1.14 A wall has inner and outer surface temperatures of 16 and 6°C, respectively. The interior and exterior air temperatures are 20 and 5°C, respectively. The inner and outer convection heat transfer coefficients are 5 and 20 W/m²·K, respectively. Calculate the heat flux from the interior air to the wall, from the wall to the exterior air, and from the wall to the interior air. Is the wall under steady-state conditions?

1.15 The free convection heat transfer coefficient on a thin hot vertical plate suspended in still air can be determined from observations of the change in plate temperature with time as it cools. Assuming the plate is isothermal and radiation exchange with its surroundings is negligible, evaluate the convection coefficient at the instant of time when the plate temperature is 245°C and the change in plate temperature with time \( \frac{dT}{dt} \) is \(-0.028 \text{ K/s}\). The ambient air temperature is 25°C and the plate measures 0.4 × 0.4 m with a mass of 4.25 kg and a specific heat of 2770 J/kg·K.

1.16 A transmission case measures \( W = 0.30 \text{ m} \) on a side and receives a power input of \( P_i = 150 \text{ hp} \) from the engine.

If the transmission efficiency is \( \eta = 0.93 \) and airflow over the case corresponds to \( T_\infty = 30°C \) and \( h = 200 \text{ W/m}^2·\text{K} \), what is the surface temperature of the transmission? What is the thermal resistance associated with convection?

1.17 A cartridge electrical heater is shaped as a cylinder of length \( L = 300 \text{ mm} \) and outer diameter \( D = 30 \text{ mm} \). Under normal operating conditions, the heater dissipates 2 kW while submerged in a water flow that is at 20°C and provides a convection heat transfer coefficient of \( h = 5000 \text{ W/m}^2·\text{K} \). Neglecting heat transfer from the ends of the heater, determine its surface temperature \( T_s \) and the thermal resistance due to convection. If the water flow is inadvertently terminated while the heater continues to operate, the heater surface is exposed to air that is also at 20°C but for which \( h = 50 \text{ W/m}^2·\text{K} \). What are the corresponding thermal resistance due to convection and surface temperature? What are the consequences of such an event?

1.18 A common procedure for measuring the velocity of an airstream involves the insertion of an electrically heated wire (called a hot-wire anemometer) into the airflow, with the axis of the wire oriented perpendicular to the flow direction. The electrical energy dissipated in the wire is assumed to be transferred to the air by forced convection. Hence, for a prescribed electrical power, the temperature of the wire depends on the convection coefficient, which, in turn, depends on the velocity of the air. Consider a wire of length \( L = 20 \text{ mm} \) and diameter \( D = 0.5 \text{ mm} \), for which a calibration of the form \( V = 6.25 \times 10^{-5} \text{ h}^2 \) has been determined. The velocity \( V \) and the convection coefficient \( h \) have units of m/s and W/m²·K, respectively. In an application involving air at a temperature of \( T_\infty = 25°C \), the surface temperature of the anemometer is maintained at \( T_s = 75°C \) with a voltage drop of 5 V and an electric current of 0.1 A. What is the velocity of the air?

1.19 A square isothermal chip is of width \( w = 5 \text{ mm} \) on a side and is mounted in a substrate such that its side and back surfaces are well insulated; the front surface is exposed to the flow of a coolant at \( T_c = 15°C \). From reliability considerations, the chip temperature must not exceed \( T = 85°C \).

If the coolant is air and the corresponding convection coefficient is \( h = 200 \text{ W/m}^2·\text{K} \), what is the maximum allowable chip power? If the coolant is a dielectric liquid for which \( h = 3000 \text{ W/m}^2·\text{K} \), what is the maximum allowable power?

