the average heat transfer coefficient for a vertical plate can be expressed as

$$\overline{h}_L = 1.40\left(\frac{\Delta T}{L}\right)^{1/4} \qquad 10^4 < Ra_L < 10^9$$

$$\overline{h}_L = 0.98\Delta T^{1/3} \qquad 10^9 < Ra_L < 10^{13}$$

9.12 A solid object is to be cooled by submerging it in a quiescent fluid, and the associated free convection coefficient is given by $\overline{h} = C\Delta T^{1/4}$, where C is a constant and $\Delta T = T - T_\infty$.

(a) Invoking the lumped capacitance approximation, obtain an expression for the time required for the object to cool from an initial temperature T_i to a final temperature T_f.

(b) Consider a highly polished, 150-mm square aluminum alloy (2024) plate of 5-mm thickness, initially at 225°C, and suspended in ambient air at 25°C. Using the appropriate approximate correlation from Problem 9.11, determine the time required for the plate to reach 80°C.

(c) Plot the temperature–time history obtained from part (b) and compare with the results from a lumped capacitance analysis using a constant free convection coefficient, $\overline{h}_o$. Evaluate $\overline{h}_o$ from an appropriate correlation based on an average surface temperature of $\overline{T} = (T_i + T_f)/2$.

9.13 A household oven door of 0.5-m height and 0.7-m width reaches an average surface temperature of 32°C during operation. Estimate the heat loss to the room with ambient air at 22°C. If the door has an emissivity of 1.0 and the surroundings are also at 22°C, comment on the heat loss by free convection relative to that by radiation.

9.14 An aluminum alloy (2024) plate, heated to a uniform temperature of 227°C, is allowed to cool while vertically suspended in a room where the ambient air and surroundings are at 27°C. The plate is 0.3 m square with a thickness of 15 mm and an emissivity of 0.25.

(a) Develop an expression for the time rate of change of the plate temperature, assuming the temperature to be uniform at any time.

(b) Determine the initial rate of cooling (K/s) when the plate temperature is 227°C.

(c) Justify the uniform plate temperature assumption.

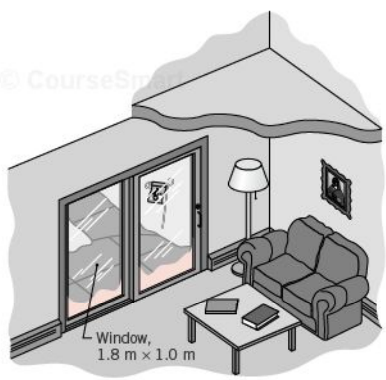
(d) Compute and plot the temperature history of the plate from $t = 0$ to the time required to reach a temperature of 30°C. Compute and plot the corresponding variations in the convection and radiation heat transfer rates.

9.15 The plate described in Problem 9.14 has been used in an experiment to determine the free convection heat transfer coefficient. At an instant of time when the plate temperature was 127°C, the time rate of change of this temperature was observed to be −0.0465 K/s. What is the corresponding free convection heat transfer coefficient? Compare this result with an estimate based on a standard empirical correlation.

9.16 The ABC Evening News Report in a news segment on hypothermia research studies at the University of Minnesota claimed that heat loss from the body is 30 times faster in 10°C water than in air at the same temperature. Is that a realistic statement?

9.17 Consider a vertical, single-pane window of equivalent width and height ($W = L = 1$ m). The interior surface is exposed to the air and walls of a room, which are each at 18°C. Under cold ambient conditions for which a thin layer of frost has formed on the inner surface, what is the heat loss through the window? How would your analysis be affected by a frost layer whose thickness is not negligible? During incipience of frost formation, where would you expect the frost to begin to develop on the window? The frost may be assumed to have an emissivity of $\varepsilon = 0.90$.

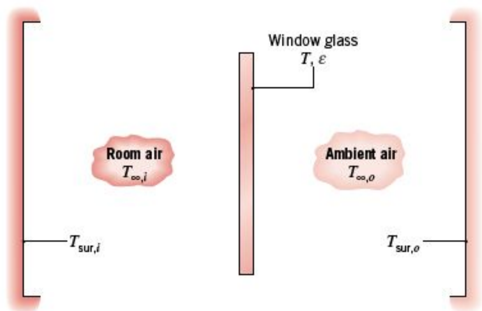
9.18 During a winter day, the window of a patio door with a height of 1.8 m and width of 1.0 m shows a frost line near its base. The room wall and air temperatures are 15°C.



