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Problems

Hydrodynamic Considerations

8.1 Fully developed conditions are known to exist for water flowing through a 25-mm-diameter tube at 0.01 kg/s and 27°C. What is the maximum velocity of the water in the tube? What is the pressure gradient associated with the flow?

8.2 What is the pressure drop associated with water at 27°C flowing with a mean velocity of 0.2 m/s through a 600-m-long cast iron pipe of 0.15-m inside diameter?

8.3 Water at 27°C flows with a mean velocity of 1 m/s through a 1-km-long pipe of 0.25-m inside diameter.

(a) Determine the pressure drop over the pipe length and the corresponding pump power requirement, if the pipe surface is smooth.

(b) If the pipe is made of cast iron and its surface is clean, determine the pressure drop and pump power requirement.

(c) For the smooth pipe condition, generate a plot of pressure drop and pump power requirement for mean velocities in the range from 0.05 to 1.5 m/s.

8.4 An engine oil cooler consists of a bundle of 25 smooth tubes, each of length $L = 2.5$ m and diameter $D = 10$ mm.

(a) If oil at 300 K and a total flow rate of 24 kg/s is in fully developed flow through the tubes, what is the pressure drop and the pump power requirement?

(b) Compute and plot the pressure drop and pump power requirement as a function of flow rate for $10 \leq \dot{m} \leq 30$ kg/s.

8.5 For fully developed laminar flow through a parallel-plate channel, the x-momentum equation has the form

$$\mu\left(\frac{d^2u}{dy^2}\right) = \frac{dp}{dx} = \text{constant}$$

The purpose of this problem is to develop expressions for the velocity distribution and pressure gradient analogous to those for the circular tube in Section 8.1.

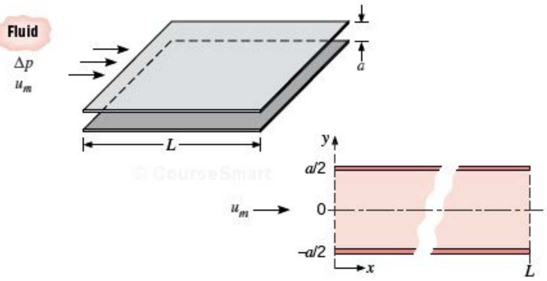
(a) Show that the velocity profile, $u(y)$, is parabolic and of the form

$$u(y) = \frac{3}{2}u_m\left[1 - \frac{y^2}{(a/2)^2}\right]$$

where u_m is the mean velocity

$$u_m = -\frac{a^2}{12\mu}\left(\frac{dp}{dx}\right)$$

and $-dp/dx = \Delta p/L$, where Δp is the pressure drop across the channel of length L.



(b) Write an expression defining the friction factor, f, using the hydraulic diameter D_h as the characteristic length. What is the hydraulic diameter for the parallel-plate channel?

(c) The friction factor is estimated from the expression $f = C/Re_{D_h}$, where C depends upon the flow cross section, as shown in Table 8.1. What is the coefficient C for the parallel-plate channel?

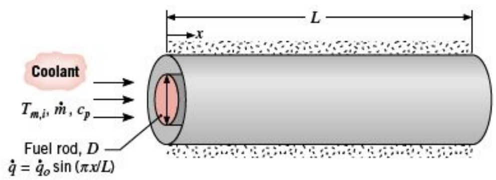
(d) Air flow in a parallel-plate channel with a separation of 5 mm and a length of 200 mm experiences a pressure drop of $\Delta p = 3.75$ N/m^2. Calculate the mean velocity and the Reynolds number for air at atmospheric pressure and 300 K. Is the assumption of fully developed flow reasonable for this application? If not, what is the effect on the estimate for u_m?

Thermal Entry Length and Energy Balance Considerations

8.6 Consider pressurized water, engine oil (unused), and NaK (22%/78%) flowing in a 20-mm-diameter tube.

(a) Determine the mean velocity, the hydrodynamic entry length, and the thermal entry length for each of the fluids when the fluid temperature is 366 K and the flow rate is 0.01 kg/s.

