causing the local convection coefficient to have a radial dependence of the form \( h(r) = a + br^n \), where \( a, b, \) and \( n \) are constants. Determine the rate of heat transfer to the plate, expressing your result in terms of \( T_m, T_r, r_m, a, b, \) and \( n \).

6.8 Laminar flow normally persists on a smooth flat plate until a critical Reynolds number value is reached. However, the flow can be tripped to a turbulent state by adding roughness to the leading edge of the plate. For a particular situation, experimental results show that the local heat transfer coefficients for laminar and turbulent conditions are

\[
\begin{align*}
  h_{\text{ lam}}(x) &= 1.74 \text{ W/m}^2\text{K} \cdot x^{-0.5} \\
  h_{\text{ turb}}(x) &= 3.98 \text{ W/m}^2\text{K} \cdot x^{-0.2}
\end{align*}
\]

Calculate the average heat transfer coefficients for laminar and turbulent conditions for plates of length \( L = 0.1 \text{ m} \) and \( 1 \text{ m} \).

6.9 Experiments have been conducted to determine local heat transfer coefficients for flow perpendicular to a long, isothermal bar of rectangular cross section. The bar is of width \( c \) parallel to the flow, and height \( d \) normal to the flow. For Reynolds numbers in the range \( 10^4 \leq Re_c \leq 5 \times 10^4 \), the face-averaged Nusselt numbers are well correlated by an expression of the form

\[
\overline{Nu}_c = \frac{h_d k}{c} = C Re_c^{\alpha} Pr^{1/3}
\]

The values of \( C \) and \( m \) for the front face, side faces, and back face of the rectangular rod are found to be the following:

<table>
<thead>
<tr>
<th>Face</th>
<th>( c/d )</th>
<th>( C )</th>
<th>( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>( 0.33 \leq c/d \leq 1.33 )</td>
<td>0.674</td>
<td>1/2</td>
</tr>
<tr>
<td>Side</td>
<td>0.33</td>
<td>0.153</td>
<td>2/3</td>
</tr>
<tr>
<td>Side</td>
<td>1.33</td>
<td>0.107</td>
<td>2/3</td>
</tr>
<tr>
<td>Back</td>
<td>0.33</td>
<td>0.174</td>
<td>2/3</td>
</tr>
<tr>
<td>Back</td>
<td>1.33</td>
<td>0.153</td>
<td>2/3</td>
</tr>
</tbody>
</table>

Determine the value of the average heat transfer coefficient for the entire exposed surface (that is, averaged over all four faces) of a \( c = 40\text{-mm}-\text{wide}, d = 30\text{-mm}-\text{tall} \) rectangular rod. The rod is exposed to air in cross flow at \( V = 10 \text{ m/s}, T_m = 300 \text{ K} \). Provide a plausible explanation of the relative values of the face-averaged heat transfer coefficients on the front, side, and back faces.

6.10 A concentrating solar collector consists of a parabolic reflector and a collector tube of diameter \( D \), through which flows a working fluid that is heated with concentrated solar irradiation. Throughout the day, the reflector is slowly repositioned to track the sun. For wind conditions characterized by a steady, horizontal flow normal to the tube axis, the local heat transfer coefficient on the tube surface varies, as shown in the schematic for various reflector positions.

(a) Estimate the value of the average heat transfer coefficient over the entire collector tube surface for each of the three cases.

(b) Assuming the tube receives the same amount of solar irradiation in each case, which case would have the highest collector efficiency?

6.11 Helium at a free stream temperature of \( T_m = 25^\circ \text{C} \) is in parallel flow over a flat plate of length \( L = 3 \text{ m} \) and temperature \( T_r = 85^\circ \text{C} \). However, obstacles placed in the flow intensify mixing with increasing distance \( x \) from the leading edge, and the spatial variation of temperatures measured in the boundary layer is correlated by an expression of the form \( T(x) = 25 + 60 \exp(-600xy) \), where \( x \) and \( y \) are in meters. Determine and plot the manner in which the local convection coefficient \( h \) varies with \( x \). Evaluate the average convection coefficient \( \overline{h} \) for the plate.
(b) It is desirable for the chip operating temperature to be independent of the location of the customer. What air velocity is required for operation in Mexico City if the chip temperature is to be the same as at sea level?

6.33 Consider the chip on the circuit board of Problem 6.31. To ensure reliable operation over extended periods, the chip temperature should not exceed 85°C. Assuming the availability of forced air at \( T_{in} = 25°C \) and applicability of the prescribed heat transfer correlation, compute and plot the maximum allowable chip power dissipation \( P_c \) as a function of air velocity for \( 1 \leq V \leq 25 \text{ m/s} \). If the chip surface has an emissivity of 0.80 and the board is mounted in a large enclosure whose walls are at 25°C, what is the effect of radiation on the \( P_c - V \) plot?

6.34 The defroster of an automobile functions by discharging warm air on the inner surface of the windshield. To prevent condensation of water vapor on the surface, the temperature of the air and the surface convection coefficient \( (T_{s,i}, h_i) \) must be large enough to maintain a surface temperature \( T_{s,i} \) that is at least as high as the dewpoint \( (T_{d,i} \geq T_{dp}) \).

