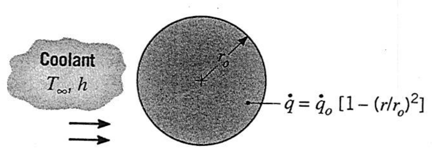
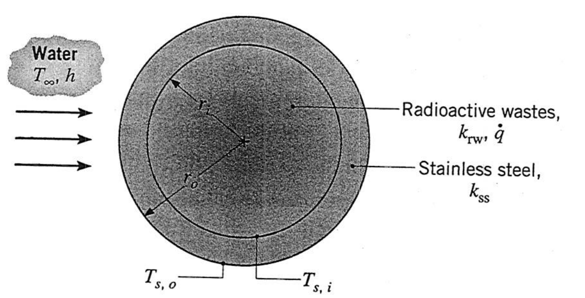
3.93 A radioactive material of thermal conductivity k is cast as a solid sphere of radius r_o and placed in a liquid bath for which the temperature T_∞ and convection coefficient h are known. Heat is uniformly generated within the solid at a volumetric rate of $\dot{q}$. Obtain the steady-state radial temperature distribution in the solid, expressing your result in terms of r_o, $\dot{q}$, k, h, and T_∞.

3.94 Radioactive wastes are packed in a thin-walled spherical container. The wastes generate thermal energy nonuniformly according to the relation $\dot{q} = \dot{q}_o[1 - (r/r_o)^2]$, where $\dot{q}$ is the local rate of energy generation per unit volume, $\dot{q}_o$ is a constant, and r_o is the radius of the container. Steady-state conditions are maintained by submerging the container in a liquid that is at T_∞ and provides a uniform convection coefficient h.



Determine the temperature distribution, $T(r)$, in the container. Express your result in terms of $\dot{q}_o$, r_o, T_∞, h, and the thermal conductivity k of the radioactive wastes.

3.95 Radioactive wastes ($k_{rw} = 20$ W/m · K) are stored in a spherical, stainless steel ($k_{ss} = 15$ W/m · K) container of inner and outer radii equal to $r_i = 0.5$ m and $r_o = 0.6$ m. Heat is generated volumetrically within the wastes at a uniform rate of $\dot{q} = 10^5$ W/m^3, and the outer surface of the container is exposed to a water flow for which $h = 1000$ W/m^2 · K and $T_\infty = 25$°C.



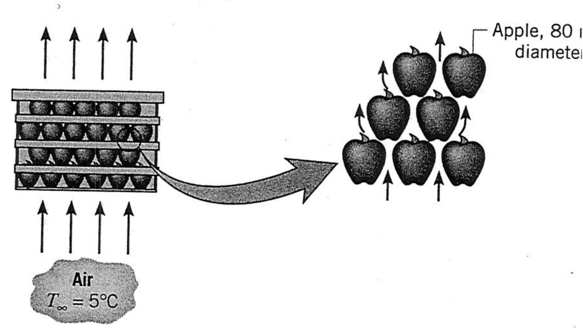
(a) Evaluate the steady-state outer surface temperature, $T_{s,o}$.

(b) Evaluate the steady-state inner surface temperature, $T_{s,i}$.

(c) Obtain an expression for the temperature distribution, $T(r)$, in the radioactive wastes. Express your result in terms of r_i, $T_{s,i}$, k_{rw}, and $\dot{q}$. Evaluate the temperature at $r = 0$.

[(d)] A proposed extension of the foregoing design volves storing waste materials having the s thermal conductivity but twice the heat genera ($\dot{q} = 2 \times 10^5$ W/m^3) in a stainless steel containe equivalent inner radius ($r_i = 0.5$ m). Safety con erations dictate that the maximum system temp ture not exceed 475°C and that the container thickness be no less than $t = 0.04$ m and prefera at or close to the original design ($t = 0.1$ m). Ass the effect of varying the outside convection coe cient to a maximum achievable value of $h = 5($ W/m^2 · K (by increasing the water velocity) and container wall thickness. Is the proposed extens feasible? If so, recommend suitable operating design conditions for h and t, respectively.