8.13 Consider a cylindrical nuclear fuel rod of length L and diameter D that is encased in a concentric tube. Pressurized water flows through the annular region between the rod and the tube at a rate $\dot{m}$, and the outer surface of the tube is well insulated. Heat generation occurs within the fuel rod, and the volumetric generation rate is known to vary sinusoidally with distance along the rod. That is, $\dot{q}(x) = \dot{q}_o \sin(\pi x/L)$, where $\dot{q}_o$ (W/m³) is a constant. A uniform convection coefficient h may be assumed to exist between the surface of the rod and the water.



(a) Obtain expressions for the local heat flux $q''(x)$ and the total heat transfer q from the fuel rod to the water.

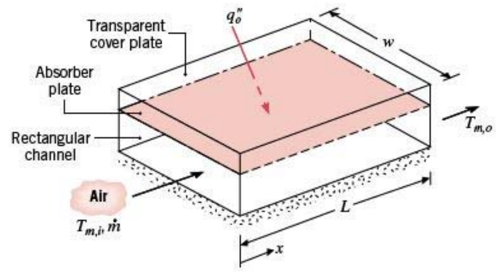
(b) Obtain an expression for the variation of the mean temperature $T_m(x)$ of the water with distance x along the tube.

(c) Obtain an expression for the variation of the rod surface temperature $T_s(x)$ with distance x along the tube. Develop an expression for the x location at which this temperature is maximized.

8.14 In a particular application involving fluid flow at a rate $\dot{m}$ through a circular tube of length L and diameter D, the surface heat flux is known to have a sinusoidal variation with x, which is of the form $q''_s(x) = q''_{s,m} \sin(\pi x/L)$. The maximum flux, $q''_{s,m}$, is a known constant, and the fluid enters the tube at a known temperature, $T_{m,i}$. Assuming the convection coefficient to be constant, how do the mean temperature of the fluid and the surface temperature vary with x?

8.15 A flat-plate solar collector is used to heat atmospheric air flowing through a rectangular channel. The bottom surface of the channel is well insulated, while the top surface is subjected to a uniform heat flux q''_o, which is due to the net effect of solar radiation absorption and heat exchange between the absorber and cover plates.

(a) Beginning with an appropriate differential control volume, obtain an equation that could be used to determine the mean air temperature $T_m(x)$ as a function of distance along the channel. Solve this equation to obtain an expression for the mean temperature of the air leaving the collector.



(b) With air inlet conditions of $\dot{m} = 0.1$ kg/s and $T_{m,i} = 40°C$, what is the air outlet temperature if $L = 3$ m, $w = 1$ m, and $q''_o = 700$ W/m²? The specific heat of air is $c_p = 1008$ J/kg · K.

8.16 Atmospheric air enters the heated section of a circular tube at a flow rate of 0.005 kg/s and a temperature of 20°C. The tube is of diameter $D = 50$ mm, and fully developed conditions with $h = 25$ W/m² · K exist over the entire length of $L = 3$ m.

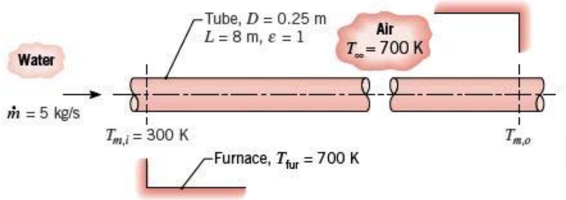
(a) For the case of uniform surface heat flux at $q''_s = 1000$ W/m², determine the total heat transfer rate q and the mean temperature of the air leaving the tube $T_{m,o}$. What is the value of the surface temperature at the tube inlet $T_{s,i}$ and outlet $T_{s,o}$? Sketch the axial variation of T_s and T_m. On the same figure, also sketch (qualitatively) the axial variation of T_s and T_m for the more realistic case in which the local convection coefficient varies with x.