Consider a windshield of length \( L = 800 \text{ mm} \) and thickness \( t = 6 \text{ mm} \) and driving conditions for which the vehicle moves at a velocity of \( V = 70 \text{ mph} \) in ambient air at \( T_{in} = -15°C \). From laboratory experiments, a model of the vehicle, the average convection coefficient on the outer surface of the windshield is known to be correlated by an expression of the form \( \overline{h_{w,i}} = 0.030 \text{ Re}^{0.82} \text{ Pr}^{0.13} \), where \( \text{Re} = V L / \nu \). Air properties may be approximated as \( k = 0.023 \text{ W/m-K} \), \( \nu = 12.5 \times 10^{-6} \text{ m/s} \), and \( \text{Pr} = 0.71 \). If \( T_{dp} = 10°C \) and \( T_{s,i} = 50°C \), what is the smallest value of \( h_i \) required to prevent condensation on the inner surface?

6.35 A microscale detector monitors a steady flow \( (T_w = 27°C, V = 10 \text{ m/s}) \) of air for the possible presence of small, hazardous particulate matter that may be suspended in the room. The sensor is heated to a slightly higher temperature to induce a chemical reaction associated with certain substances of interest that might impinge on the sensor’s active surface. The active surface produces an electric current if such surface reactions occur; the electric current is then sent to an alarm.

To maximize the sensor head’s surface area and, in turn, the probability of capturing and detecting a particle, the sensor head is designed with a very complex shape. The value of the average heat transfer coefficient associated with the heated sensor must be known so that the required electrical power to the sensor can be determined.

Consider a sensor with a characteristic dimension of \( L_s = 80 \mu \text{m} \). A scale model of the sensor is placed in a recirculating (closed) wind tunnel using hydrogen as the working fluid. If the wind tunnel operates at a hydrogen absolute pressure of 0.5 atm and velocity of \( V = 0.5 \text{ m/s} \), find the required hydrogen temperature and characteristic dimension of the scale model, \( L_{sw} \).

**Reynolds Analogy**

6.36 A thin, flat plate that is \( 0.2 \text{ m} \times 0.2 \text{ m} \) on a side is oriented parallel to an atmospheric airstream having a velocity of 40 m/s. The air is at a temperature of \( T_w = 20°C \), while the plate is maintained at \( T_s = 120°C \). The air flows over the top and bottom surfaces of the plate, and measurement of the drag force reveals a value of 0.075 N. What is the rate of heat transfer from both sides of the plate to the air?

6.37 Atmospheric air is in parallel flow \( (u_w = 10 \text{ m/s}, T_w = 15°C) \) over a flat heater surface that is to be maintained at a temperature of 90°C. The heater surface area is 0.25 m², and the airflow is known to induce a drag force of 0.15 N on the heater. What is the electrical power needed to maintain the prescribed surface temperature?

6.38 Determine the drag force imparted to the top surface of the flat plate of Example 6.4 for water temperatures of 300 K and 350 K. Assume the plate dimension in the \( z \)-direction is \( W = 1 \text{ m} \).

6.39 A thin, flat plate that is \( 0.2 \text{ m} \times 0.2 \text{ m} \) on a side with rough top and bottom surfaces is placed in a wind tunnel so that its surfaces are parallel to an atmospheric airstream having a velocity of 30 m/s. The air is at a temperature of \( T_w = 20°C \) while the plate is maintained at \( T_s = 80°C \). The plate is rotated 45° about its center point, as shown in the schematic. Air flows over the top and bottom surfaces of the plate, and measurement of the heat transfer rate is 2000 W. What is the drag force on the plate?
6.48 Consider cross flow of gas X over an object having a characteristic length of \( L = 0.1 \text{ m} \). For a Reynolds number of \( 1 \times 10^6 \), the average heat transfer coefficient is \( 25 \text{ W/m}^2 \cdot \text{K} \). The same object is then impregnated with liquid Y and subjected to the same flow conditions. Given the following thermophysical properties, what is the average convection mass transfer coefficient?

<table>
<thead>
<tr>
<th></th>
<th>( \nu (\text{m}^2/\text{s}) )</th>
<th>( k (\text{W/m} \cdot \text{K}) )</th>
<th>( \alpha (\text{m}^2/\text{s}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas X</td>
<td>( 21 \times 10^{-6} )</td>
<td>0.030</td>
<td>( 29 \times 10^{-6} )</td>
</tr>
<tr>
<td>Liquid Y</td>
<td>( 3.75 \times 10^{-7} )</td>
<td>0.665</td>
<td>( 1.65 \times 10^{-7} )</td>
</tr>
<tr>
<td>Vapor Y</td>
<td>( 4.25 \times 10^{-5} )</td>
<td>0.023</td>
<td>( 4.55 \times 10^{-5} )</td>
</tr>
<tr>
<td>Mixture of gas X–vapor Y:</td>
<td>( Sc = 0.72 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) What is the rate of water loss due to evaporation on the summer day?

(b) What is the total rate of convective heat loss on the summer day?

6.49 An object of irregular shape has a characteristic length of \( L = 1 \text{ m} \) and is maintained at a uniform surface temperature of \( T_s = 325 \text{ K} \). It is suspended in an airstream that is at atmospheric pressure (\( p = 1 \text{ atm} \)) and has a velocity of \( V = 100 \text{ m/s} \) and a temperature of \( T_w = 275 \text{ K} \). The average heat flux from the surface to the air is \( 12,000 \text{ W/m}^2 \). Referring to the foregoing situation as case 1, consider the following cases and determine whether conditions are analogous to those of case 1. Each case involves an object of the same shape, which is suspended in an airstream in the same manner. Where analogous behavior does exist, determine the corresponding value of the average heat or mass transfer convection coefficient, as appropriate.

