

## References

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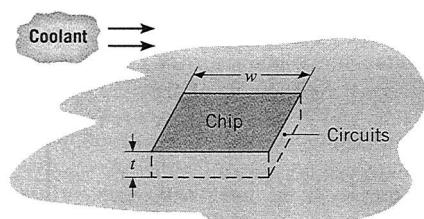
## Problems

### Conduction

- 1.1 The thermal conductivity of a sheet of rigid, extruded insulation is reported to be  $k = 0.029 \text{ W/m} \cdot \text{K}$ . The measured temperature difference across a 20-mm-thick sheet of the material is  $T_1 - T_2 = 10^\circ\text{C}$ .
  - (a) What is the heat flux through a  $2 \text{ m} \times 2 \text{ m}$  sheet of the insulation?
  - (b) What is the rate of heat transfer through the sheet of insulation?
- 1.2 A concrete wall, which has a surface area of  $20 \text{ m}^2$  and is  $0.30 \text{ m}$  thick, separates conditioned room air from ambient air. The temperature of the inner surface of the wall is maintained at  $25^\circ\text{C}$ , and the thermal conductivity of the concrete is  $1 \text{ W/m} \cdot \text{K}$ .
  - (a) Determine the heat loss through the wall for outer surface temperatures ranging from  $-15^\circ\text{C}$  to  $38^\circ\text{C}$ , which correspond to winter and summer extremes, respectively. Display your results graphically.
  - (b) On your graph, also plot the heat loss as a function of the outer surface temperature for wall materials having thermal conductivities of  $0.75$  and  $1.25 \text{ W/m} \cdot \text{K}$ . Explain the family of curves you have obtained.
- 1.3 The concrete slab of a basement is  $11 \text{ m}$  long,  $8 \text{ m}$  wide, and  $0.20 \text{ m}$  thick. During the winter, temperatures are nominally  $17^\circ\text{C}$  and  $10^\circ\text{C}$  at the top and bottom surfaces, respectively. If the concrete has a thermal conductivity of  $1.4 \text{ W/m} \cdot \text{K}$ , what is the rate of heat loss through the slab? If the basement is heated by a gas furnace operating at an efficiency of  $\eta_f = 0.90$  and natural gas is priced at  $C_g = \$0.01/\text{MJ}$ , what is the daily cost of the heat loss?
- 1.4 The heat flux through a wood slab  $50 \text{ mm}$  thick, whose inner and outer surface temperatures are  $40$  and  $20^\circ\text{C}$ , respectively, has been determined to be  $40 \text{ W/m}^2$ . What is the thermal conductivity of the wood?
- 1.5 The inner and outer surface temperatures of a glass window  $5 \text{ mm}$  thick are  $15$  and  $5^\circ\text{C}$ . What is the heat loss through a window that is  $1 \text{ m}$  by  $3 \text{ m}$  on a side? The thermal conductivity of glass is  $1.4 \text{ W/m} \cdot \text{K}$ .
- 1.6 A glass window of width  $W = 1 \text{ m}$  and height  $H = 2 \text{ m}$  is  $5 \text{ mm}$  thick and has a thermal conductivity of  $k_g = 1.4 \text{ W/m} \cdot \text{K}$ . If the inner and outer surface temperatures of the glass are  $15^\circ\text{C}$  and  $-20^\circ\text{C}$ , respectively, on a cold winter day, what is the rate of heat loss through the glass? To reduce heat loss through windows, it is customary to use a double pane construction in which adjoining panes are separated by an air space. If the spacing is  $10 \text{ mm}$  and the glass surfaces in contact with the air have temperatures of  $10^\circ\text{C}$  and  $-15^\circ\text{C}$ , what is the rate of heat loss from a  $1 \text{ m} \times 2 \text{ m}$  window? The thermal conductivity of air is  $k_a = 0.024 \text{ W/m} \cdot \text{K}$ .
- 1.7 A freezer compartment consists of a cubical cavity that is  $2 \text{ m}$  on a side. Assume the bottom to be perfectly insulated. What is the minimum thickness of styrofoam insulation ( $k = 0.030 \text{ W/m} \cdot \text{K}$ ) that must be applied to the top and side walls to ensure a heat load of less than  $500 \text{ W}$ , when the inner and outer surfaces are  $-10$  and  $35^\circ\text{C}$ ?
- 1.8 An inexpensive food and beverage container is fabricated from  $25\text{-mm-thick}$  polystyrene ( $k = 0.023 \text{ W/m} \cdot \text{K}$ ) and has interior dimensions of  $0.8 \text{ m} \times 0.6 \text{ m} \times 0.6 \text{ m}$ . Under conditions for which an inner surface temperature of approximately  $2^\circ\text{C}$  is maintained by an ice-water mixture and an outer surface temperature of  $20^\circ\text{C}$  is maintained by the ambient, what is the heat flux through the container wall? Assuming negligible heat gain through the  $0.8 \text{ m} \times 0.6 \text{ m}$  base of the cooler, what is the total heat load for the prescribed conditions?
- 1.9 What is the thickness required of a masonry wall having thermal conductivity  $0.75 \text{ W/m} \cdot \text{K}$  if the heat rate is to be  $80\%$  of the heat rate through a composite structural wall having a thermal conductivity of  $0.25 \text{ W/m} \cdot \text{K}$  and a thickness of  $100 \text{ mm}$ ? Both walls are subjected to the same surface temperature difference.
- 1.10 The  $5\text{-mm-thick}$  bottom of a  $200\text{-mm-diameter}$  pan may be made from aluminum ( $k = 240 \text{ W/m} \cdot \text{K}$ ) or