(b) If the surface heat flux varies linearly with x, such that q''_s (W/m²) = 500x (m), what are the values of q, $T_{m,o}$, $T_{s,i}$, and $T_{s,o}$? Sketch the axial variation of T_s and T_m. On the same figure, also sketch (qualitatively) the axial variation of T_s and T_m for the more realistic case in which the local convection coefficient varies with x.

(c) For the two heating conditions of parts (a) and (b), plot the mean fluid and surface temperatures, $T_m(x)$ and $T_s(x)$, respectively, as functions of distance along the tube. What effect will a fourfold increase in the convection coefficient have on the temperature distributions?

(d) For each type of heating process, what heat fluxes are required to achieve an air outlet temperature of 125°C? Plot the temperature distributions.

8.17 Water at 300 K and a flow rate of 5 kg/s enters a black, thin-walled tube, which passes through a large furnace whose walls and air are at a temperature of 700 K. The diameter and length of the tube are 0.25 m and 8 m, respectively. Convection coefficients associated with water flow through the tube and air flow over the tube are 300 $W/m^2 \cdot K$ and 50 $W/m^2 \cdot K$, respectively.



(a) Write an expression for the linearized radiation coefficient corresponding to radiation exchange between the outer surface of the pipe and the furnace walls. Explain how to calculate this coefficient if the surface temperature of the tube is represented by the arithmetic mean of its inlet and outlet values.

(b) Determine the outlet temperature of the water, $T_{m,o}$.

8.18 Slug flow is an idealized tube flow condition for which the velocity is assumed to be uniform over the entire tube cross section. For the case of laminar slug flow with a uniform surface heat flux, determine the form of the fully developed temperature distribution $T(r)$ and the Nusselt number Nu_D.

8.19 Superimposing a control volume that is differential in x on the tube flow conditions of Figure 8.8, derive Equation 8.45a.

8.20 An experimental nuclear core simulation apparatus consists of a long thin-walled metallic tube of diameter D and length L, which is electrically heated to produce the sinusoidal heat flux distribution

$$q''_s(x) = q''_o \sin\left(\frac{\pi x}{L}\right)$$

where x is the distance measured from the tube inlet. Fluid at an inlet temperature $T_{m,i}$ flows through the tube at a rate of $\dot{m}$. Assuming the flow is turbulent and fully developed over the entire length of the tube, develop expressions for:

(a) the total rate of heat transfer, q, from the tube to the fluid;

(b) the fluid outlet temperature, $T_{m,o}$;

(c) the axial distribution of the wall temperature, $T_s(x)$; and

(d) the magnitude and position of the highest wall temperature.

(e) Consider a 40-mm-diameter tube of 4-m length with a sinusoidal heat flux distribution for which q''_o = 10,000 W/m^2. Fluid passing through the tube has a flow rate of 0.025 kg/s, a specific heat of 4180 $J/kg \cdot K$, an entrance temperature of 25°C, and a convection coefficient of 1000 $W/m^2 \cdot K$. Plot the mean fluid and surface temperatures as a function of distance along the tube. Identify important features of the distributions. Explore the effect of ±25% changes in the convection coefficient and the heat flux on the distributions.

8.21 Water at 20°C and a flow rate of 0.1 kg/s enters a heated, thin-walled tube with a diameter of 15 mm and length of 2 m. The wall heat flux provided by the heating elements depends on the wall temperature according to the relation

$$q''_s(x) = q''_{s,o}[1 + \alpha(T_s - T_{ref})]$$

where $q''_{s,o} = 10^4$ W/m^2, $\alpha = 0.2$ K^{-1}, T_{ref} = 20°C, and T_s is the wall temperature in °C. Assume fully developed flow and thermal conditions with a convection coefficient of 3000 $W/m^2 \cdot K$.

(a) Beginning with a properly defined differential control volume in the tube, derive expressions for the variation of the water, $T_m(x)$, and the wall, $T_s(x)$, temperatures as a function of distance from the tube inlet.