3.96 Unique characteristics of biologically active materi such as fruits, vegetables, and other products require s cial care in handling. Following harvest and separati from producing plants, glucose is catabolized to produ carbon dioxide, water vapor, and heat, with attendant ternal energy generation. Consider a carton of appl each of 80-mm diameter, which is ventilated with air 5°C and a velocity of 0.5 m/s. The corresponding value the heat transfer coefficient is 7.5 W/m^2 · K. Within ea apple thermal energy is uniformly generated at a total r of 4000 J/kg · day. The density and thermal conductivi of the apple are 840 kg/m^3 and 0.5 W/m · K, respectivel



(a) Determine the apple center and surfac temperatures.

[(b)] For the stacked arrangement of apples within th crate, the convection coefficient depends on th velocity as $h = C_1 V^{0.425}$, where $C_1 = 10.1$ W/m^2 K · (m/s)$^{0.425}$. Compute and plot the center an surface temperatures as a function of the air veloc ity for $0.1 \leq V \leq 1$ m/s.

3.97 Consider the plane wall, long cylinder, and sphere shown schematically, each with the same characteristic length a, thermal conductivity k, and uniform volumetric energy generation rate $\dot{q}$.

effects may be neglected, and the Pyrex may be assumed to have a thermal conductivity of 1.4 W/m · K.

3.55 Consider the liquid oxygen storage system and the laboratory environmental conditions of Problem 1.49. To reduce oxygen loss due to vaporization, an insulating layer should be applied to the outer surface of the container. Consider using a laminated aluminum foil/glass mat insulation, for which the thermal conductivity and surface emissivity are $k = 0.00016$ W/m · K and $\varepsilon = 0.20$, respectively.

(a) If the container is covered with a 10-mm-thick layer of insulation, what is the percentage reduction in oxygen loss relative to the uncovered container?

(b) Compute and plot the oxygen evaporation rate (kg/s) as a function of the insulation thickness t for $0 \leq t \leq 50$ mm.

3.56 In Example 3.5, an expression was derived for the critical insulation radius of an insulated, cylindrical tube. Derive the expression that would be appropriate for an insulated sphere.

3.57 A hollow aluminum sphere, with an electrical heater in the center, is used in tests to determine the thermal conductivity of insulating materials. The inner and outer radii of the sphere are 0.15 and 0.18 m, respectively, and testing is done under steady-state conditions with the inner surface of the aluminum maintained at 250°C. In a particular test, a spherical shell of insulation is cast on the outer surface of the sphere to a thickness of 0.12 m. The system is in a room for which the air temperature is 20°C and the convection coefficient at the outer surface of the insulation is 30 W/m² · K. If 80 W are dissipated by the heater under steady-state conditions, what is the thermal conductivity of the insulation?

3.58 A spherical tank for storing liquid oxygen on the space shuttle is to be made from stainless steel of 0.80-m outer diameter and 5-mm wall thickness. The boiling point and latent heat of vaporization of liquid oxygen are 90 K and 213 kJ/kg, respectively. The tank is to be installed in a large compartment whose temperature is to be maintained at 240 K. Design a thermal insulation system that will maintain oxygen losses due to boiling below 1 kg/day.

3.59 A spherical, cryosurgical probe may be imbedded in diseased tissue for the purpose of freezing, and thereby destroying, the tissue. Consider a probe of 3-mm diameter whose surface is maintained at −30°C when imbedded in 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)?

3.60 A spherical vessel used as a reactor for producing pharmaceuticals has a 10-mm-thick stainless steel wall (k = 17 W/m · K) and an inner diameter of 1 m. The exterior surface of the vessel is exposed to ambient air (T_∞ = 25°C) for which a convection coefficient of 6 W/m² · K may be assumed.

(a) During steady-state operation, an inner surface temperature of 50°C is maintained by energy generated within the reactor. What is the heat loss from the vessel?

(b) If a 20-mm-thick layer of fiberglass insulation (k = 0.040 W/m · K) is applied to the exterior of the vessel and the rate of thermal energy generation is unchanged, what is the inner surface temperature of the vessel?

