insulated on the back side in part (b).

Properties The heat of fusion and the density of ice are given to be 333.7 kJ/kg and 920 kg/m³, respectively.



Analysis (a) The refrigeration load is determined from

$$\dot{Q}_{\text{load}} = hA(T_{\text{air}} - T_s) + \epsilon A \sigma (T_w^4 - T_s^4)$$

$$= (10)(40 \times 12)(20 - 0) + (0.95)(40 \times 12)(5.67 \times 10^{-8})[298^4 - 273^4] = 156,300 \text{ W}$$

(b) The time it takes to melt 3 mm of ice is determined from

$$t = \frac{LW \delta \rho h_{if}}{\dot{Q}_{\text{load}}} = \frac{(40 \times 12 \text{ m}^2)(0.003 \text{ m})(920 \text{ kg/m}^3)(333.7 \times 10^3 \text{ J/kg})}{156,300 \text{ J/s}} = 2831 \text{ s} = 47.2 \text{ min}$$

Fundamentals of Engineering (FE) Exam Problems

1-139 Which equation below is used to determine the heat flux for conduction?

- (a) $-kA \frac{dT}{dx}$ (b) $-k \text{ grad } T$ (c) $h(T_2 - T_1)$ (d) $\varepsilon \sigma T^4$ (e) None of them

Answer (b) $-k \text{ grad } T$

1-140 Which equation below is used to determine the heat flux for convection?

- (a) $-kA \frac{dT}{dx}$ (b) $-k \text{ grad } T$ (c) $h(T_2 - T_1)$ (d) $\varepsilon \sigma T^4$ (e) None of them

Answer (c) $h(T_2 - T_1)$

1-141 Which equation below is used to determine the heat flux emitted by thermal radiation from a surface?

- (a) $-kA \frac{dT}{dx}$ (b) $-k \text{ grad } T$ (c) $h(T_2 - T_1)$ (d) $\varepsilon \sigma T^4$ (e) None of them

Answer (d) $\varepsilon \sigma T^4$

1-142 A 1-kW electric resistance heater in a room is turned on and kept on for 50 minutes. The amount of energy transferred to the room by the heater is

- (a) 1 kJ (b) 50 kJ (c) 3000 kJ (d) 3600 kJ (e) 6000 kJ

Answer (c) 3000 kJ

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
We= 1 [kJ/s]
time=50*60 [s]
We_total=We*time [kJ]
```

"Wrong Solutions:"

W1_Etotal=We*time/60 "using minutes instead of s"

W2_Etotal=We "ignoring time"

1-143 A 2-kW electric resistance heater submerged in 30-kg water is turned on and kept on for 10 min. During the process, 500 kJ of heat is lost from the water. The temperature rise of water is

- (a) 5.6°C (b) 9.6°C (c) 13.6°C (d) 23.3°C (e) 42.5°C

Answer (a) 5.6°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
C=4.18 [kJ/kg-K]
m=30 [kg]
Q_loss=500 [kJ]
time=10*60 [s]
W_e=2 [kJ/s]
"Applying energy balance E_in-E_out=dE_system gives"
time*W_e-Q_loss = dU_system
dU_system=m*C*DELTA_T
```

"Some Wrong Solutions with Common Mistakes:"

```
time*W_e = m*C*W1_T "Ignoring heat loss"
time*W_e+Q_loss = m*C*W2_T "Adding heat loss instead of subtracting"
time*W_e-Q_loss = m*1.0*W3_T "Using specific heat of air or not using specific heat"
```

1-144 Eggs with a mass of 0.15 kg per egg and a specific heat of 3.32 kJ/kg·°C are cooled from 32°C to 10°C at a rate of 300 eggs per minute. The rate of heat removal from the eggs is