(b) Using a numerical integration scheme, calculate and plot the temperature distributions, $T_m(x)$ and $T_s(x)$, on the same graph. Identify and comment on the main features of the distributions. *Hint*: The *IHT* integral function *DER*(T_m,x) can be used to perform the integration along the length of the tube.

(c) Calculate the total rate of heat transfer to the water.

Heat Transfer Correlations: Circular Tubes

8.22 Engine oil is heated by flowing through a circular tube of diameter D = 50 mm and length L = 25 m and whose surface is maintained at 150°C.

(a) If the flow rate and inlet temperature of the oil are 0.5 kg/s and 20°C, what is the outlet temperature $T_{m,o}$? What is the total heat transfer rate q for the tube?

(b) For flow rates in the range $0.5 \leq \dot{m} \leq 2.0$ kg/s, compute and plot the variations of $T_{m,o}$ and q with $\dot{m}$. For what flow rate(s) are q and $T_{m,o}$ maximized? Explain your results.

8.23 Engine oil flows through a 25-mm-diameter tube at a rate of 0.5 kg/s. The oil enters the tube at a temperature of 25°C, while the tube surface temperature is maintained at 100°C.

(a) Determine the oil outlet temperature for a 5-m and for a 100-m long tube. For each case, compare the flow rate on the time t_c required to reach a value of $T_c = 160°C$.

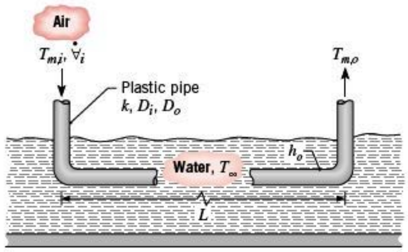
8.29 The mold that is used in an injection molding process is constructed of metal ($\rho = 7800\ kg/m^3$, $c = 450\ J/kg \cdot K$). The mold, to be heated to 190°C prior to injection of the thermoplastic material, must be subsequently cooled before ejection of the finished part. Pressurized water at 30°C is available for cooling. The mold has dimensions 50 mm × 100 mm × 40 mm and the mold designer must specify inclusion of N cooling passages, of diameter 5 mm, to be machined into the mold. If one passage can be placed every 10 mm along the length or width of the mold, the designer can therefore specify either five 100-mm-long passages or ten 50-mm-long passages. The total mass flow rate of water, divided equally among the channels, is 0.02 kg/s. Which configuration ($N = 5$ long passages or $N = 10$ short passages) should the mold designer specify in order to cool the mold faster and, in turn, increase the number of parts that can be manufactured daily? What is the initial rate of cooling of the mold (°C/s)? The velocity profile in each channel is fully developed prior to entering the hot mold. Neglect the mass of the thermoplastic part.

8.30 The evaporator section of a heat pump is installed in a large tank of water, which is used as a heat source during the winter. As energy is extracted from the water, it begins to freeze, creating an ice/water bath at 0°C, which may be used for air conditioning during the summer. Consider summer cooling conditions for which air is passed through an array of copper tubes, each of inside diameter $D = 50$ mm, submerged in the bath.

(a) If air enters each tube at a mean temperature of $T_{m,i} = 24°C$ and a flow rate of $\dot{m} = 0.01$ kg/s, what tube length L is needed to provide an exit temperature of $T_{m,o} = 14°C$? With 10 tubes passing through a tank of total volume $V = 10\ m^3$, which initially contains 80% ice by volume, how long would it take to completely melt the ice? The density and latent heat of fusion of ice are 920 kg/m³ and 3.34×10^5 J/kg, respectively.

(b) The air outlet temperature may be regulated by adjusting the tube mass flow rate. For the tube length determined in part (a), compute and plot $T_{m,o}$ as a function of $\dot{m}$ for $0.005 \le \dot{m} \le 0.05$ kg/s. If the dwelling cooled by this system requires approximately 0.05 kg/s of air at 16°C, what design and operating conditions should be prescribed for the system?