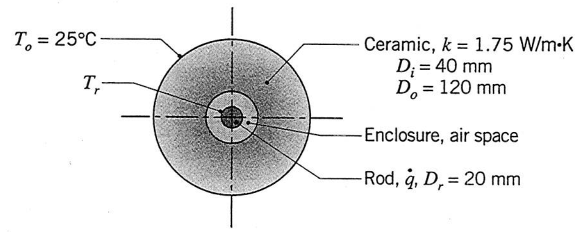
3.61 The wall of a spherical tank of 1-m diameter contains an exothermic chemical reaction and is at 200°C when the ambient air temperature is 25°C. What thickness of urethane foam is required to reduce the exterior temperature to 40°C, assuming the convection coefficient is 20 W/m² · K for both situations? What is the percentage reduction in heat rate achieved by using the insulation?

3.62 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 hea at a rate of $\dot{q} = 5 \times 10^5$ W/m³. It is proposed to submerge the container in oceanic waters that are at a temperature o $T_\infty = 10$°C and provide a uniform convection coefficien of $h = 500$ W/m² · K at the outer surface of the container Are there any problems associated with this proposal?

3.63 As an alternative to storing radioactive materials i oceanic waters, it is proposed that the system of Probler 3.62 be placed in a large tank for which the flow of wate and hence the convection coefficient h, can be controlle Compute and plot the maximum temperature of the lea $T(r_1)$, as a function of h for $100 \leq h \leq 1000$ W/m² · K. the temperature of the lead is not to exceed 500 K, what the minimum allowable value of h? To improve system r liability, it is desirable to increase the thickness of th stainless steel shell. For h = 300, 500, and 1000 W/m² · compute and plot the maximum lead temperature as a fun tion of shell thickness for $r_3 \geq 0.30$ m. What are the corr sponding values of the maximum allowable thickness?

3.64 The energy transferred from the anterior chamber of t eye through the cornea varies considerably dependi on whether a contact lens is worn. Treat the eye as contact resistance of $R''_{t,c} = 3 \times 10^{-4}\,m^2 \cdot K/W$. The convection heat transfer coefficient at the outer surface of the sheath is $10\,W/m^2 \cdot K$, and the temperature of the ambient air is 20°C. If the temperature of the insulation may not exceed 50°C, what is the maximum allowable electrical power that may be dissipated per unit length of the conductor? What is the critical radius of the insulation?

3.44 Electric current flows through a long rod generating thermal energy at a uniform volumetric rate of $\dot{q} = 2 \times 10^6\,W/m^3$. The rod is concentric with a hollow ceramic cylinder, creating an enclosure that is filled with air.



The thermal resistance per unit length due to radiation between the enclosure surfaces is $R'_{rad} = 0.30\,m \cdot K/W$, and the coefficient associated with free convection in the enclosure is $h = 20\,W/m^2 \cdot K$.

(a) Construct a thermal circuit that can be used to calculate the surface temperature of the rod, T_r. Label all temperatures, heat rates, and thermal resistances, and evaluate each thermal resistance.

(b) Calculate the surface temperature of the rod for the prescribed conditions.

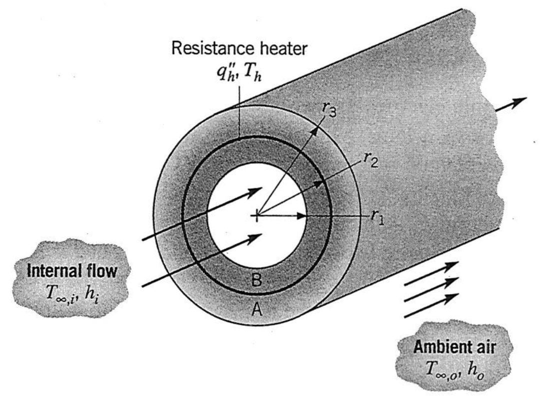
3.45 The evaporator section of a refrigeration unit consists of thin-walled, 10-mm-diameter tubes through which refrigerant passes at a temperature of −18°C. Air is cooled as it flows over the tubes, maintaining a surface convection coefficient of $100\,W/m^2 \cdot K$, and is subsequently routed to the refrigerator compartment.

(a) For the foregoing conditions and an air temperature of −3°C, what is the rate at which heat is extracted from the air per unit tube length?