(a) The values of \( T_s, T_w, \) and \( p \) remain the same, but \( L = 2 \text{ m} \) and \( V = 50 \text{ m/s} \).

(b) The values of \( T_s \), and \( T_w \) remain the same, but \( L = 2 \text{ m}, V = 50 \text{ m/s}, \) and \( p = 0.2 \text{ atm} \).

(c) The surface is coated with a liquid film that evaporates into the air. The entire system is at \( 300 \text{ K} \), and the diffusion coefficient for the air–vapor mixture is \( D_{\text{AB}} = 1.12 \times 10^{-5} \text{ m}^2/\text{s} \). Also, \( L = 2 \text{ m}, V = 50 \text{ m/s}, \) and \( p = 1 \text{ atm} \).

(d) The surface is coated with another liquid film for which \( D_{\text{AB}} = 1.12 \times 10^{-4} \text{ m}^2/\text{s} \), and the system is at \( 300 \text{ K} \). In this case \( L = 2 \text{ m}, V = 250 \text{ m/s}, \) and \( p = 0.2 \text{ atm} \).

6.50 On a cool day in April a scantily clothed runner is known to lose heat at a rate of 450 W when running on a level surface because of convection to the surrounding air at \( T_w = 15^\circ \text{C} \). The runner’s skin remains dry and at a temperature of \( T_s = 30^\circ \text{C} \). Three months later, the runner is running uphill at the same speed, but the day is warm and humid with a temperature of \( T_w = 33^\circ \text{C} \) and a relative humidity of \( \phi_s = 60\% \). The runner is now drenched in sweat and has a uniform surface temperature of \( 35^\circ \text{C} \). Under both conditions constant air properties may be assumed with \( V = 1.6 \times 10^{-3} \text{ m}^3/\text{s}, k = 0.026 \text{ W/m} \cdot \text{K}, Pr = 0.70, \) and \( D_{\text{AB}} \) (water vapor–air) = \( 2.3 \times 10^{-5} \text{ m}^2/\text{s} \).

(a) What is the rate of water loss due to evaporation on the summer day?

(b) What is the total rate of convective heat loss on the summer day?

6.51 An experiment involves the flow of air at atmospheric pressure and 300 K over an object of characteristic length \( L = 1 \text{ m} \) that is coated with species A. The measured average mass transfer coefficients are shown in the table. Determine the Schmidt, Reynolds, and Sherwood numbers for each case. If \( \tilde{S}n \) is related to \( Re \) and \( Sc \) by an expression of the form \( \tilde{S}n = CRe^{m}Sc^{n} \), determine the values of \( C, m, \) and \( n \) by analyzing the experimental results. Based on the values you have determined for the expression, calculate the area-averaged mass transfer coefficient for evaporation of benzene in air flowing at a velocity of 3.0 m/s over the object.

<table>
<thead>
<tr>
<th>Species</th>
<th>( V (\text{m/s}) )</th>
<th>( \tilde{h}_m \times 10^{3} (\text{m/s}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Naphthalene</td>
<td>1.5</td>
<td>3.6</td>
</tr>
<tr>
<td>Acetone</td>
<td>2.5</td>
<td>8.0</td>
</tr>
</tbody>
</table>

6.52 An industrial process involves the evaporation of water from a liquid film that forms on a contoured surface. Dry air is passed over the surface, and from laboratory measurements the convection heat transfer correlation is of the form

\[
\overline{N_{\text{nuf}}} = 0.43 \text{Re}^{0.58} \text{Pr}^{0.4}
\]

(a) For an air temperature and velocity of 27°C and 10 m/s, respectively, what is the rate of evaporation from a surface of 1-m² area and characteristic length \( L = 1 \text{ m} \)? Approximate the density of saturated vapor as \( \rho_{s, \text{sat}} = 0.0077 \text{ kg/m}^3 \).

(b) What is the steady-state temperature of the liquid film?

6.53 The naphthalene sublimation technique involves the use of a mass transfer experiment coupled with an analysis based on the heat and mass transfer analogy to obtain local or average convection heat transfer coefficients for complex surface geometries. A coating of naphthalene, which is a volatile solid at room temperature, is applied to the surface and is then subjected to airflow in a wind tunnel. Alternatively, solid objects
irradiation is $G_s = 900 \text{ W/m}^2$. Turbulent flow may be assumed over the entire length of the roof.

(a) For equivalent values of the solar absorptivity and the emissivity of the outer surface ($\alpha_s = \varepsilon = 0.6$), estimate the average temperature $T_{s,o}$ of the outer surface. What is the corresponding heat load imposed on the refrigeration system?

(b) A special finish ($\alpha_s = 0.2$, $\varepsilon = 0.8$) may be applied to the outer surface. What effect would such an application have on the surface temperature and the heat load?

(c) If, with $\alpha_s = \varepsilon = 0.6$, the roof is not insulated ($t_{s} = 0$), what are the corresponding values of the surface temperature and the heat load?

7.17 The top surface of a compartment consists of very smooth (A) and highly roughened (B) portions, and the surface is placed in an atmospheric airstream. In the interest of minimizing total convection heat transfer to the surface, which orientation, (1) or (2), is preferred? If $T_s = 10^\circ\text{C}$, $T_w = 35^\circ\text{C}$, and $u_w = 25$ m/s, what is the rate of convection heat transfer to the entire surface for this orientation?