8.31 To cool a summer home without using a vapor-compression refrigeration cycle, air is routed through a plastic pipe ($k = 0.15\ W/m \cdot K$, $D_i = 0.15$ m, $D_o = 0.17$ m) that is submerged in an adjoining body of water. The water temperature is nominally at $T_\infty = 17°C$, and a convection coefficient of $h_o \approx 1500\ W/m^2 \cdot K$ is maintained at the outer surface of the pipe.



If air from the home enters the pipe at a temperature of $T_{m,i} = 29°C$ and a volumetric flow rate of $\dot{\forall}_i = 0.025\ m^3/s$, what pipe length L is needed to provide a discharge temperature of $T_{m,o} = 21°C$? What is the fan power required to move the air through this length of pipe if its inner surface is smooth?

8.32 Water flowing at 2 kg/s through a 40-mm-diameter tube is to be heated from 25 to 75°C by maintaining the tube surface temperature at 100°C.

(a) What is the required tube length for these conditions?

(b) In order to design a water heating system, we wish to consider using tube diameters in the range from 30 to 50 mm. What are the required tube lengths for water flow rates of 1, 2, and 3 kg/s? Represent this design information graphically.

(c) Plot the pressure gradient as a function of tube diameter for the three flow rates. Assume the tube wall is smooth.

8.33 Consider the conditions associated with the hot water pipe of Problem 7.56, but now account for the convection resistance associated with water flow at a mean velocity of $u_m = 0.5$ m/s in the pipe. What is the corresponding daily cost of heat loss per meter of the uninsulated pipe?

8.34 A thick-walled, stainless steel (AISI 316) pipe of inside and outside diameters $D_i = 20$ mm and $D_o = 40$ mm is heated electrically to provide a uniform heat generation rate of $\dot{q} = 10^6\ W/m^3$. The outer surface of the pipe is insulated, while water flows through the pipe at a rate of $\dot{m} = 0.1$ kg/s.

(a) If the water inlet temperature is $T_{m,i} = 20°C$ and the desired outlet temperature is $T_{m,o} = 40°C$, what is the required pipe length?

(b) What are the location and value of the maximum pipe temperature?

8.35 Consider the encased pipe of Problem 4.29, but now allow for the difference between the mean temperature of the fluid, which changes along the pipe length, and that of the pipe.

(a) For the prescribed values of k, D, w, h, and T_∞ and a pipe of length $L = 100$ m, what is the outlet temperature $T_{m,o}$ of water that enters the pipe at a temperature of $T_{m,i} = 90°C$ and a flow rate of $\dot{m} = 2$ kg/s?

(b) What is the pressure drop of the water and the corresponding pump power requirement?

(c) Subject to the constraint that the width of the duct is fixed at $w = 0.30$ m, explore the effects of the flow rate and the pipe diameter on the outlet temperature.

8.36 Water flows through a thick-walled tube with an inner diameter of 12 mm and a length of 8 m. The tube is immersed in a well-stirred, hot reaction tank maintained at 85°C, and the conduction resistance of the tube wall (based on the inner surface area) is $R''_{cd} = 0.002\ m^2 \cdot K/W$. The inlet temperature of the process fluid is $T_{m,i} = 20°C$, and the flow rate is 33 kg/h.

(a) Estimate the outlet temperature of the process fluid, $T_{m,o}$. Assume, and then justify, fully developed flow and thermal conditions within the tube.

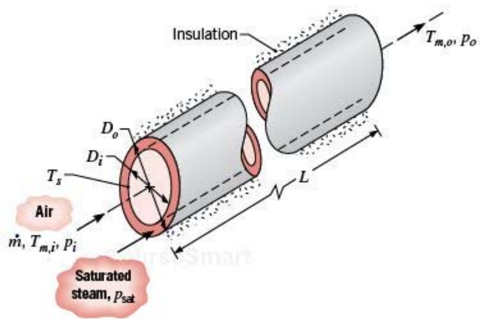
(b) Do you expect $T_{m,o}$ to increase or decrease if combined thermal and hydrodynamic entry conditions exist within the tube? Estimate the outlet temperature of the water for this condition.