1.20 For a boiling process such as shown in Figure 1.5c, the ambient temperature \( T_a \) in Newton’s law of cooling is replaced by the saturation temperature of the fluid \( T_{sat} \). Consider a situation where the heat flux from the hot plate is \( q'' = 20 \times 10^3 \text{ W/m}^2 \). If the fluid is water at atmospheric pressure and the convection heat transfer coefficient is \( h_s = 20 \times 10^3 \text{ W/m}^2·\text{K} \), determine the upper surface temperature of the plate, \( T_{sat} \). In an effort to minimize the surface temperature, a technician proposes replacing the water with a dielectric fluid whose saturation temperature is \( T_{sat,d} = 52°C \). If the heat transfer coefficient associated with the dielectric fluid is \( h_d = 3 \times 10^3 \text{ W/m}^2·\text{K} \), will the technician’s plan work?
2.16 Compare and contrast the heat capacity \( \rho c_p \) of common brick, plain carbon steel, engine oil, water, and soil. Which material provides the greatest amount of thermal energy storage per unit volume? Which material would you expect to have the lowest cost per unit heat capacity? Evaluate properties at 300 K.

2.17 A cylindrical rod of stainless steel is insulated on its exterior surface except for the ends. The steady-state temperature distribution is \( T(x) = a - bxL \), where \( a = 305 \text{ K} \) and \( b = 10 \text{ K} \). The diameter and length of the rod are \( D = 20 \text{ mm} \) and \( L = 100 \text{ mm} \), respectively. Determine the heat flux along the rod, \( q^* \). Hint: The mass of the rod is \( m = 0.248 \text{ kg} \).

2.19 Consider a one-dimensional plane wall of thickness \( 2L \) that experiences uniform volumetric heat generation. The surface temperatures of the wall are maintained at \( T_{s1} \) and \( T_{s2} \) as shown in the sketch. Verify, by direct substitution, that an expression of the form

\[
T(x) = \frac{qL^2}{2k} \left(1 - \frac{x^2}{L^2}\right) + \frac{2}{L} \left( T_{s2} - T_{s1} \right) + \frac{2}{L} \left( T_{s1} + T_{s2} \right)
\]

satisfies the steady-state form of the heat diffusion equation. Determine an expression for the heat flux distribution, \( q^*(x) \).

2.20 A pan is used to boil water by placing it on a stove, from which heat is transferred at a fixed rate \( q_w \). There are two stages to the process. In Stage 1, the water is taken from its initial (room) temperature \( T_i \) to the boiling point, as heat is transferred from the pan by natural convection. During this stage, a constant value of the convection coefficient \( h \) may be assumed, while the bulk temperature of the water increases with time, \( T_w = T_w(t) \). In Stage 2, the water has come to a boil, and its temperature remains at a fixed value, \( T_w = T_{boil} \), as heating continues. Consider a pan bottom of thickness \( L \) and diameter \( D \), with a coordinate system corresponding to \( x = 0 \) and \( x = L \) for the surfaces in contact with the stove and water, respectively.

(a) Write the form of the heat equation and the boundary/initial conditions that determine the variation of temperature with position and time, \( T(x, t) \), in the pan bottom during Stage 1. Express your result in terms of the parameters \( q_w, D, L, h, \) and \( T_{boil} \) as well as appropriate properties of the pan material.

(b) During Stage 2, the surface of the pan in contact with the water is at a fixed temperature, \( T(L, t) = T_i > T_w \). Write the form of the heat equation and boundary conditions that determine the temperature distribution \( T(x) \) in the pan bottom. Express your result in terms of the parameters \( q_w, D, L, \) and \( T_i \) as well as appropriate properties of the pan material.

2.21 Uniform internal heat generation at \( \dot{q} = 6 \times 10^7 \text{ W/m}^3 \) is occurring in a cylindrical nuclear reactor fuel rod of 60-mm diameter, and under steady-state conditions
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(d) Determine the radial distribution of the heat flux at the end faces of the cylinder, \( q''(r, z_1) \) and \( q''(r, z_0) \). What are the corresponding heat rates? Are they into or out of the cylinder?

(e) Verify that your results are consistent with an overall energy balance on the cylinder.