7.18 Calculate the value of the average heat transfer coefficient for the plate of Problem 7.17 when the entire plate is rotated $90^\circ$ so that half of the leading edge consists of a very smooth portion (A) and the other half consists of a highly roughened portion (B).

7.19 Steel (AISI 1010) plates of thickness $\delta = 6$ mm and length $L = 1$ m on a side are conveyed from a heat treatment process and are concurrently cooled by atmospheric air of velocity $u_a = 10$ m/s and $T_a = 20^\circ\text{C}$ in parallel flow over the plates.

For an initial plate temperature of $T_i = 300^\circ\text{C}$, what is the rate of heat transfer from the plate? What is the corresponding rate of change of the plate temperature? The velocity of the air is much larger than that of the plate.

7.20 Consider a rectangular fin that is used to cool a motorcycle engine. The fin is 0.15 m long and at a temperature of $250^\circ\text{C}$, while the motorcycle is moving at 80 km/h in air at $27^\circ\text{C}$. The air is in parallel flow over both surfaces of the fin, and turbulent flow conditions may be assumed to exist throughout.

(a) What is the rate of heat removal per unit width of the fin?

(b) Generate a plot of the heat removal rate per unit width of the fin for motorcycle speeds ranging from 10 to 100 km/h.

7.21 The Weather Channel reports that it is a hot, muggy day with an air temperature of $90^\circ\text{F}$, a 10 mph breeze out of the southwest, and bright sunshine with a solar insolation of 400 W/m$^2$. Consider the wall of a metal building over which the prevailing wind blows. The length of the wall in the wind direction is 10 m, and the emissivity is 0.93. Assume that all the solar irradiation is absorbed, that the surroundings are at $T_{sur} = 85^\circ\text{F}$, and that flow is fully turbulent over the wall. Estimate the average wall temperature.

7.22 An array of electronic chips is mounted within a sealed rectangular enclosure, and cooling is implemented by attaching an aluminum heat sink ($k = 180$ W/m·K). The base of the heat sink has dimensions of $w_1 = w_2 = 100$ mm, while the 6 fins are of thickness $t = 10$ mm.
7.25 A steel strip emerges from the hot roll section of a steel mill at a speed of 20 m/s and a temperature of 1200 K. Its length and thickness are \( L = 100 \text{ m} \) and \( \delta = 0.003 \text{ m} \), respectively, and its density and specific heat are 7900 kg/m\(^3\) and 640 J/kg \cdot \text{K}, respectively.

Accounting for heat transfer from the top and bottom surfaces and neglecting radiation and strip conduction effects, determine the time rate of change of the strip temperature at a distance of 1 m from the leading edge and at the trailing edge. Determine the distance from the leading edge at which the minimum cooling rate is reached.

7.26 A flat plate of width 1 m and length 0.2 m is maintained at a temperature of 32°C. Ambient fluid at 22°C flows across the top of the plate in parallel flow. Determine the average heat transfer coefficient, the convection heat transfer rate from the top of the plate, and the drag force on the plate for the following:

(a) The fluid is water flowing at a velocity of 0.5 m/s.
(b) The nanofluid of Example 2.2 is flowing at a velocity of 0.5 m/s.
(c) Water is flowing at a velocity of 2.5 m/s.
(d) The nanofluid of Example 2.2 is flowing at a velocity of 2.5 m/s.

7.27 One hundred electrical components, each dissipating 25 W, are attached to one surface of a square (0.2 m \times 0.2 m) copper plate, and all the dissipated energy is transferred to water in parallel flow over the opposite surface. A protuberance at the leading edge of the plate acts to trip the boundary layer, and the plate itself may be assumed to be isothermal. The water velocity and temperature are \( u_w = 2 \text{ m/s} \) and \( T_w = 17°C \), and the water’s thermophysical properties may be approximated as \( v = 0.96 \times 10^{-6} \text{ m}^2/\text{s} \), \( k = 0.620 \text{ W/m} \cdot \text{K} \), and \( Pr = 5.2 \).

(a) What is the temperature of the copper plate?
(b) If each component has a plate contact surface area of 1 cm\(^2\) and the corresponding contact resistance is \( 2 \times 10^{-4} \text{ m}^2 \cdot \text{K/W} \), what is the component temperature? Neglect the temperature variation across the thickness of the copper plate.

7.28 The boundary layer associated with parallel flow over an isothermal plate may be tripped at any x-location by using a fine wire that is stretched across the width of the plate. Determine the value of the critical Reynolds number \( Re_{crit} \) that is associated with the optimal location of the trip wire from the leading edge that will result in maximum heat transfer from the warm plate to the cool fluid.

7.29 Air at atmospheric pressure and a temperature of 25°C is in parallel flow at a velocity of 5 m/s over a 1-m-long flat plate that is heated from below with a uniform heat flux of 1250 W/m\(^2\). Assume the flow is fully turbulent over the length of the plate.

(a) Calculate the plate surface temperature, \( T_s(L) \), and the local convection coefficient, \( h_s(L) \), at the trailing edge, \( x = L \).
(b) Calculate the average temperature of the plate surface, \( \bar{T}_p \).
(c) Plot the variation of the surface temperature, \( T_s(x) \), and the convection coefficient, \( h_p(x) \), with distance on the same graph. Explain the key features of these distributions.

7.30 Consider atmospheric air at \( u_w = 2 \text{ m/s} \) and \( T_w = 300 \text{ K} \) in parallel flow over an isothermal flat plate of length \( L = 1 \text{ m} \) and temperature \( T_s = 350 \text{ K} \).