(a) Explain why the window would show a frost layer at the base rather than at the top.

(b) Estimate the heat loss through the window due to free convection and radiation. Assume the window has a uniform temperature of 0°C and the emissivity of the glass surface is 0.94. If the room has electric baseboard heating, estimate the corresponding daily cost of the window heat loss for a utility rate of 0.08 \$/kW · h.

9.19 A vertical, thin pane of window glass that is 1 m on a side separates quiescent room air at $T_{\infty,i} = 20°C$ from quiescent ambient air at $T_{\infty,o} = -20°C$. The walls of the room and the external surroundings (landscape, buildings, etc.) are also at $T_{sur,i} = 20°C$ and $T_{sur,o} = -20°C$, respectively.



If the glass has an emissivity of $\varepsilon = 1$, what is its temperature T? What is the rate of heat loss through the glass?

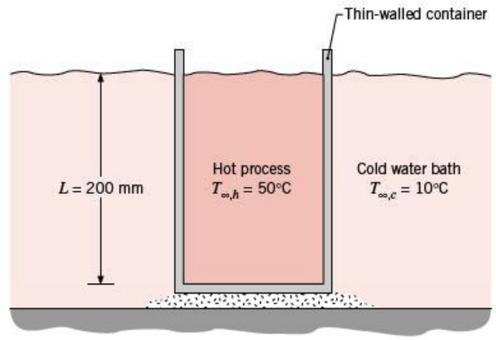
9.20 Consider the conditions of Problem 9.19, but now allow for a difference between the inner and outer surface temperatures, $T_{s,i}$ and $T_{s,o}$, of the window. For a glass thickness and thermal conductivity of $t_g = 10$ mm and $k_g = 1.4$ W/m · K, respectively, evaluate $T_{s,i}$ and $T_{s,o}$. What is the heat loss through the window?

9.21 Consider the conveyor system described in Problem 7.24, but under conditions for which the conveyor is not moving and the air is quiescent. Radiation effects and interactions between boundary layers on adjoining surfaces may be neglected.

(a) For the prescribed plate dimensions and initial temperature, as well as the prescribed air temperature, what is the initial rate of heat transfer from one of the plates?

(b) How long does it take for a plate to cool from 300°C to 100°C? Comment on the assumption of negligible radiation.

9.22 A thin-walled container with a hot process fluid at 50°C is placed in a quiescent, cold water bath at 10°C. Heat transfer at the inner and outer surfaces of the container may be approximated by free convection from a vertical plate.



(a) Determine the overall heat transfer coefficient between the hot process fluid and the cold water bath. Assume the properties of the hot process fluid are those of water.

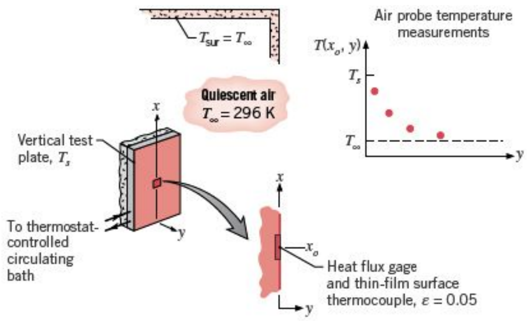
(b) Generate a plot of the overall heat transfer coefficient as a function of the hot process fluid temperature $T_{\infty,h}$ for the range 20 to 60°C, with all other conditions remaining the same.

9.23 Consider an experiment to investigate the transition to turbulent flow in a free convection boundary layer that develops along a vertical plate suspended in a large room. The plate is constructed of a thin heater that is sandwiched between two aluminum plates and may be assumed to be isothermal. The heated plate is 1 m high and 2 m wide. The quiescent air and the surroundings are both at 25°C.

(a) The exposed surfaces of the aluminum plate are painted with a very thin coating of high emissivity ($\varepsilon = 0.95$) paint. Determine the electrical power that must be supplied to the heater to sustain the plate at a temperature of $T_s = 35°C$. How much of the plate is exposed to turbulent conditions in the free convection boundary layer?