2.40 A spherical shell of inner and outer radii \( r_1 \) and \( r_2 \), respectively, contains heat-dissipating components, and at a particular instant the temperature distribution in the shell is known to be of the form

\[
T(r) = \frac{C_1}{r} + C_2
\]

Are conditions steady-state or transient? How do the heat flux and heat rate vary with radius?

2.41 A chemically reacting mixture is stored in a thin-walled spherical container of radius \( r_1 = 200 \) mm, and the exothermic reaction generates heat at a uniform, but temperature-dependent volumetric rate of \( \dot{q} = \dot{q}_o \exp(-A/T_c) \), where \( \dot{q}_o = 5000 \) W/m\(^3\), \( A = 75 \) K, and \( T_c \) is the mixture temperature in kelvins. The vessel is enclosed by an insulating material of outer radius \( r_2 \), thermal conductivity \( k \), and emissivity \( \varepsilon \). The outer surface of the insulation experiences convection heat transfer and net radiation exchange with the adjoining air and large surroundings, respectively.

(b) Applying Fourier’s law, show that the rate of heat transfer by conduction through the insulation may be expressed as

\[
q_c = \frac{4\pi k(T_{s1} - T_{s2})}{(1/r_1) - (1/r_2)}
\]

Applying an energy balance to a control surface about the container, obtain an alternative expression for \( q_c \), expressing your result in terms of \( \dot{q} \) and \( r_1 \).

(c) Applying an energy balance to a control surface placed around the outer surface of the insulation, obtain an expression from which \( T_{s2} \) may be determined as a function of \( \dot{q} \), \( r_1 \), \( h \), \( T_{sw} \), \( \varepsilon \), and \( T_{sw} \).

(d) The process engineer wishes to maintain a reactor temperature of \( T_r = T(r_1) = 95^\circ \)C under conditions for which \( k = 0.05 \) W/m \( \cdot \) K, \( r_2 = 208 \) mm, \( h = 5 \) W/m\(^2\) \( \cdot \) K, \( \varepsilon = 0.9 \), \( T_a = 25^\circ \)C, and \( T_{sw} = 35^\circ \)C. What is the actual reactor temperature and the outer surface temperature \( T_{s2} \) of the insulation?

(e) Compute and plot the variation of \( T_{s2} \) with \( r_2 \) for \( 201 \leq r_2 \leq 210 \) mm. The engineer is concerned about potential burn injuries to personnel who may come into contact with the exposed surface of the insulation. Is increasing the insulation thickness a practical solution to maintaining \( T_{s2} \leq 45^\circ \)C? What other parameter could be varied to reduce \( T_{s2} \)?

Graphical Representations

2.42 A thin electrical heater dissipating 4000 W/m\(^2\) is sandwiched between two 25-mm-thick plates whose exposed surfaces experience convection with a fluid for which \( T_w = 20^\circ \)C and \( h = 400 \) W/m\(^2\) \( \cdot \) K. The thermophysical properties of the plate material are \( \rho = 2500 \) kg/m\(^3\), \( c = 700 \) J/kg \( \cdot \) K, and \( k = 5 \) W/m \( \cdot \) K.

(a) On \( T - x \) coordinates, sketch the steady-state temperature distribution for \(-L \leq x \leq +L\). Calculate values of the temperatures at the surfaces, \( x = \pm L \), and

\[
\begin{align*}
\text{Fluid} & \quad T_w, h \\
\text{Electric heater, } q'' & \quad \rho, c, k
\end{align*}
\]

Sketch the temperature distribution, \( T(r) \), labeling key features.
the midpoint, $x = 0$. Label this distribution as Case 1, and explain its salient features.

(b) Consider conditions for which there is a loss of coolant and existence of a nearly adiabatic condition on the $x = +L$ surface. On the $T - x$ coordinates used for part (a), sketch the corresponding steady-state temperature distribution and indicate the temperatures at $x = 0, \pm L$. Label the distribution as Case 2, and explain its key features.