(a) Compute the local convection coefficient at the leading and trailing edges of the hot plate with and without an unheated starting length of \( \xi = 1 \text{ m} \).
(b) Compute the average convection coefficient for the plate for the same conditions as part (a).
(c) Plot the variation of the local convection coefficient over the plate with and without an unheated starting length.

7.31 The cover plate of a flat-plate solar collector is at 15°C, while ambient air at 10°C is in parallel flow over the plate, with \( u_w = 2 \text{ m/s} \).
(a) What is the rate of convective heat loss from the plate?
(b) If the plate is installed 2 m from the leading edge of a roof and flush with the roof surface, what is the rate of convective heat loss?

7.32 An array of 10 silicon chips, each of length \( L = 10 \text{ mm} \) on a side, is insulated on one surface and cooled on the opposite surface by atmospheric air in parallel flow with \( T_w = 24^\circ \text{C} \) and \( u_w = 40 \text{ m/s} \). When in use, the same electrical power is dissipated in each chip, maintaining a uniform heat flux over the entire cooled surface.

If the temperature of each chip may not exceed 80\(^{\circ}\)C, what is the maximum allowable power per chip? What is the maximum allowable power if a turbulence promoter is used to trip the boundary layer at the leading edge? Would it be preferable to orient the array normal, instead of parallel, to the airflow?

7.33 A square (10 mm \( \times 10 \text{ mm} \)) silicon chip is insulated on one side and cooled on the opposite side by atmospheric air in parallel flow at \( u_w = 20 \text{ m/s} \) and \( T_w = 24 \text{C} \). When in use, electrical power dissipation within the chip maintains a uniform heat flux at the cooled surface. If the chip temperature may not exceed 80\(^{\circ}\)C at any point on its surface, what is the maximum allowable power? What is the maximum allowable power if the chip is flush mounted in a substrate that provides for an unheated starting length of 20 mm?

**Cylinder in Cross Flow**

7.34 Consider the following fluids, each with a velocity of \( V = 3 \text{ m/s} \) and a temperature of \( T_w = 20 \text{C} \), in cross flow over a 10-mm-diameter cylinder maintained at 50\(^{\circ}\)C: atmospheric air, saturated water, and engine oil.

(a) Calculate the rate of heat transfer per unit length, \( q' \), using the Churchill-Bernstein correlation.
(b) Generate a plot of \( q' \) as a function of fluid velocity for 0.5 \( \leq V \leq 10 \text{ m/s} \).

7.35 An \( L = 1 \text{ m-long vertical copper tube} \) of inner diameter \( D_i = 20 \text{ mm} \) and wall thickness \( t = 2 \text{ mm} \) contains liquid water at \( T_w = 0 \text{C} \). On a winter day, air at \( V = 3 \text{ m/s} \), \( T_w = -20 \text{C} \) is in cross flow over the tube.

(a) Determine the rate of heat loss per unit mass from the water (W/kg) when the tube is full of water.
(b) Determine the rate of heat loss from the water (W/kg) when the tube is half full.

7.36 A long, cylindrical, electrical heating element of diameter \( D = 12 \text{ mm} \), thermal conductivity \( k = 240 \text{ W/m \cdot K} \), density \( \rho = 2700 \text{ kg/m}^3 \), and specific heat \( c_p = 900 \text{ J/kg \cdot K} \) is installed in a duct for which air moves in cross flow over the heater at a temperature and velocity of 30\(^{\circ}\)C and 8 m/s, respectively.

(a) Neglecting radiation, estimate the steady-state surface temperature when, per unit length of the heater, electrical energy is being dissipated at a rate of 1000 W/m.
(b) If the heater is activated from an initial temperature of 30\(^{\circ}\)C, estimate the time required for the surface temperature to come within 10\(^{\circ}\)C of its steady-state value.

7.37 Consider the conditions of Problem 7.36, but now allow for radiation exchange between the surface of the heating element (\( \varepsilon = 0.8 \)) and the walls of the duct, which form a large enclosure at 30\(^{\circ}\)C.

(a) Evaluate the steady-state surface temperature.
(b) If the heater is activated from an initial temperature of 30\(^{\circ}\)C, estimate the time required for the surface temperature to come within 10\(^{\circ}\)C of the steady-state value.
(c) To guard against overheating due to unanticipated excursions in the blower output, the heater controller is designed to maintain a fixed surface temperature of 275\(^{\circ}\)C. Determine the power dissipation required to maintain this temperature for air velocities in the range 5 \( \leq V \leq 10 \text{ m/s} \).

7.38 Determine the convection heat transfer coefficient, thermal resistance for convection, and the convection heat transfer rate that are associated with air at atmospheric pressure in cross flow over a cylinder of diameter \( D = 100 \text{ mm} \) and length \( L = 2 \text{ m} \). The cylinder temperature is \( T_c = 70 \text{C} \) while the air velocity and temperature are \( V = 3 \text{ m/s} \) and \( T_w = 20 \text{C} \), respectively. Plot the convection heat transfer coefficient and the heat transfer rate from the cylinder over the range 0.05 m \( \leq D \leq 0.5 \text{ m} \).