- (a) 11 kW (b) 80 kW (c) 25 kW (d) 657 kW (e) 55 kW

Answer (e) 55 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
C=3.32 [kJ/kg-K]
m_egg=0.15 [kg]
T1=32 [C]
T2=10 [C]
n=300 "eggs/min"
m=n*m_egg/60 "kg/s"
"Applying energy balance E_in-E_out=dE_system gives"
"-E_out = dU_system"
Qout=m*C*(T1-T2) "kJ/s"
"Some Wrong Solutions with Common Mistakes:"
W1_Qout = m*C*T1 "Using T1 only"
W2_Qout = m_egg*C*(T1-T2) "Using one egg only"
W3_Qout = m*C*T2 "Using T2 only"
W4_Qout=m_egg*C*(T1-T2)*60 "Finding kJ/min"
```

1-145 A cold bottled drink ($m = 2.5 \text{ kg}$, $c_p = 4200 \text{ J/kg}\cdot^\circ\text{C}$) at 5°C is left on a table in a room. The average temperature of the drink is observed to rise to 15°C in 30 minutes. The average rate of heat transfer to the drink is

- (a) 23 W (b) 29 W (c) 58 W (d) 88 W (e) 122 W

Answer: (c) 58 W

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
c=4200 [J/kg-K]
m=2.5 [kg]
T1=5 [C]
T2=15 [C]
time = 30*60 [s]
"Applying energy balance E_in-E_out=dE_system gives"
Q=m*c*(T2-T1)
Qave=Q/time
```

"Some Wrong Solutions with Common Mistakes:"

```
W1_Qave = m*c*T1/time "Using T1 only"
W2_Qave = c*(T2-T1)/time "Not using mass"
W3_Qave = m*c*T2/time "Using T2 only"
```

1-146 Water enters a pipe at 20°C at a rate of 0.25 kg/s and is heated to 60°C . The rate of heat transfer to the water is

- (a) 10 kW (b) 20.9 kW (c) 41.8 kW (d) 62.7 kW (e) 167.2 kW

Answer (c) 41.8 kW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
T_in=20 [C]
T_out=60 [C]
m_dot=0.25 [kg/s]
c_p=4.18 [kJ/kg-C]
Q_dot=m_dot*c_p*(T_out-T_in)
```

"Some Wrong Solutions with Common Mistakes"

```
W1_Q_dot=m_dot*(T_out-T_in) "Not using specific heat"
W2_Q_dot=c_p*(T_out-T_in) "Not using mass flow rate"
W3_Q_dot=m_dot*c_p*T_out "Using exit temperature instead of temperature change"
```

1-147 Air enters a 12-m-long, 7-cm-diameter pipe at 50°C at a rate of 0.06 kg/s. The air is cooled at an average rate of 400 W per m² surface area of the pipe. The air temperature at the exit of the pipe is

- (a) 4.3°C (b) 17.5°C (c) 32.5°C (d) 43.4°C (e) 45.8°C

Answer (c) 32.5°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
L=12 [m]
D=0.07 [m]
T1=50 [C]
m_dot=0.06 [kg/s]
q=400 [W/m^2]
A=pi*D*L
Q_dot=q*A
c_p=1007 [J/kg-C] "Table A-15"
Q_dot=m_dot*c_p*(T1-T2)
```

"Some Wrong Solutions with Common Mistakes"

```
q=m_dot*c_p*(T1-W1_T2) "Using heat flux, q instead of rate of heat transfer, Q_dot"
Q_dot=m_dot*4180*(T1-W2_T2) "Using specific heat of water"
Q_dot=m_dot*c_p*W3_T2 "Using exit temperature instead of temperature change"
```

1-148 Heat is lost steadily through a 0.5-cm thick 2 m × 3 m window glass whose thermal conductivity is 0.7 W/m·°C. The inner and outer surface temperatures of the glass are measured to be 12°C to 9°C. The rate of heat loss by conduction through the glass is

- (a) 420 W (b) 5040 W (c) 17,600 W (d) 1256 W (e) 2520 W

Answer (e) 2520 W

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
A=3*2 [m^2]
L=0.005 [m]
T1=12 [C]
T2=9 [C]
k=0.7 [W/m-C]
Q=k*A*(T1-T2)/L
```

"Some Wrong Solutions with Common Mistakes:"