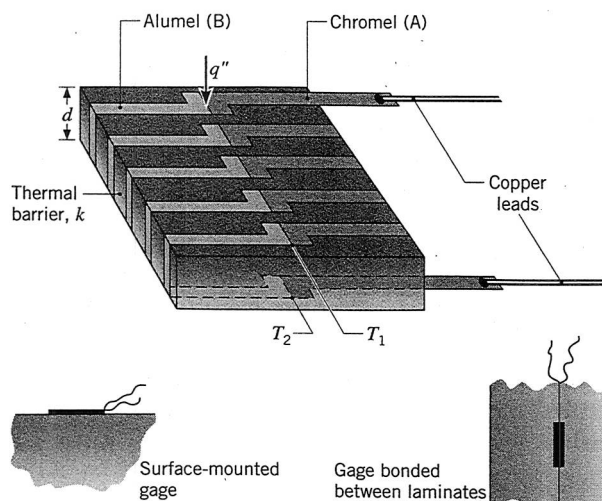
copper ( $k = 390 \text{ W/m} \cdot \text{K}$ ). When used to boil water, the surface of the bottom exposed to the water is nominally at  $110^\circ\text{C}$ . If heat is transferred from the stove to the pan at a rate of  $600 \text{ W}$ , what is the temperature of the surface in contact with the stove for each of the two materials?

- 1.11** A square silicon chip ( $k = 150 \text{ W/m} \cdot \text{K}$ ) is of width  $w = 5 \text{ mm}$  on a side and of thickness  $t = 1 \text{ mm}$ . The chip is mounted in a substrate such that its side and back surfaces are insulated, while the front surface is exposed to a coolant.



If  $4 \text{ W}$  are being dissipated in circuits mounted to the back surface of the chip, what is the steady-state temperature difference between back and front surfaces?

- 1.12** A gage for measuring heat flux to a surface or through a laminated material employs five thin-film, chromel/alumel (type K) thermocouples deposited on the upper and lower surfaces of a wafer with a thermal conductivity of  $1.4 \text{ W/m} \cdot \text{K}$  and a thickness of  $0.25 \text{ mm}$ .
- Determine the heat flux  $q''$  through the gage when the voltage output at the copper leads is  $350 \mu\text{V}$ . The Seebeck coefficient of the type-K thermocouple materials is approximately  $40 \mu\text{V}/^\circ\text{C}$ .
  - What precaution should you take in using a gage of this nature to measure heat flow through the laminated structure shown?