(b) The experimentalist speculates that the roughness of the paint is affecting the transition to turbulence in the boundary layer and decides to remove the paint and polish the aluminum surface ($\varepsilon = 0.05$). If the same power is supplied to the plate as in part (a), what is the steady-state plate temperature? How much of the plate is exposed to turbulent conditions in the free convection boundary layer?

9.24 A square plate of pure aluminum, 0.5 m on a side and 16 mm thick, is initially at 300°C and is suspended in a large chamber. The walls of the chamber are maintained at 27°C, as is the enclosed air. If the surface emissivity of the plate is 0.25, what is the initial cooling rate? Is it flow channels. The heat flux and surface temperature are measured at discrete locations along the x-axis by miniature sensors using thin-film thermocouple technology. The fluid temperature in the boundary layer is measured using a microwire thermocouple probe. The plate is mounted within a room under stable climate control. For the series of observations tabulated below, the quiescent air and room wall temperatures were 296 K. Your task is to process the experimental observations and compare them to results from the similarity solution for laminar free convection (Section 9.4).



The following table provides measurements from the heat flux sensor at six x-locations for the specified plate–air temperature difference.

	$T_s - T_\infty = 7.7$ K					
x (mm)	25	75	175	275	375	475
q''_{tot} (W/m^2)	41.4	27.2	22.0	20.1	18.3	17.2

Measurements obtained from the air temperature probe are provided next for three discrete y-locations at two x-locations. The local Grashof numbers corresponding to the x-locations have been calculated to simplify your analysis.

	$T_s - T_\infty = 7.3$ K					
	$x = 200$ mm, $Gr_x = 7.6 \times 10^6$			$x = 400$ mm, $Gr_x = 6.0 \times 10^7$		
y(mm)	2.5	5.0	10.0	2.5	5.0	10.0
$T(x, y) - T_\infty$(K)	5.5	3.8	1.6	5.9	4.5	2.0

(a) The surfaces of the heat flux sensors experience free convection and radiation exchange with the surroundings. Write an expression for estimating the radiation heat flux from the sensor as a function of the surface emissivity, the temperature of the surroundings, and the temperature difference $(T_s - T_\infty)$.

(b) Using the expression derived in part (a), apply a correction to the measured total heat flux, q''_{tot}, to obtain the convection heat flux, q''_{cv}, and calculate the convection coefficient. Extend the first table above to include the results of your analysis.

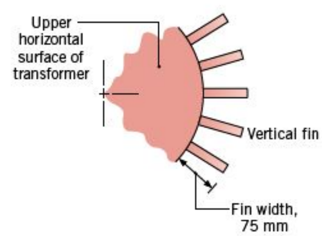
(c) Calculate and plot the local convection coefficient, $h_x(x)$, as a function of the x-coordinate using the similarity solution, Eqs. 9.19 and 9.20. On the same graph, plot the experimental points. Comment on the comparison between the experimental and analytical results.

(d) For the conditions in the second table, compare the experimental boundary-layer air temperature measurements with those from the similarity solution, Figure 9.4*b*. Summarize the results of your analysis using the similarity parameter, η, and the dimensionless temperature, T^*. Comment on the comparison between the experimental and analytical results.

Horizontal and Inclined Plates

9.33 Consider the transformer of Problem 8.97, whose lateral surface is being maintained at 47°C by a forced convection coolant line removing 1000 W. It is desired to explore cooling of the transformer by free convection and radiation, assuming the surface to have an emissivity of 0.80.

(a) Determine how much power could be removed by free convection and radiation from the lateral *and* the upper horizontal surfaces when the ambient temperature and the surroundings are at 27°C.



(b) Vertical fins, 5 mm thick, 75 mm wide, and 500 mm long, can easily be welded to the lateral surface. What is the heat removal rate by free convection if 30 such fins are attached?

9.34 Airflow through a long, 0.2-m-square air conditioning duct maintains the outer duct surface temperature at 10°C. If the horizontal duct is uninsulated and exposed to air at 35°C in the crawlspace beneath a home, what is the heat gain per unit length of the duct?

9.35 Consider the conditions of Example 9.3, including the effect of adding insulation of thickness t and thermal

W/m · K, $\varepsilon = 0.5$). The base of the fin is maintained at 150°C, while the quiescent ambient air and the surroundings are at 25°C. Assume the fin tip is adiabatic.