```
W1_Q=k*(T1-T2)/L "Not using area"
W2_Q=k*2*A*(T1-T2)/L "Using areas of both surfaces"
W3_Q=k*A*(T1+T2)/L "Adding temperatures instead of subtracting"
W4_Q=k*A*L*(T1-T2) "Multiplying by thickness instead of dividing by it"
```


1-149 Steady heat conduction occurs through a 0.3-m thick 9 m by 3 m composite wall at a rate of 1.2 kW. If the inner and outer surface temperatures of the wall are 15°C and 7°C, the effective thermal conductivity of the wall is

- (a) 0.61 W/m·°C (b) 0.83 W/m·°C (c) 1.7 W/m·°C (d) 2.2 W/m·°C (e) 5.1 W/m·°C

Answer (c) 1.7 W/m·°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
A=9*3 [m^2]
L=0.3 [m]
T1=15 [C]
T2=7 [C]
Q=1200 [W]
Q=k*A*(T1-T2)/L
```

"Wrong Solutions:"

```
Q=W1_k*(T1-T2)/L "Not using area"
Q=W2_k*2*A*(T1-T2)/L "Using areas of both surfaces"
Q=W3_k*A*(T1+T2)/L "Adding temperatures instead of subtracting"
Q=W4_k*A*L*(T1-T2) "Multiplying by thickness instead of dividing by it"
```

1-150 Heat is lost through a brick wall ($k = 0.72$ W/m·°C), which is 4 m long, 3 m wide, and 25 cm thick at a rate of 500 W. If the inner surface of the wall is at 22°C, the temperature at the midplane of the wall is

- (a) 0°C (b) 7.5°C (c) 11.0°C (d) 14.8°C (e) 22°C

Answer (d) 14.8°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
k=0.72 [W/m-C]
Length=4 [m]
Width=3 [m]
L=0.25 [m]
Q_dot=500 [W]
T1=22 [C]
A=Length*Width
Q_dot=k*A*(T1-T_middle)/(0.5*L)
```

"Some Wrong Solutions with Common Mistakes"

```
Q_dot=k*A*(T1-W1_T_middle)/L "Using L instead of 0.5L"
W2_T_middle=T1/2 "Just taking the half of the given temperature"
```

1-151 A 10-cm high and 20-cm wide circuit board houses on its surface 100 closely spaced chips, each generating heat at a rate of 0.08 W and transferring it by convection and radiation to the surrounding medium at 40°C. Heat transfer from the back surface of the board is negligible. If the combined convection and radiation heat transfer coefficient on the surface of the board is 22 W/m²·°C, the average surface temperature of the chips is

- (a) 72.4°C (b) 66.5°C (c) 40.4°C (d) 58.2°C (e) 49.1°C

Answer (d) 58.2°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
A=0.1*0.2 [m^2]
Q= 100*0.08 [W]
Tair=40 [C]
h=22 [W/m^2-C]
Q= h*A*(Ts-Tair)
```

"Wrong Solutions:"

Q= h*(W1_Ts-Tair) "Not using area"

Q= h*2*A*(W2_Ts-Tair) "Using both sides of surfaces"

Q= h*A*(W3_Ts+Tair) "Adding temperatures instead of subtracting"

Q/100= h*A*(W4_Ts-Tair) "Considering 1 chip only"

1-152 A 40-cm-long, 0.4-cm-diameter electric resistance wire submerged in water is used to determine the convection heat transfer coefficient in water during boiling at 1 atm pressure. The surface temperature of the wire is measured to be 114°C when a wattmeter indicates the electric power consumption to be 7.6 kW. The heat transfer coefficient is

- (a) 108 kW/m²·°C (b) 13.3 kW/m²·°C (c) 68.1 kW/m²·°C (d) 0.76 kW/m²·°C (e) 256 kW/m²·°C

Answer (a) 108 kW/m²·°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
L=0.4 [m]
D=0.004 [m]
A=pi*D*L [m^2]
We=7.6 [kW]
Ts=114 [C]
Tf=100 [C] "Boiling temperature of water at 1 atm"
We= h*A*(Ts-Tf)
```

"Wrong Solutions:"

We= W1_h*(Ts-Tf) "Not using area"

We= W2_h*(L*pi*D^2/4)*(Ts-Tf) "Using volume instead of area"

We= W3_h*A*Ts "Using Ts instead of temp difference"

1-153 While driving down a highway early in the evening, the air flow over an automobile establishes an overall heat transfer coefficient of $25 \text{ W/m}^2\cdot\text{K}$. The passenger cabin of this automobile exposes 8 m^2 of surface to the moving ambient air. On a day when the ambient temperature is 33°C , how much cooling must the air conditioning system supply to maintain a temperature of 20°C in the passenger cabin?

- (a) 0.65 MW (b) 1.4 MW (c) 2.6 MW (d) 3.5 MW (e) 0.94 MW

Answer (c) 2.6 MW

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
h=25 [W/m^2-C]
A=8 [m^2]
T_1=33 [C]
T_2=20 [C]
Q=h*A*(T_2-T_1)
```