7.39 A long, thin metal plate is hung vertically after a heat treating process. The plate, of width \( W = 0.2 \text{ m} \), vertical dimension of 3 m, and an initial temperature of \( T_i = 320 \text{C} \), is cooled by atmospheric air of velocity \( V = 4 \text{ m/s} \) and \( T_w = 30 \text{C} \). Determine the initial rate of heat loss from the plate if the air is in parallel flow over the plate. Account for heat loss from both surfaces of the thin plate. Determine the initial rate of heat loss if the plate is turned so that its width is perpendicular to the air flow. Account for heat loss from both the front surface and the back surface of the plate. Which orientation will maximize the cooling rate?
7.40 Pin fins are to be specified for use in an industrial cooling application. The fins will be subjected to a gas in cross flow at \( V = 10 \text{ m/s} \). The cylindrical fin has a diameter of \( D = 15 \text{ mm} \), and the cross-sectional area is the same for each configuration shown in the sketch.

Cross sections of cylindrical and square fins in cross flow

For fins of equal length and therefore equal mass, which fin has the largest heat transfer rate? Assume the gas properties are those of air at \( T = 350 \text{ K} \). \textbf{Hint:} Assume the fins can be treated as infinitely long and apply the Hilpert correlation to the fin of circular cross section.

7.41 Air at \( 27^\circ C \) and a velocity of \( 5 \text{ m/s} \) passes over the small region \( A_0 \) \((20 \times 20 \text{ mm})\) on a large surface, which is maintained at \( T_s = 127^\circ C \). For these conditions, \( 0.5 \text{ W} \) is removed from the surface \( A_0 \). To increase the heat removal rate, a stainless steel (AISI 304) pin fin of diameter \( 5 \text{ mm} \) is affixed to \( A_0 \), which is assumed to remain at \( T_s = 127^\circ C \).

(a) Determine the maximum possible heat removal rate through the fin.
(b) What fin length would provide a close approximation to the heat rate found in part (a)? \textbf{Hint:} Refer to Example 3.9.
(c) Determine the fin effectiveness, \( \varepsilon \).
(d) What is the percentage increase in the heat rate from \( A_0 \) due to installation of the fin?

7.42 Hot water at \( 50^\circ C \) is routed from one building in which it is generated to an adjoining building in which it is used for space heating. Transfer between the buildings occurs in a steel pipe \((k = 60 \text{ W/m} \cdot \text{K})\) of 100-mm outside diameter and 8-mm wall thickness. During the winter, representative environmental conditions involve air at \( T_w = -5^\circ C \) and \( V = 3 \text{ m/s} \) in cross flow over the pipe.

(a) If the cost of producing the hot water is $0.10 per \( \text{kW} \cdot \text{h} \), what is the representative daily cost of heat loss from an uninsulated pipe to the air per meter of pipe length? The convection resistance associated with water flow in the pipe may be neglected.
(b) Determine the savings associated with application of a 10-mm-thick coating of urethane insulation \((k = 0.026 \text{ W/m} \cdot \text{K})\) to the outer surface of the pipe.

7.43 In a manufacturing process, long aluminum rods of square cross section with \( d = 25 \text{ mm} \) are cooled from an initial temperature of \( T_i = 400^\circ C \). Which configuration in the sketch should be used to minimize the time needed for the rods to reach a \textit{safe-to-handle} temperature of \( 60^\circ C \) when exposed to air in cross flow at \( V = 8 \text{ m/s} \), \( T_w = 30^\circ C \)? What is the required cooling time for the preferred configuration? The emissivity of the rods is \( \varepsilon = 0.10 \) and the surroundings temperature is \( T_{sur} = 20^\circ C \).

7.44 A fine wire of diameter \( D \) is positioned across a passage to determine flow velocity from heat transfer characteristics. Current is passed through the wire to heat it, and the heat is dissipated to the flowing fluid by convection. The resistance of the wire is determined from electrical measurements, and the temperature is known from the resistance.

(a) For a fluid of arbitrary Prandtl number, develop an expression for its velocity in terms of the difference between the temperature of the wire and the free stream temperature of the fluid.
(b) What is the velocity of an airstream at 1 atm and \( 25^\circ C \), if a wire of 0.5-mm diameter achieves a temperature of \( 40^\circ C \) while dissipating 35 W/m?
7.45 To determine air velocity changes, it is proposed to measure the electric current required to maintain a platinum wire of 0.25-mm diameter at a constant temperature of 77°C in a stream of air at 27°C.

(a) Assuming Reynolds numbers in the range 40 < Re < 1000, develop a relationship between the wire current and the velocity of the air that is in cross flow over the wire. Use this result to establish a relation between fractional changes in the current, ΔII/I, and the air velocity, ΔV/V.

(b) Calculate the current required when the air velocity is 15 m/s and the electrical resistivity of the platinum wire is 17.1 × 10⁻⁵ Ω · m.

7.46 Determine the rate of convection heat loss from both the top and the bottom of a flat plate at T₀ = 80°C with air in parallel flow at Tₘ = 25°C, uₘ = 3 m/s. The plate is t = 1 mm thick, L = 25 mm long, and w = 50 mm deep. Neglect the heat loss from the edges of the plate. Compare the rate of convection heat loss from the plate to the rate of convection heat loss from an Lₘ = 50-mm-long cylinder of the same volume as that of the plate. The convective conditions associated with the cylinder are the same as those associated with the plate.

7.47 A temperature sensor of 10.5-mm diameter experiences cross flow of water with a free stream temperature of 80°C and variable velocity. Derive an expression for the convection heat transfer coefficient as a function of the sensor surface temperature Tₛ for the range 20 < Tₛ < 80°C and for velocities V in the range 0.005 < V < 0.20 m/s. Use the Zukauskas correlation for the range 40 < Reₘ < 1000 and assume that the Prandtl number of water has a linear temperature dependence.