(c) With the system operating as described in part (b), the surface $x = -L$ also experiences a sudden loss of coolant. This dangerous situation goes undetected for 15 min, at which time the power to the heater is de-activated. Assuming no heat losses from the surfaces of the plates, what is the eventual ($t \to \infty$), uniform, steady-state temperature distribution in the plates? Show this distribution as Case 3 on your sketch, and explain its key features. Hint: Apply the conservation of energy requirement on a time-interval basis, Eq. 1.12b, for the initial and final conditions corresponding to Case 2 and Case 3, respectively.

(d) On $T - t$ coordinates, sketch the temperature history at the plate locations $x = 0, \pm L$ during the transient period between the distributions for Cases 2 and 3. Where and when will the temperature in the system achieve a maximum value?

2.43 The plane wall with constant properties and no internal heat generation shown in the figure is initially at a uniform temperature $T_0$. Suddenly the surface at $x = L$ is heated by a fluid at $T_w$ having a convection heat transfer coefficient $h$. The boundary at $x = 0$ is perfectly insulated.

(a) Write the differential equation, and identify the boundary and initial conditions that could be used to determine the temperature as a function of position and time in the wall.

(b) On $T - x$ coordinates, sketch the temperature distributions for the following conditions: initial condition ($t \leq 0$), steady-state condition ($t \to \infty$), and two intermediate times.

(c) On $q''_w - t$ coordinates, sketch the heat flux at the locations $x = 0, x = L$. That is, show qualitatively how $q''_w(0, t)$ and $q''_w(L, t)$ vary with time.

(d) Write an expression for the total energy transferred to the wall per unit volume of the wall ($J/m^3$).

2.44 Consider the steady-state temperature distributions within a composite wall composed of Material A and Material B for the two cases shown. There is no internal generation, and the conduction process is one-dimensional.

Case 1

Case 2

Answer the following questions for each case. Which material has the higher thermal conductivity? Does the thermal conductivity vary significantly with temperature? If so, how? Describe the heat flux distribution $q''_w(x)$ through the composite wall. If the thickness and thermal conductivity of each material were both doubled and the boundary temperatures remained the same, what would be the effect on the heat flux distribution?

Case 1. Linear temperature distributions exist in both materials, as shown.

Case 2. Nonlinear temperature distributions exist in both materials, as shown.

2.45 A plane wall has constant properties, no internal heat generation, and is initially at a uniform temperature $T_0$. Suddenly, the surface at $x = L$ is heated by a fluid at $T_w$ having a convection coefficient $h$. At the same instant, the electrical heater is energized, providing a constant heat flux $q''_w$ at $x = 0$.

(a) On $T - x$ coordinates, sketch the temperature distributions for the following conditions: initial
$T(x = 0) = 30^\circ C$ and $q^*_r = 100 \text{ W/m}^2$ using the expression for the minimum effective thermal conductivity of a porous medium, the expression for the maximum effective thermal conductivity of a porous medium, Maxwell's expression, and for the case where $k_{\text{eff}}(x) = k_r$.

**Alternative Conduction Analysis**

3.32 Use the alternative conduction analysis of Section 3.2 to derive an expression relating the radial heat rate, $q_r$, to the wall temperatures $T_{1w}$ and $T_{2w}$ of the hollow cylinder of Figure 3.7. Use your expression to calculate the heat transfer rate associated with a $L = 2 \text{ m}$ long cylinder of inner and outer radii of $r_1 = 50 \text{ mm}$ and $r_2 = 75 \text{ mm}$, respectively. The thermal conductivity of the cylindrical wall is $k = 2.5 \text{ W/m} \cdot \text{K}$, and the inner and outer surface temperatures are $T_{1w} = 100^\circ C$ and $T_{2w} = 67^\circ C$, respectively.

3.33 The diagram shows a conical section fabricated from pure aluminum. It is of circular cross section having diameter $D = a x^{1/2}$, where $a = 0.5 \text{ m}^{1/2}$. The small end is located at $x = 25 \text{ mm}$ and the large end at $x = 125 \text{ mm}$. The end temperatures are $T_1 = 600 \text{ K}$ and $T_2 = 400 \text{ K}$, while the lateral surface is well insulated.