1-154 A room is heated by a 1.2 kW electric resistance heater whose wires have a diameter of 4 mm and a total length of 3.4 m. The air in the room is at 23°C and the interior surfaces of the room are at 17°C . The convection heat transfer coefficient on the surface of the wires is $8 \text{ W/m}^2\cdot^\circ\text{C}$. If the rates of heat transfer from the wires to the room by convection and by radiation are equal, the surface temperature of the wires is

- (a) 3534°C (b) 1778°C (c) 1772°C (d) 98°C (e) 25°C

Answer (b) 1778°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
D=0.004 [m]
L=3.4 [m]
W_dot_e=1200 [W]
T_infinity=23 [C]
T_surr=17 [C]
h=8 [W/m^2-C]
A=pi*D*L
Q_dot_conv=W_dot_e/2
Q_dot_conv=h*A*(T_s-T_infinity)
```

"Some Wrong Solutions with Common Mistakes"

```
Q_dot_conv=h*A*(W1_T_s-T_surr) "Using T_surr instead of T_infinity"
Q_dot_conv/1000=h*A*(W2_T_s-T_infinity) "Using kW unit for the rate of heat transfer"
Q_dot_conv=h*(W3_T_s-T_infinity) "Not using surface area of the wires"
W_dot_e=h*A*(W4_T_s-T_infinity) "Using total heat transfer"
```

1-155 Over 90 percent of the energy dissipated by an incandescent light bulb is in the form of heat, not light. What is the temperature of a vacuum-enclosed tungsten filament with an exposed surface area of 2.03 cm^2 in a 100 W incandescent light bulb? The emissivity of tungsten at the anticipated high temperatures is about 0.35. Note that the light bulb consumes 100 W of electrical energy, and dissipates all of it by radiation.

- (a) 1870 K (b) 2230 K (c) 2640 K (d) 3120 K (e) 2980 K

Answer (b) 2230 K

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
e = 0.35
Q = 100 [W]
A = 2.03E-4 [m^2]
Q = e * A * sigma * T^4
```

1-156 On a still clear night, the sky appears to be a blackbody with an equivalent temperature of 250 K. What is the air temperature when a strawberry field cools to 0°C and freezes if the heat transfer coefficient between the plants and the air is $6 \text{ W/m}^2\cdot^\circ\text{C}$ because of a light breeze and the plants have an emissivity of 0.9?

- (a) 14°C (b) 7°C (c) 3°C (d) 0°C (e) -3°C

Answer (a) 14°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
e = 0.9
h = 6 [W/m^2-K]
T_1 = 273 [K]
T_2 = 250 [K]
h * (T - T_1) = e * sigma * (T_1^4 - T_2^4)
```

1-157 A 30-cm diameter black ball at 120°C is suspended in air, and is losing heat to the surrounding air at 25°C by convection with a heat transfer coefficient of 12 W/m²·°C, and by radiation to the surrounding surfaces at 15°C. The total rate of heat transfer from the black ball is

- (a) 322 W (b) 595 W (c) 234 W (d) 472 W (e) 2100 W

Answer: (b) 595 W

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
sigma=5.67E-8 [W/m^2-K^4]
eps=1
D=0.3 [m]
A=pi*D^2
h_conv=12 [W/m^2-C]
Ts=120 [C]
Tf=25 [C]
Tsurr=15 [C]
Q_conv=h_conv*A*(Ts-Tf)
Q_rad=eps*sigma*A*((Ts+273)^4-(Tsurr+273)^4)
Q_total=Q_conv+Q_rad
```

"Wrong Solutions:"

W1_Ql=Q_conv "Ignoring radiation"