8.37 Atmospheric air enters a 10-m-long, 150-mm-diameter uninsulated heating duct at 60°C and 0.04 kg/s. The duct surface temperature is approximately constant at $T_s = 15°C$.

(a) What are the outlet air temperature, the heat rate q, and pressure drop Δp for these conditions?

(b) To illustrate the tradeoff between heat transfer rate and pressure drop considerations, calculate q and Δp for diameters in the range from 0.1 to 0.2 m. In your analysis, maintain the total surface area, $A_s = \pi DL$, at the value computed for part (a). Plot q, Δp, and L as a function of the duct diameter.

8.38 An air heater for an industrial application consists of an insulated, concentric tube annulus, for which air flows through a thin-walled inner tube. Saturated steam flows through the outer annulus, and condensation of the steam maintains a uniform temperature T_s on the tube surface.



Consider conditions for which air enters a 50-mm-diameter tube at a pressure of 5 atm, a temperature of $T_{m,i} = 17°C$, and a flow rate of $\dot{m} = 0.03$ kg/s, while saturated steam at 2.455 bars condenses on the outer surface of the tube. If the length of the annulus is $L = 5$ m, what are the outlet temperature $T_{m,o}$ and pressure p_o of the air? What is the mass rate at which condensate leaves the annulus?

8.39 The products of combustion from a burner are routed to an industrial application through a thin-walled metallic duct of diameter $D_i = 1$ m and length $L = 100$ m. The gas enters the duct at atmospheric pressure and a mean temperature and velocity of $T_{m,i} = 1600$ K and $u_{m,i} = 10$ m/s, respectively. It must exit the duct at a temperature that is no less than $T_{m,o} = 1400$ K. What is the minimum thickness of an alumina-silica insulation ($k_{ins} = 0.125\ W/m \cdot K$) needed to meet the outlet requirement under worst case conditions for which the duct is exposed to ambient air at $T_\infty = 250$ K and a cross-flow velocity of $V = 15$ m/s? The properties of the gas may be approximated as those of air, and as a first estimate, the effect of the insulation thickness on the convection coefficient and thermal resistance associated with the cross flow may be neglected.

8.40 Liquid mercury at 0.5 kg/s is to be heated from 300 to 400 K by passing it through a 50-mm-diameter tube whose surface is maintained at 450 K. Calculate the required tube length by using an appropriate liquid metal convection heat transfer correlation. Compare your result with that which would have been obtained by using a correlation appropriate for $Pr \gtrsim 0.7$.

8.41 The surface of a 50-mm-diameter, thin-walled tube is maintained at 100°C. In one case air is in cross flow over the tube with a temperature of 25°C and a velocity of 30 m/s. In another case air is in fully developed flow through the tube with a temperature of 25°C and a mean velocity of 30 m/s. Compare the heat flux from the tube to the air for the two cases.

by free convection with ambient air at 27°C, what is the outlet temperature of the water? The free convection heat transfer coefficient is 5 W/m² · K.

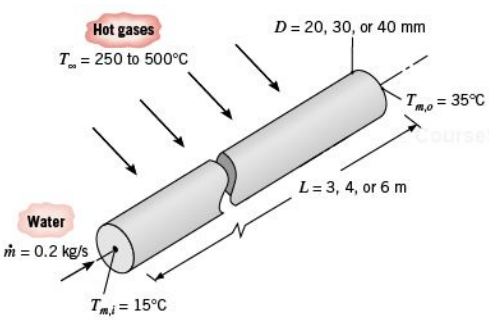
8.57 A thick-walled steel pipe ($k = 60$ W/m · K) carrying hot water is cooled externally by a cross-flow airstream at a velocity of 20 m/s and a temperature of 25°C. The inner and outer diameters of the pipe are $D_i = 20$ mm and $D_o = 25$ mm, respectively. At a certain location along the pipe, the mean temperature of the water is 80°C. Assuming the flow inside the tube is fully developed with a Reynolds number of 20,000, find the heat transfer rate to the airstream per unit pipe length.