(a) Derive an expression for the temperature distribution $T(x)$ in symbolic form, assuming one-dimensional conditions. Sketch the temperature distribution.

(b) Calculate the heat rate $q_r$.

3.34 A truncated solid cone is of circular cross section, and its diameter is related to the axial coordinate by an expression of the form $D = a x^{1/2}$, where $a = 2.0 \text{ m}^{1/2}$.

The sides are well insulated, while the top surface of the cone at $x_1$ is maintained at $T_1$ and the bottom surface at $x_2$ is maintained at $T_2$.

(a) Obtain an expression for the temperature distribution $T(x)$.

(b) What is the rate of heat transfer across the cone if it is constructed of pure aluminum with $x_1 = 0.080 \text{ m}$, $T_1 = 100^\circ C$, $x_2 = 0.240 \text{ m}$, and $T_2 = 20^\circ C$?

3.35 From Figure 2.5 it is evident that, over a wide temperature range, the temperature dependence of the thermal conductivity of many solids may be approximated by a linear expression of the form $k = k_c + a T$, where $k_c$ is a positive constant and $a$ is a coefficient that may be positive or negative. Obtain an expression for the heat flux across a plane wall whose inner and outer surfaces are maintained at $T_0$ and $T_1$, respectively. Sketch the forms of the temperature distribution corresponding to $a > 0$, $a = 0$, and $a < 0$.

3.36 Consider a tube wall of inner and outer radii $r_i$ and $r_o$, whose temperatures are maintained at $T_i$ and $T_o$, respectively. The thermal conductivity of the cylinder is temperature dependent and may be represented by an expression of the form $k = k_c(1 + a T)$, where $k_c$ and $a$ are constants. Obtain an expression for the heat transfer rate per unit length of the tube. What is the thermal resistance of the tube wall?

3.37 Measurements show that steady-state conduction through a plane wall without heat generation produced a convex temperature distribution such that the midpoint temperature was $\Delta T_m$ higher than expected for a linear temperature distribution.

3.38 A device used to measure the surface temperature of an object to within a spatial resolution of approximately 50 nm is shown in the schematic. It consists of an extremely sharp-tipped stylus and an extremely small cantilever that is scanned across the surface. The probe
tissue that is at 37°C. A spherical layer of frozen tissue forms around the probe, with a temperature of 0°C existing at the phase front (interface) between the frozen and normal tissue. If the thermal conductivity of frozen tissue is approximately 1.5 W/m·K and heat transfer at the phase front may be characterized by an effective convection coefficient of 50 W/m²·K, what is the thickness of the layer of frozen tissue (assuming negligible perfusion)?

3.56 A composite spherical shell of inner radius \( r_1 = 0.25 \) m is constructed from lead of outer radius \( r_2 = 0.30 \) m and AISI 302 stainless steel of outer radius \( r_3 = 0.31 \) m. The cavity is filled with radioactive wastes that generate heat at a rate of \( \dot{q} = 5 \times 10^3 \) W/m³. It is proposed to submerge the container in oceanic waters that are at a temperature of \( T_{\infty} = 10^\circ\)C and provide a uniform convection coefficient of \( h = 500 \) W/m²·K at the outer surface of the container. Are there any problems associated with this proposal?

3.57 The energy transferred from the anterior chamber of the eye through the cornea varies considerably depending on whether a contact lens is worn. Treat the eye as a spherical system and assume the system to be at steady state. The convection coefficient \( h_2 \) is unchanged with and without the contact lens in place. The cornea and the lens cover one-third of the spherical surface area.

Values of the parameters representing this situation are as follows:

- \( r_1 = 10.2 \) mm
- \( r_2 = 12.7 \) mm
- \( r_3 = 16.5 \) mm
- \( T_{\infty} = 21^\circ\)C
- \( T_{\text{air}} = 37^\circ\)C
- \( k_1 = 0.80 \) W/m·K
- \( k_2 = 0.35 \) W/m·K
- \( h_2 = 6 \) W/m²·K
- \( h_1 = 12 \) W/m²·K

(a) Construct the thermal circuits, labeling all potentials and flows for the systems excluding the contact lens and including the contact lens. Write resistance elements in terms of appropriate parameters.