## Convection

- 1.13** You've experienced convection cooling if you've ever extended your hand out the window of a moving vehicle or into a flowing water stream. With the surface of your hand at a temperature of  $30^\circ\text{C}$ , determine the convection heat flux for (a) a vehicle speed of  $35 \text{ km/h}$  in air at  $-5^\circ\text{C}$  with a convection coefficient of  $40 \text{ W/m}^2 \cdot \text{K}$  and (b) a velocity of  $0.2 \text{ m/s}$  in a water stream at  $10^\circ\text{C}$  with a convection coefficient of  $900 \text{ W/m}^2 \cdot \text{K}$ . Which condition would *feel* colder? Contrast these results with a heat loss of approximately  $30 \text{ W/m}^2$  under normal room conditions.

- 1.14** Air at  $40^\circ\text{C}$  flows over a long,  $25\text{-mm}$ -diameter cylinder with an embedded electrical heater. In a series of tests, measurements were made of the power per unit length,  $P'$ , required to maintain the cylinder surface temperature at  $300^\circ\text{C}$  for different freestream velocities  $V$  of the air. The results are as follows:

Air velocity, $V$ (m/s)	1	2	4	8	12
Power, $P'$ (W/m)	450	658	983	1507	1963

- Determine the convection coefficient for each velocity, and display your results graphically.
  - Assuming the dependence of the convection coefficient on the velocity to be of the form  $h = CV^n$ , determine the parameters  $C$  and  $n$  from the results of part (a).
- 1.15** An electric resistance heater is embedded in a long cylinder of diameter  $30 \text{ mm}$ . When water with a temperature of  $25^\circ\text{C}$  and velocity of  $1 \text{ m/s}$  flows crosswise over the cylinder, the power per unit length required to maintain the surface at a uniform temperature of  $90^\circ\text{C}$  is  $28 \text{ kW/m}$ . When air, also at  $25^\circ\text{C}$ , but with a velocity of  $10 \text{ m/s}$  is flowing, the power per unit length required to maintain the same surface temperature is  $400 \text{ W/m}$ . Calculate and compare the convection coefficients for the flows of water and air.
- 1.16** A cartridge electrical heater is shaped as a cylinder of length  $L = 200 \text{ mm}$  and outer diameter  $D = 20 \text{ mm}$ . Under normal operating conditions the heater dissipates  $2 \text{ kW}$  while submerged in a water flow that is at  $20^\circ\text{C}$  and provides a convection heat transfer coefficient of  $h = 5000 \text{ W/m}^2 \cdot \text{K}$ . Neglecting heat transfer from the ends of the heater, determine its surface temperature  $T_s$ . If the water flow is inadvertently terminated while the heater continues to operate, the heater surface is exposed to air that is also at  $20^\circ\text{C}$  but for which  $h = 50 \text{ W/m}^2 \cdot \text{K}$ . What is the corresponding surface temperature? What are the consequences of such an event?

If the transmission efficiency is  $\eta = 0.93$  and air flow over the case corresponds to  $T_\infty = 30^\circ\text{C}$  and  $h = 200 \text{ W/m}^2 \cdot \text{K}$ , what is the surface temperature of the transmission?

## Radiation

**1.24** Under conditions for which the same room temperature is maintained by a heating or cooling system, it is not uncommon for a person to feel chilled in the winter but comfortable in the summer. Provide a plausible explanation for this situation (with supporting calculations) by considering a room whose air temperature is maintained at  $20^\circ\text{C}$  throughout the year, while the walls of the room are nominally at  $27^\circ\text{C}$  and  $14^\circ\text{C}$  in the summer and winter, respectively. The exposed surface of a person in the room may be assumed to be at a temperature of  $32^\circ\text{C}$  throughout the year and to have an emissivity of 0.90. The coefficient associated with heat transfer by natural convection between the person and the room air is approximately  $2 \text{ W/m}^2 \cdot \text{K}$ .

**1.25** A spherical interplanetary probe of 0.5-m diameter contains electronics that dissipate 150 W. If the probe surface has an emissivity of 0.8 and the probe does not receive radiation from other surfaces, as, for example, from the sun, what is its surface temperature?

**1.26** An instrumentation package has a spherical outer surface of diameter  $D = 100 \text{ mm}$  and emissivity  $\varepsilon = 0.25$ . The package is placed in a large space simulation chamber whose walls are maintained at  $77 \text{ K}$ . If operation of the electronic components is restricted to the temperature range  $40 \leq T \leq 85^\circ\text{C}$ , what is the range of acceptable power dissipation for the package? Display your results graphically, showing also the effect of variations in the emissivity by considering values of 0.20 and 0.30.