8.58 Heat is to be removed from a reaction vessel operating at 75°C by supplying water at 27°C and 0.12 kg/s through a thin-walled tube of 15-mm diameter. The convection coefficient between the tube outer surface and the fluid in the vessel is 3000 W/m² · K.

(a) If the outlet water temperature cannot exceed 47°C, what is the maximum rate of heat transfer from the vessel?

(b) What tube length is required to accomplish the heat transfer rate of part (a)?

8.59 A heating contractor must heat 0.2 kg/s of water from 15°C to 35°C using hot gases in cross flow over a thin-walled tube.



Your assignment is to develop a series of design graphs that can be used to demonstrate acceptable combinations of tube dimensions (D and L) and of hot gas conditions (T_∞ and V) that satisfy this requirement. In your analysis, consider the following parameter ranges: $D = 20$, 30, or 40 mm; $L = 3$, 4, or 6 m; $T_\infty = 250$, 375, or 500°C; and $20 \leq V \leq 40$ m/s.

8.60 A thin-walled tube with a diameter of 6 mm and length of 20 m is used to carry exhaust gas from a smoke stack to the laboratory in a nearby building for analysis. The gas enters the tube at 200°C and with a mass flow rate of 0.003 kg/s. Autumn winds at a temperature of 15°C blow directly across the tube at a velocity of 5 m/s. Assume the thermophysical properties of the exhaust gas are those of air.

(a) Estimate the average heat transfer coefficient for the exhaust gas flowing inside the tube.

(b) Estimate the heat transfer coefficient for the air flowing across the outside of the tube.

(c) Estimate the overall heat transfer coefficient U and the temperature of the exhaust gas when it reaches the laboratory.

8.61 A 50-mm-diameter, thin-walled metal pipe covered with a 25-mm-thick layer of insulation (0.085 W/m · K) and carrying superheated steam at atmospheric pressure is suspended from the ceiling of a large room. The steam temperature entering the pipe is 120°C, and the air temperature is 20°C. The convection heat transfer coefficient on the outer surface of the covered pipe is 10 W/m² · K. If the velocity of the steam is 10 m/s, at what point along the pipe will the steam begin condensing?

8.62 A thin-walled, uninsulated 0.3-m-diameter duct is used to route chilled air at 0.05 kg/s through the attic of a large commercial building. The attic air is at 37°C, and natural circulation provides a convection coefficient of 2 W/m² · K at the outer surface of the duct. If chilled air enters a 15-m-long duct at 7°C, what is its exit temperature and the rate of heat gain? Properties of the chilled air may be evaluated at an assumed average temperature of 300 K.

8.63 The problem of heat losses from a fluid moving through a buried pipeline has received considerable attention. Practical applications include the trans-Alaska pipeline, as well as power plant steam and water distribution lines. Consider a steel pipe of diameter D that is used to transport oil flowing at a rate $\dot{m}_o$ through a cold region. The pipe is covered with a layer of insulation of thickness t and thermal conductivity k_i and is buried in soil to a depth z (distance from the soil surface to the pipe centerline). Each section of pipe is of length L and extends between pumping stations in which the oil is heated to ensure low viscosity and hence low pump power requirements. The temperature of the oil entering the pipe from a pumping station and the temperature of the ground above the pipe are designated as $T_{m,i}$ and T_s, respectively, and are known.

Consider conditions for which the oil (o) properties may be approximated as $\rho_o = 900$ kg/m³, $c_{p,o} = 2000$ J/kg · K, $\nu_o = 8.5 \times 10^{-4}$ m²/s, $k_o = 0.140$ W/m · K, $Pr_o = 10^4$; the oil flow rate is $\dot{m}_o = 500$ kg/s; and the pipe diameter is 1.2 m.