(b) Determine the rate of heat loss from the anterior chamber with and without the contact lens in place.

(c) Discuss the implication of your results.

3.58 The outer surface of a hollow sphere of radius \( r_1 \) is subjected to a uniform heat flux \( q_1^* \). The inner surface at \( r_1 \) is held at a constant temperature \( T_{\text{in}} \).

(a) Develop an expression for the temperature distribution \( T(r) \) in the sphere wall in terms of \( q_1^* \), \( T_{\text{in}} \), \( r_1 \), \( r_2 \), and the thermal conductivity of the wall material \( k \).

(b) If the inner and outer sphere radii are \( r_1 = 50 \) mm and \( r_2 = 100 \) mm, what heat flux \( q_1^* \) is required to maintain the outer surface at \( T_{\text{out}} = 50^\circ\)C, while the inner surface is at \( T_{\text{in}} = 20^\circ\)C? The thermal conductivity of the wall material is \( k = 10 \) W/m·K.

3.59 A spherical shell of inner and outer radii \( r_1 \) and \( r_2 \), respectively, is filled with a heat-generating material that provides for a uniform volumetric generation rate (W/m³) of \( \dot{q} \). The outer surface of the shell is exposed to a fluid having a temperature \( T_\infty \), and a convection coefficient \( h \). Obtain an expression for the steady-state temperature distribution \( T(r) \) in the shell, expressing your result in terms of \( r_1 \), \( r_2 \), \( \dot{q} \), \( h \), \( T_\infty \), and the thermal conductivity \( k \) of the shell material.

3.60 A spherical tank of 4-m diameter contains a liquefied-petroleum gas at -60°C. Insulation with a thermal conductivity of 0.06 W/m·K and thickness 250 mm is applied to the tank to reduce the heat gain.

(a) Determine the radial position in the insulation layer at which the temperature is 0°C when the ambient air temperature is 20°C and the convection coefficient on the outer surface is 6 W/m²·K.

(b) If the insulation is pervious to moisture from the atmospheric air, what conclusions can you reach about the formation of ice in the insulation? What effect will ice formation have on heat gain to the LP gas? How could this situation be avoided?

3.61 Liquid nitrogen (\( T = 77 \) K) is stored in a thin-walled, spherical container that is covered with a uniformly thick insulation layer of thermal conductivity \( k = 0.15 \) W/m·K. The outer surface temperature of the insulation is at \( T_{\text{out}} = 20^\circ\)C. Due to space constraints, the outer radius of the insulation is fixed at \( r_2 = 0.5 \) m. Determine the radius of the thin-walled, spherical container that will yield the minimum heat transfer rate per unit nitrogen volume. Also calculate the minimum heat transfer rate per unit nitrogen volume.

3.62 One modality for destroying malignant tissue involves imbedding a small spherical heat source of radius \( r_0 \) within the tissue and maintaining local temperatures
Consider a packed bed of 75-mm-diameter aluminum spheres \((\rho = 2700 \text{ kg/m}^3, c = 950 \text{ J/kg \cdot K}, k = 240 \text{ W/m \cdot K})\) and a charging process for which gas enters the storage unit at a temperature of \(T_{g,i} = 300^\circ\text{C}\). If the initial temperature of the spheres is \(T_i = 25^\circ\text{C}\) and the convection coefficient is \(h = 75 \text{ W/m}^2 \cdot \text{K}\), how long does it take a sphere near the inlet of the system to accumulate 90% of the maximum possible thermal energy? What is the corresponding temperature at the center of the sphere? Is there any advantage to using copper instead of aluminum?