(b) If the refrigerator's defrost unit malfunctions, frost will slowly accumulate on the outer tube surface. Assess the effect of frost formation on the cooling capacity of a tube for frost layer thicknesses in the range $0 \le \delta \le 4$ mm. Frost may be assumed to have a thermal conductivity of $0.4\,W/m \cdot K$.

(c) The refrigerator is disconnected after the defrost unit malfunctions and a 2-mm-thick layer of frost has formed. If the tubes are in ambient air for which $T_\infty = 20°C$ and natural convection maintains a convection coefficient of $2\,W/m^2 \cdot K$, how long will it take for the frost to melt? The frost may be assun to have a mass density of $700\,kg/m^3$ and a lat heat of fusion of 334 kJ/kg.

3.46 A composite cylindrical wall is composed of two ma rials of thermal conductivity k_A and k_B, which are se rated by a very thin, electric resistance heater for wh interfacial contact resistances are negligible.



Liquid pumped through the tube is at a temperature T and provides a convection coefficient h_i at the inner su face of the composite. The outer surface is exposed ambient air, which is at $T_{\infty,o}$ and provides a convecti coefficient of h_o. Under steady-state conditions, a ur form heat flux of q''_h is dissipated by the heater.

(a) Sketch the equivalent thermal circuit of the syste and express all resistances in terms of releva variables.

(b) Obtain an expression that may be used to determi the heater temperature, T_h.

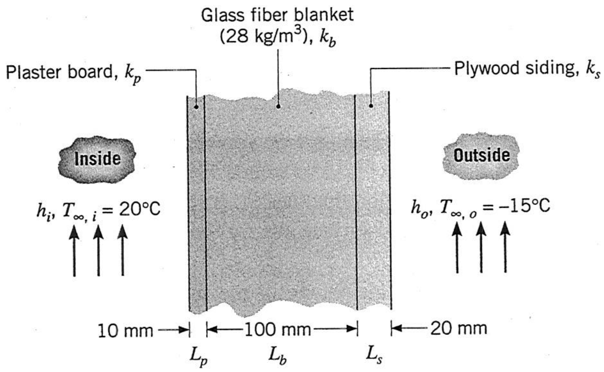
(c) Obtain an expression for the ratio of heat flows the outer and inner fluids, q'_o/q'_i. How might tl variables of the problem be adjusted to minimi: this ratio?

3.47 An electrical current of 700 A flows through a stainle steel cable having a diameter of 5 mm and an electric resistance of $6 \times 10^{-4}\,\Omega/m$ (i.e., per meter of cab length). The cable is in an environment having a ten perature of 30°C, and the total coefficient associate with convection and radiation between the cable and tl environment is approximately $25\,W/m^2 \cdot K$.

(a) If the cable is bare, what is its surface temperature

(b) If a very thin coating of electrical insulation applied to the cable, with a contact resistance ($0.02\,m^2 \cdot K/W$, what are the insulation and cabl surface temperatures?

3.13 A house has a composite wall of wood, fiberglass insulation, and plaster board, as indicated in the sketch. On a cold winter day the convection heat transfer coefficients are $h_o = 60\ \text{W/m}^2 \cdot \text{K}$ and $h_i = 30\ \text{W/m}^2 \cdot \text{K}$. The total wall surface area is 350 m².



(a) Determine a symbolic expression for the total thermal resistance of the wall, including inside and outside convection effects for the prescribed conditions.

(b) Determine the total heat loss through the wall.

(c) If the wind were blowing violently, raising h_o to $300\ \text{W/m}^2 \cdot \text{K}$, determine the percentage increase in the heat loss.

(d) What is the controlling resistance that determines the amount of heat flow through the wall?