(a) Estimate the fin heat rate, q_f. Use an average fin surface temperature of 125°C in estimating the free convection coefficient and the linearized radiation coefficient. How sensitive is this estimate to your choice of the average fin surface temperature?

(b) Use the finite-difference method of solution to obtain q_f when the convection and radiation coefficients are based on local, rather than average, temperatures for the fin. How does your result compare with the analytical solution of part (a)?

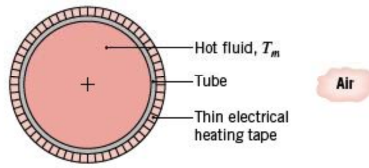
9.65 Consider the hot water pipe of Problem 7.56, but under conditions for which the ambient air is not in cross flow over the pipe and is, instead, quiescent. Accounting for the effect of radiation with a pipe emissivity of $\varepsilon_p = 0.6$, what is the corresponding daily cost of heat loss per unit length of the uninsulated pipe?

9.66 Common practice in chemical processing plants is to clad pipe insulation with a durable, thick aluminum foil. The functions of the foil are to confine the batt insulation and to reduce heat transfer by radiation to the surroundings. Because of the presence of chlorine (at chlorine or seaside plants), the aluminum foil surface, which is initially bright, becomes etched with in-service time. Typically, the emissivity might change from 0.12 at installation to 0.36 with extended service. For a 300-mm-diameter foil-covered pipe whose surface temperature is 90°C, will this increase in emissivity due to degradation of the foil finish have a significant effect on heat loss from the pipe? Consider two cases with surroundings and ambient air at 25°C: (a) quiescent air and (b) a cross-wind velocity of 10 m/s.

9.67 Consider the electrical heater of Problem 7.43. If the blower were to malfunction, terminating airflow while the heater continued to operate at 1000 W/m, what temperature would the heater assume? How long would it take to come within 10°C of this temperature? Allow for radiation exchange between the heater ($\varepsilon = 0.8$) and the duct walls, which are also at 27°C.

9.68 A computer code is being developed to analyze a 12.5-mm-diameter, cylindrical sensor used to determine ambient air temperature. The sensor experiences free convection while positioned horizontally in quiescent air at $T_\infty = 27$°C. For the temperature range from 30 to 80°C, derive an expression for the convection coefficient as a function of only $\Delta T = T_s - T_\infty$, where T_s is the sensor temperature. Evaluate properties at an appropriate film temperature and show what effect this approximation has on the convection coefficient estimate.

9.69 A thin-walled tube of 20-mm diameter passes hot fluid at a mean temperature of 45°C in an experimental flow loop. The tube is mounted horizontally in quiescent air at a temperature of 15°C. To satisfy the stringent temperature control requirements of the experiment, it was decided to wind thin electrical heating tape on the outer surface of the tube to prevent heat loss from the hot fluid to the ambient air.



(a) Neglecting radiation heat loss, calculate the heat flux q''_e that must be supplied by the electrical tape to ensure a uniform fluid temperature.

(b) Assuming the emissivity of the tape is 0.95 and the surroundings are also at 15°C, calculate the required heat flux.

(c) The heat loss may be reduced by wrapping the heating tape in a layer of insulation. For 85% magnesia insulation ($k = 0.050$ W/m · K) having a surface emissivity of $\varepsilon = 0.60$, compute and plot the required heat flux q''_e as a function of insulation thickness in the range from 0 to 20 mm. For this range, compute and plot the convection and radiation heat rates per unit tube length as a function of insulation thickness.

9.70 A billet of stainless steel, AISI 316, with a diameter of 150 mm and a length of 500 mm emerges from a heat treatment process at 200°C and is placed in an unstirred oil bath maintained at 20°C.

(a) Determine whether it is advisable to position the billet in the bath with its centerline horizontal or vertical in order to decrease the cooling time.

(b) Estimate the time for the billet to cool to 30°C for the preferred arrangement.

9.71 Long stainless steel rods of 50-mm diameter are preheated to a uniform temperature of 1000 K before being suspended from an overhead conveyor for transport to a hot forming operation. The conveyor is in a large room whose walls and air are at 300 K.

(a) Assuming the linear motion of the rod to have a negligible effect on convection heat transfer from its surface, determine the average convection coefficient at the start of the transport process.

(b) If the surface emissivity of the rod is $\varepsilon = 0.40$, what is the effective radiation heat transfer coefficient at the start of the transport process?