**1.27** Consider the conditions of Problem 1.22. However, now the plate is in a vacuum with a surrounding temperature of  $25^\circ\text{C}$ . What is the emissivity of the plate? What is the rate at which radiation is emitted by the surface?

**1.28** An overhead 25-m-long, uninsulated industrial steam pipe of 100 mm diameter is routed through a building whose walls and air are at  $25^\circ\text{C}$ . Pressurized steam maintains a pipe surface temperature of  $150^\circ\text{C}$ , and the coefficient associated with natural convection is  $h = 10 \text{ W/m}^2 \cdot \text{K}$ . The surface emissivity is  $\varepsilon = 0.8$ .

- What is the rate of heat loss from the steam line?
- If the steam is generated in a gas-fired boiler operating at an efficiency of  $\eta_f = 0.90$  and natural gas is priced at  $C_g = \$0.01$  per MJ, what is the annual cost of heat loss from the line?

**1.29** If  $T_s \approx T_{\text{sur}}$  in Equation 1.9, the radiation heat transfer coefficient may be approximated as

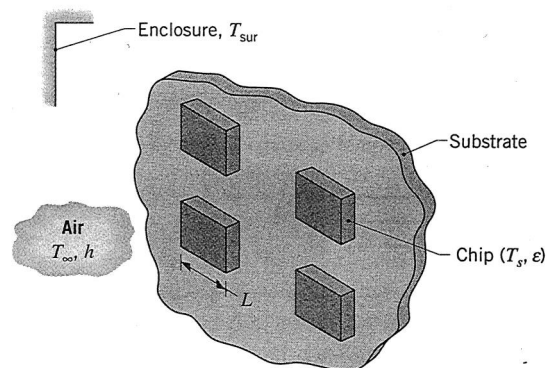
$$h_{r,a} = 4\varepsilon\sigma\bar{T}^3$$

where  $\bar{T} \equiv (T_s + T_{\text{sur}})/2$ . We wish to assess the validity of this approximation by comparing values of  $h_r$  and  $h_{r,a}$  for the following conditions. In each case represent your results graphically and comment on the validity of the approximation.

- Consider a surface of either polished aluminum ( $\varepsilon = 0.05$ ) or black paint ( $\varepsilon = 0.9$ ), whose temperature may exceed that of the surroundings ( $T_{\text{sur}} = 25^\circ\text{C}$ ) by 10 to  $100^\circ\text{C}$ . Also compare your results with values of the coefficient associated with free convection in air ( $T_\infty = T_{\text{sur}}$ ), where  $h \text{ (W/m}^2 \cdot \text{K)} = 0.98 \Delta T^{1/3}$ .
- Consider initial conditions associated with placing a workpiece at  $T_s = 25^\circ\text{C}$  in a large furnace whose wall temperature may be varied over the range  $100 \leq T_{\text{sur}} \leq 1000^\circ\text{C}$ . According to the surface finish or coating, its emissivity may assume values of 0.05, 0.2, and 0.9. For each emissivity, plot the relative error,  $(h_r - h_{r,a})/h_r$ , as a function of the furnace temperature.

**1.30** Consider the conditions of Problem 1.18. With heat transfer by convection to air, the maximum allowable chip power is found to be 0.35 W. If consideration is also given to net heat transfer by radiation from the chip surface to large surroundings at  $15^\circ\text{C}$ , what is the percentage increase in the maximum allowable chip power afforded by this consideration? The chip surface has an emissivity of 0.9.

**1.31** Chips of width  $L = 15 \text{ mm}$  on a side are mounted to a substrate that is installed in an enclosure whose walls and air are maintained at a temperature of  $T_{\text{sur}} = T_\infty = 25^\circ\text{C}$ . The chips have an emissivity of  $\varepsilon = 0.60$  and a maximum allowable temperature of  $T_s = 85^\circ\text{C}$ .



- If heat is rejected from the chips by radiation and natural convection, what is the maximum operating