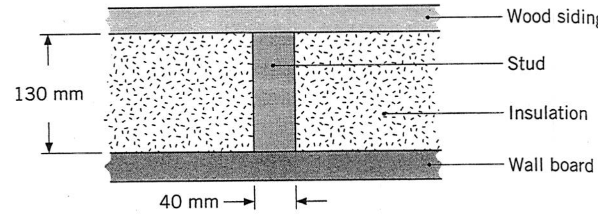
3.14 Consider the composite wall of Problem 3.13 under conditions for which the inside air is still characterized by $T_{\infty,i} = 20°\text{C}$ and $h_i = 30\ \text{W/m}^2 \cdot \text{K}$. However, use the more realistic conditions for which the outside air is characterized by a diurnal (time) varying temperature of the form

$$T_{\infty,o}(\text{K}) = 273 + 5 \sin\left(\frac{2\pi}{24}t\right) \qquad 0 \le t \le 12\ \text{h}$$

$$T_{\infty,o}(\text{K}) = 273 + 11 \sin\left(\frac{2\pi}{24}t\right) \qquad 12 \le t \le 24\ \text{h}$$

with $h_o = 60\ \text{W/m}^2 \cdot \text{K}$. Assuming quasisteady conditions for which changes in energy storage within the wall may be neglected, estimate the daily heat loss through the wall if its total surface area is 200 m².

3.15 Consider a composite wall that includes an 8-mm-thick hardwood siding, 40-mm by 130-mm hardwood studs on 0.65-m centers with glass fiber insulation (paper faced, 28 kg/m³), and a 12-mm layer of gypsum (vermiculite) wall board.



What is the thermal resistance associated with a wall that is 2.5 m high by 6.5 m wide (having 10 studs, each 2.5 m high)?

3.16 The thermal characteristics of a small, dormitory refrigerator are determined by performing two separate experiments, each with the door closed and the refrigerator placed in ambient air at $T_\infty = 25°\text{C}$. In one case, an electric heater is suspended in the refrigerator cavity, while the refrigerator is unplugged. With the heater dissipating 20 W, a steady-state temperature of 90°C is recorded within the cavity. With the heater removed and the refrigerator now in operation, the second experiment involves maintaining a steady-state cavity temperature of 5°C for a fixed time interval and recording the electrical energy required to operate the refrigerator. In such an experiment for which steady operation is maintained over a 12-hour period, the input electrical energy is 125,000 J. Determine the refrigerator's coefficient of performance (COP).

3.17 In the design of buildings, energy conservation requirements dictate that the exterior surface area, A_s, be minimized. This requirement implies that, for a desired floor space, there may be optimum values associated with the number of floors and horizontal dimensions of the building. Consider a design for which the total floor space, A_f, and the vertical distance between floors, H_f, are prescribed.

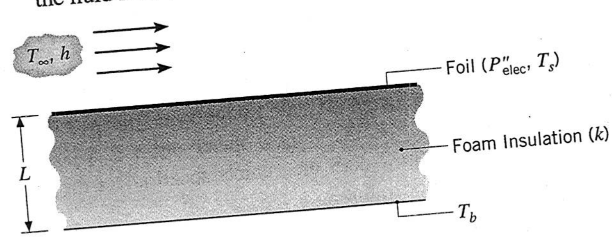
(a) If the building has a square cross section of width W on a side, obtain an expression for the value of W that would minimize heat loss to the surroundings. Heat loss may be assumed to occur from the four vertical side walls and from a flat roof. Express your result in terms of A_f and H_f.

(b) If $A_f = 32{,}768\ \text{m}^2$ and $H_f = 4$ m, for what values of W and N_f (the number of floors) is the heat loss minimized? If the average overall heat transfer coefficient is $U = 1\ \text{W/m}^2 \cdot \text{K}$ and the difference between the inside and ambient air temperatures is 25°C, what is the corresponding heat loss? What is the percent reduction in heat loss compared with a building for $N_f = 2$?

3.18 When raised to very high temperatures, many conventional liquid fuels dissociate into hydrogen and other components. Thus the advantage of a *solid oxide fuel* the heat flux required to achieve bonding. Plot your results as a function of L_f for $0 \leq L_f \leq 1$ mm.

3.5 The walls of a refrigerator are typically constructed by sandwiching a layer of insulation between sheet metal panels. Consider a wall made from fiberglass insulation of thermal conductivity $k_i = 0.046$ W/m · K and thickness $L_i = 50$ mm and steel panels, each of thermal conductivity $k_p = 60$ W/m · K and thickness $L_p = 3$ mm. If the wall separates refrigerated air at $T_{\infty,i} = 4°C$ from ambient air at $T_{\infty,o} = 25°C$, what is the heat gain per unit surface area? Coefficients associated with natural convection at the inner and outer surfaces may be approximated as $h_i = h_o = 5$ W/m^2 · K.