W2_Q=Q_rad "ignoring convection"

W3_Q=Q_conv+eps*sigma*A*(Ts^4-Tsurr^4) "Using C in radiation calculations"

W4_Q=Q_total/A "not using area"

1-158 A 3-m² black surface at 140°C is losing heat to the surrounding air at 35°C by convection with a heat transfer coefficient of 16 W/m²·°C, and by radiation to the surrounding surfaces at 15°C. The total rate of heat loss from the surface is

- (a) 5105 W (b) 2940 W (c) 3779 W (d) 8819 W (e) 5040 W

Answer (d) 8819 W

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
sigma=5.67E-8 [W/m^2-K^4]
eps=1
A=3 [m^2]
h_conv=16 [W/m^2-C]
Ts=140 [C]
Tf=35 [C]
Tsurr=15 [C]
Q_conv=h_conv*A*(Ts-Tf)
Q_rad=eps*sigma*A*((Ts+273)^4-(Tsurr+273)^4)
Q_total=Q_conv+Q_rad
```

"Some Wrong Solutions with Common Mistakes:"

W1_Ql=Q_conv "Ignoring radiation"

W2_Q=Q_rad "ignoring convection"

W3_Q=Q_conv+eps*sigma*A*(Ts^4-Tsurr^4) "Using C in radiation calculations"

W4_Q=Q_total/A "not using area"

1-159 A person's head can be approximated as a 25-cm diameter sphere at 35°C with an emissivity of 0.95. Heat is lost from the head to the surrounding air at 25°C by convection with a heat transfer coefficient of 11 W/m²·°C, and by radiation to the surrounding surfaces at 10°C. Disregarding the neck, determine the total rate of heat loss from the head.

- (a) 22 W (b) 27 W (c) 49 W (d) 172 W (e) 249 W

Answer: (c) 49 W

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
sigma=5.67E-8 [W/m^2-K^4]
eps=0.95
D=0.25 [m]
A=pi*D^2
h_conv=11 [W/m^2-C]
Ts=35 [C]
Tf=25 [C]
Tsurr=10 [C]
Q_conv=h_conv*A*(Ts-Tf)
Q_rad=eps*sigma*A*((Ts+273)^4-(Tsurr+273)^4)
Q_total=Q_conv+Q_rad
```

"Wrong Solutions:"

W1_QI=Q_conv "Ignoring radiation"

W2_Q=Q_rad "ignoring convection"

W3_Q=Q_conv+eps*sigma*A*(Ts^4-Tsurr^4) "Using C in radiation calculations"

W4_Q=Q_total/A "not using area"

1-160 A person standing in a room loses heat to the air in the room by convection and to the surrounding surfaces by radiation. Both the air in the room and the surrounding surfaces are at 20°C. The exposed surfaces of the person is 1.5 m² and has an average temperature of 32°C, and an emissivity of 0.90. If the rates of heat transfer from the person by convection and by radiation are equal, the combined heat transfer coefficient is

- (a) 0.008 W/m²·°C (b) 3.0 W/m²·°C (c) 5.5 W/m²·°C (d) 8.3 W/m²·°C (e) 10.9 W/m²·°C

Answer (e) 10.9 W/m²·°C

Solution Solved by EES Software. Solutions can be verified by copying-and-pasting the following lines on a blank EES screen.

```
T_infinity=20 [C]
T_surr=20 [C]
T_s=32 [C]
A=1.5 [m^2]
epsilon=0.90
sigma=5.67E-8 [W/m^2-K^4]
Q_dot_rad=epsilon*A*sigma*((T_s+273)^4-(T_surr+273)^4)
Q_dot_total=2*Q_dot_rad
Q_dot_total=h_combined*A*(T_s-T_infinity)
```

"Some Wrong Solutions with Common Mistakes"

Q_dot_rad=W1_h_combined*A*(T_s-T_infinity) "Using radiation heat transfer instead of total heat transfer"

Q_dot_rad_1=epsilon*A*sigma*(T_s^4-T_surr^4) "Using C unit for temperature in radiation calculation"

2*Q_dot_rad_1=W2_h_combined*A*(T_s-T_infinity)

1-161 . . . 1-164 Design and Essay Problems