7.48 An aluminum transmission line with a diameter of 20 mm has an electrical resistance of Rₑₑₑ = 2.636 × 10⁻⁴ Ω/m and carries a current of 700 A. The line is subjected to frequent and severe cross winds, increasing the probability of contact between adjacent lines, thereby causing sparks and creating a potential fire hazard for nearby vegetation. The remedy is to insulate the line, but with the adverse effect of increasing the conductor operating temperature.

(a) Calculate the conductor temperature when the air temperature is 20°C and the line is subjected to cross flow with a velocity of 10 m/s.

(b) Calculate the conductor temperature for the same conditions, but with a 2-mm-thick insulation having a thermal conductivity of 0.15 W/m · K.

(c) Calculate and plot the temperatures of the bare and insulated conductors for wind velocities in the range from 2 to 20 m/s. Comment on features of the curves and the effect of the wind velocity on the conductor temperatures.

7.49 To augment heat transfer between two flowing fluids, it is proposed to insert a 100-mm-long, 5-mm-diameter 2024 aluminum pin fin through the wall separating the two fluids. The pin is inserted to a depth of d into fluid 1. Fluid 1 is air with a mean temperature of 10°C and velocity of 10 m/s. Fluid 2 is air with a mean temperature of 40°C and velocity of 3 m/s.

(a) Determine the rate of heat transfer from the warm air to the cool air through the pin fin for d = 50 mm.

(b) Plot the variation of the heat transfer rate with the insertion distance, d. Does an optimal insertion distance exist?

7.50 An uninsulated steam pipe is used to transport high-temperature steam from one building to another. The pipe is of 0.5-m diameter, has a surface temperature of 150°C, and is exposed to ambient air at –10°C. The air moves in cross flow over the pipe with a velocity of 5 m/s.

(a) What is the rate of heat loss per unit length of pipe?

(b) Consider the effect of insulating the pipe with a rigid urethane foam (κ = 0.026 W/m · K). Evaluate and plot the rate of heat loss as a function of the thickness δ of the insulation layer for 0 ≤ δ ≤ 50 mm.

7.51 A thermocouple is inserted into a hot air duct to measure the air temperature. The thermocouple (T₁) is soldered to the tip of a steel thermocouple well of length L = 0.15 m and inner and outer diameters of Dᵢ = 5 mm and Dₒ = 10 mm. A second thermocouple (T₂) is used to measure the duct wall temperature.
Consider conditions for which the air velocity in the duct is \( V = 3 \, \text{m/s} \) and the two thermocouples register temperatures of \( T_1 = 450 \, \text{K} \) and \( T_2 = 375 \, \text{K} \). Neglecting radiation, determine the air temperature \( T_{\text{a}} \). Assume that, for steel, \( k = 35 \, \text{W/m} \cdot \text{K} \), and, for air, \( \rho = 0.774 \, \text{kg/m}^3 \), \( \mu = 251 \times 10^{-5} \, \text{N} \cdot \text{s/m}^2 \), \( k = 0.0373 \, \text{W/m} \cdot \text{K} \), and \( Pr = 0.686 \).

### 7.52

In a manufacturing process, a long, coated plastic rod \( (\rho = 2200 \, \text{kg/m}^3, \, c = 800 \, \text{J/kg} \cdot \text{K}, \, k = 1 \, \text{W/m} \cdot \text{K}) \) of diameter \( D = 20 \, \text{mm} \) is initially at a uniform temperature of 25°C and is suddenly exposed to a cross flow of air at \( T_{\text{a}} = 350^\circ \text{C} \) and \( V = 50 \, \text{m/s} \).

(a) How long will it take for the surface of the rod to reach 175°C, the temperature above which the special coating will cure?  
(b) Generate a plot of the time to reach 175°C as a function of air velocity for \( 5 \leq V \leq 50 \, \text{m/s} \).

### 7.53

In an extrusion process, copper wire emerges from the extruder at a velocity \( V_e \), and is cooled by convection heat transfer to air in cross flow over the wire, as well as by radiation to the surroundings.

(a) By applying conservation of energy to a differential control surface of length \( dx \), which either moves with the wire or is stationary and through which the wire passes, derive a differential equation that governs the temperature distribution, \( T(x) \), along the wire. In your derivation, the effect of axial conduction along the wire may be neglected. Express your result in terms of the velocity, diameter, and properties of the wire \( (V_e, D, \rho, c_p, \varepsilon) \), the convection coefficient associated with the cross flow \( \left( h \right) \), and the environmental temperatures \( (T_{\text{a}}, T_{\text{w}}) \).

(b) Neglecting radiation, obtain a closed form solution to the foregoing equation. For \( V_e = 0.2 \, \text{m/s}, \, D = 5 \, \text{mm}, \, V = 5 \, \text{m/s}, \, T_{\text{a}} = 25^\circ \text{C} \), and an initial wire temperature of \( T_i = 600^\circ \text{C} \), compute the temperature \( T_e \) of the wire at \( x = L = 5 \, \text{m} \). The density and specific heat of the copper are \( \rho = 8900 \, \text{kg/m}^3 \) and \( c_p = 400 \, \text{J/kg} \cdot \text{K} \), while properties of the air may be taken to be \( k = 0.037 \, \text{W/m} \cdot \text{K}, \, v = 3 \times 10^{-5} \, \text{m/s} \), and \( Pr = 0.69 \).