3.6 A technique for measuring convection heat transfer coefficients involves bonding one surface of a thin metallic foil to an insulating material and exposing the other surface to the fluid flow conditions of interest.



By passing an electric current through the foil, heat is dissipated uniformly within the foil and the corresponding flux, P''_{elec}, may be inferred from related voltage and current measurements. If the insulation thickness L and thermal conductivity k are known and the fluid, foil, and insulation temperatures (T_∞, T_s, T_b) are measured, the convection coefficient may be determined. Consider conditions for which $T_\infty = T_b = 25°C$, $P''_{elec} = 2000$ W/m^2, $L = 10$ mm, and $k = 0.040$ W/m · K.

(a) With water flow over the surface, the foil temperature measurement yields $T_s = 27°C$. Determine the convection coefficient. What error would be incurred by assuming all of the dissipated power to be transferred to the water by convection?

(b) If, instead, air flows over the surface and the temperature measurement yields $T_s = 125°C$, what is the convection coefficient? The foil has an emissivity of 0.15 and is exposed to large surroundings at 25°C. What error would be incurred by assuming all of the dissipated power to be transferred to the air by convection?

[(c)] Typically, heat flux gages are operated at a fixed temperature (T_s), in which case the power dissipation provides a direct measure of the convection coefficient. For $T_s = 27°C$, plot P''_{elec} as a function of h_o for $10 \leq h_o \leq 1000$ W/m^2 · K. What effect does h_o have on the error associated with neglecting conduction through the insulation?

3.7 The *wind chill*, which is experienced on a cold, windy d is related to increased heat transfer from exposed hur skin to the surrounding atmosphere. Consider a laye fatty tissue that is 3 mm thick and whose interior surfac maintained at a temperature of 36°C. On a calm day convection heat transfer coefficient at the outer surfa 25 W/m^2 · K, but with 30 km/h winds it reaches 65 W K. In both cases the ambient air temperature is −15°C

(a) What is the ratio of the heat loss per unit area fro skin for the calm day to that for the windy day?

(b) What will be the skin outer surface temperatu the calm day? For the windy day?

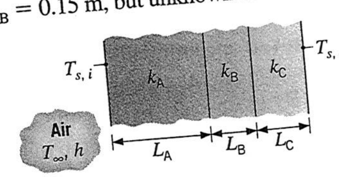
(c) What temperature would the air have to assu the calm day to produce the same heat loss occ with the air temperature at −15°C on the wind

3.8 A thermopane window consists of two pieces o 7 mm thick that enclose an air space 7 mm thic window separates room air at 20°C from outsid ent air at −10°C. The convection coefficient ass with the inner (room-side) surface is 10 W/m^2 ·

(a) If the convection coefficient associated outer (ambient) air is $h_o = 80$ W/m^2 · K, the heat loss through a window that is 0. by 0.5 m wide? Neglect radiation, and as air enclosed between the panes to be stag

[(b)] Compute and plot the effect of h_o on the for $10 \leq h_o \leq 100$ W/m^2 · K. Repeat thi tion for a triple-pane construction in whi pane and a second air space of equival ness are added.

3.9 The composite wall of an oven consists of thre two of which are of known thermal conductivi W/m · K and $k_C = 50$ W/m · K, and known thic 0.30 m and $L_C = 0.15$ m. The third material, sandwiched between materials A and C, is of k ness, $L_B = 0.15$ m, but unknown thermal cond



Under steady-state operating conditions, r reveal an outer surface temperature of T_s $= 600°C$ inner surface temperature of $T_{s,i}$ = 600°C air temperature of $T_\infty = 800°C$. The insi coefficient h is known to be 25 W/m^2 · value of k_B?

3.10 A testing lab is contracted to measure th ductivity of various liquids as a functio temperature. Typically, the lab woul thermal conductivity and its temperat