5.14 A copper sheet of thickness \(2L = 2 \text{ mm}\) has an initial temperature of \(T_i = 118^\circ\text{C}\). It is suddenly quenched in liquid water, resulting in boiling at its two surfaces. For boiling, Newton’s law of cooling is expressed as \(q'' = h(T_g - T_{sat})\), where \(T_g\) is the solid surface temperature and \(T_{sat}\) is the saturation temperature of the fluid (in this case \(T_{sat} = 100^\circ\text{C}\)). The convection heat transfer coefficient may be expressed as \(h = 1010 \text{ W/m}^2 \cdot \text{K}^2(T_i - T_{sat})^2\). Determine the time needed for the sheet to reach a temperature of \(T = 102^\circ\text{C}\). Plot the copper temperature versus time for \(0 \leq t \leq 0.5 \text{ s}\). On the same graph, plot the copper temperature history assuming the heat transfer coefficient is constant, evaluated at the average copper temperature \(T = 110^\circ\text{C}\). Assume lumped capacitance behavior.

5.15 Carbon steel (AISI 1010) shafts of 0.1-m diameter are heat treated in a gas-fired furnace whose gases are at \(1200^\circ\text{K}\) and provide a convection coefficient of \(100 \text{ W/m}^2 \cdot \text{K}\). If the shafts enter the furnace at \(300^\circ\text{K}\), how long must they remain in the furnace to achieve a centerline temperature of \(800^\circ\text{K}\)?

5.16 Batch processes are often used in chemical and pharmaceutical operations to achieve a desired chemical composition for the final product and typically involve a transient heating operation to take the product from room temperature to the desired process temperature. Consider a situation for which a chemical of density \(\rho = 1200 \text{ kg/m}^3\) and specific heat \(c = 2200 \text{ J/kg \cdot K}\) occupies a volume of \(V = 2.25 \text{ m}^3\) in an insulated vessel. The chemical is to be heated from room temperature, \(T_i = 300^\circ\text{K}\), to a process temperature of \(T = 450^\circ\text{K}\) by passing saturated steam at \(T_h = 500^\circ\text{K}\) through a coiled, thin-walled, 20-mm-diameter tube in the vessel. Steam condensation within the tube maintains an interior convection coefficient of \(h_l = 10,000 \text{ W/m}^2 \cdot \text{K}\), while the highly agitated liquid in the stirred vessel maintains an outside convection coefficient of \(h_w = 2000 \text{ W/m}^2 \cdot \text{K}\).

If the chemical is to be heated from 300 to 450 K in 60 min, what is the required length \(L\) of the submerged tubing?

5.17 A power transistor mounted on a finned heat sink can be modeled as a spatially isothermal object with internal heat generation and an external convection resistance.

(a) Consider such a system of mass \(m\), specific heat \(c\), and surface area \(A_s\), which is initially in equilibrium with the environment at \(T_e\). Suddenly, the device is energized such that a constant heat generation \(E_i(t)\) occurs. Show that the temperature response of the device is

\[
\frac{\theta}{\theta_i} = \exp\left(-\frac{t}{RC}\right)
\]

where \(\theta = T - T(\infty)\) and \(T(\infty)\) is the steady-state temperature corresponding to \(t \rightarrow \infty\); \(\theta_i = T_i - T(\infty)\); \(T_i\) is initial temperature of device; \(R = \text{thermal resistance} \frac{1}{hA_s}\); and \(C = \text{thermal capacitance} mc\).

(b) A device which generates 100 W of heat is mounted on an aluminum heat sink weighing 0.35 kg and reaches a temperature of 100°C in ambient air at 20°C under steady-state conditions. If the device is initially at 20°C, what temperature will it reach 5 min after the power is switched on?

5.18 Molecular electronics is an emerging field associated with computing and data storage utilizing energy transfer at the molecular scale. At this scale, thermal energy is associated exclusively with the vibration of molecular chains. The primary resistance to energy transfer in these proposed devices is the contact resistance at metal-molecule interfaces. To measure the contact resistance, individual molecules are self-assembled in a usual pattern onto a very thin gold substrate. The substrate is suddenly heated by a short pulse of laser irradiation,