(c) Accounting for the effects of radiation, with \( \varepsilon = 0.55 \) and \( T_{\text{a}} = 25^\circ \text{C} \), numerically integrate the differential equation derived in part (a) to determine the temperature of the wire at \( L = 5 \, \text{m} \). Explore the effects of \( V_e \) and \( \varepsilon \) on the temperature distribution along the wire.

### Spheres

#### 7.54

Air at 25°C flows over a 10-mm-diameter sphere with a velocity of 15 m/s, while the surface of the sphere is maintained at 75°C.

(a) What is the drag force on the sphere? 
(b) What is the rate of heat transfer from the sphere? 
(c) Generate a plot of the rate of heat transfer from the sphere as a function of the air velocity for the range 1 to 25 m/s.

#### 7.55

Consider a sphere with a diameter of 20 mm and a surface temperature of 60°C that is immersed in a fluid at a temperature of 30°C and a velocity of 2.5 m/s. Calculate the drag force and the heat rate when the fluid is (a) water and (b) air at atmospheric pressure. Explain why the results for the two fluids are so different.

#### 7.56

A spherical, underwater instrument pod used to make soundings and to measure conditions in the water has a diameter of 100 mm and dissipates 400 W.

(a) Estimate the surface temperature of the pod when suspended in a bay where the current is 1 m/s and the water temperature is 15°C.

(b) Inadvertently, the pod is hauled out of the water and suspended in ambient air without deactivating the power. Estimate the surface temperature of
junctIon if the combustion gases are at 1000 K? Conduction through the lead wires may be neglected.

To determine the influence of the gas velocity on the thermocouple measurement error, compute the steady-state temperature of the thermocouple junction for velocities in the range $1 \leq V \leq 25$ m/s. The emissivity of the junction can be controlled through application of a thin coating. To reduce the measurement error, should the emissivity be increased or decreased? For $V = 5$ m/s, compute the steady-state junction temperature for emissivities in the range $0.1 \leq \varepsilon \leq 1.0$.

A thermocouple junction is inserted in a large duct to measure the temperature of hot gases flowing through the duct.

(a) If the duct surface temperature $T_s$ is less than the gas temperature $T_g$, will the thermocouple sense a temperature that is less than, equal to, or greater than $T_g$? Justify your answer on the basis of a simple analysis.

(b) A thermocouple junction in the shape of a 2-mm-diameter sphere with a surface emissivity of 0.60 is placed in a gas stream moving at 3 m/s. If the thermocouple senses a temperature of 320°C when the duct surface temperature is 175°C, what is the actual gas temperature? The gas may be assumed to have the properties of air at atmospheric pressure.

How would changes in velocity and emissivity affect the temperature measurement error? Determine the measurement error for velocities in the range $1 \leq V \leq 25$ m/s ($\varepsilon = 0.6$) and for emissivities in the range $0.1 \leq \varepsilon \leq 1.0$ ($V = 3$ m/s).

Consider temperature measurement in a gas stream using the thermocouple junction described in Problem 7.66 ($D = 2$ mm, $\varepsilon = 0.60$). If the gas velocity and temperature are 2 m/s and 500°C, respectively, what temperature will be indicated by the thermocouple if the duct surface temperature is 350°C? The gas may be assumed to have the properties of atmospheric air. What temperature will be indicated by the thermocouple if the gas pressure is doubled and all other conditions remain the same?

A preheater involves the use of condensing steam at 100°C on the inside of a bank of tubes to heat air that enters at 1 atm and 25°C. The air moves at 5 m/s in cross flow over the tubes. Each tube is 1 m long and has an outside diameter of 10 mm. The bank consists of 196 tubes in a square, aligned array for which $S_T = S_L = 15$ mm. What is the total rate of heat transfer to the air? What is the pressure drop associated with the airflow?

7.70 Consider the in-line tube bank of Problem 7.69 ($D = 10$ mm, $L = 1$ m, and $S_T = S_L = 15$ mm), with condensing steam used to heat atmospheric air entering the tube bank at $T_i = 25$°C and $V = 5$ m/s. In this case, however, the desired outlet temperature, not the number of tube rows, is known. What is the minimum value of $N_T$ needed to achieve an outlet temperature of $T_o \geq 75$°C? What is the corresponding pressure drop across the tube bank?

7.71 A tube bank uses an aligned arrangement of 15-mm-diameter tubes with $S_T = S_L = 30$ mm. There are 10 rows of tubes with 50 tubes in each row. Consider an application for which cold water flows through the tubes, maintaining the outer surface temperature at 40°C, while flue gases at 427°C and a velocity of 5 m/s are in cross flow over the tubes. The properties of the flue gas may be approximated as those of atmospheric air at 427°C. What is the total rate of heat transfer per unit length of the tubes in the bank?

7.72 An air duct heater consists of an aligned array of electrical heating elements in which the longitudinal and transverse pitches are $S_L = S_T = 24$ mm. There are 3 rows of elements in the flow direction ($N_z = 3$) and 4 elements per row ($N_T = 4$). Atmospheric air with an upstream velocity of 12 m/s and a temperature of 25°C moves in cross flow over the elements, which have a diameter of 12 mm, a length of 250 mm, and are maintained at a surface temperature of 350°C.

7.68 Repeat Example 7.7 for a more compact tube bank in which the longitudinal and transverse pitches are $S_L = S_T = 20.5$ mm. All other conditions remain the same.

7.69 A preheater involves the use of condensing steam at 100°C on the inside of a bank of tubes to heat air that...