(b) Determine the mass flow rate, the hydrodynamic entry length, and the thermal entry length for water and engine oil at 300 and 400 K and a mean velocity of 0.02 m/s.

8.7 Velocity and temperature profiles for laminar flow in a tube of radius $r_o = 10$ mm have the form

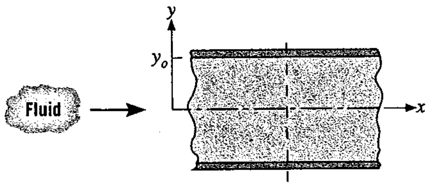
$$u(r) = 0.1[1 - (r/r_o)^2]$$
$$T(r) = 344.8 + 75.0(r/r_o)^2 - 18.8(r/r_o)^4$$

with units of m/s and K, respectively. Determine the corresponding value of the mean (or bulk) temperature, T_m, at this axial position.

8.8 At a particular axial station, velocity and temperature profiles for laminar flow in a parallel plate channel have the form

$$u(y) = 0.75[1 - (y/y_o)^2]$$
$$T(y) = 5.0 + 95.66(y/y_o)^2 - 47.83(y/y_o)^4$$

with units of m/s and °C, respectively.



Determine corresponding values of the mean velocity, u_m, and mean (or bulk) temperature, T_m. Plot the velocity and temperature distributions. Do your values of u_m and T_m appear reasonable?

8.9 In Chapter 1, it was stated that for incompressible liquids, flow work could usually be neglected in the steady-flow energy equation (Equation 1.11d). In the trans-Alaska pipeline, the high viscosity of the oil and long distances cause significant pressure drops, and it is reasonable to question whether flow work would be significant. Consider a $L = 100$ km length of pipe of diameter $D = 1.2$ m, with oil flow rate $\dot{m} = 500$ kg/s. The oil properties are $\rho = 900$ kg/m^3, $c_p = 2000$ J/kg · K, $\mu = 0.765$ N · s/m^2. Calculate the pressure drop, the flow work, and the temperature rise caused by the flow work.

8.10 When viscous dissipation is included, Equation 8.48 (multiplied by ρc_p) becomes

$$\rho c_p u \frac{\partial T}{\partial x} = \frac{k}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \mu\left(\frac{du}{dr}\right)^2$$

This problem explores the importance of viscous dissipation. The conditions under consideration are laminar, fully developed flow in a circular pipe, with u given by Equation 8.15.

(a) By integrating the left-hand side over a section of a pipe of length L and radius r_o, show that this term yields the right-hand side of Equation 8.34.

(b) Integrate the viscous dissipation term over the same volume.

(c) Find the temperature rise caused by viscous dissipation by equating the two terms calculated above. Use the same conditions as in Problem 8.9.

8.11 Water enters a tube at 27°C with a flow rate of 450 kg/h. The heat transfer from the tube wall to the fluid is given as q_s' (W/m) $= ax$, where the coefficient a is 20 W/m^2 and x (m) is the axial distance from the tube entrance.

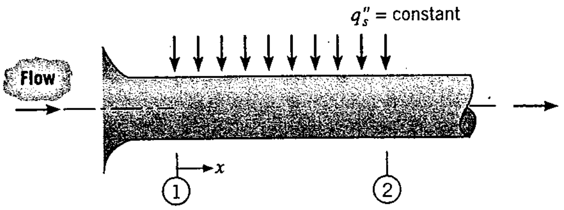
(a) Beginning with a properly defined differential control volume in the tube, derive an expression for the temperature distribution $T_m(x)$ of the water.

(b) What is the outlet temperature of the water for a heated section 30 m long?

(c) Sketch the mean fluid temperature, $T_m(x)$, and the tube wall temperature, $T_s(x)$, as a function of distance along the tube for fully developed *and* developing flow conditions.

(d) What value of a uniform wall heat flux, q_s'' (instead of $q_s' = ax$), would provide the same fluid outlet temperature as that determined in part (b)? For this type of heating, sketch the temperature distributions requested in part (c).

8.12 Consider flow in a circular tube. Within the test section length (between 1 and 2) a constant heat flux q_s'' is maintained.



(a) For the following two cases, sketch the surface temperature $T_s(x)$ and the fluid mean temperature $T_m(x)$ as a function of distance along the test section x. In case A, flow is hydrodynamically and thermally fully developed. In case B, flow is not developed.

(b) Assuming that the surface flux q_s'' and the inlet mean temperature $T_{m,1}$ are identical for both cases, will the exit mean temperature $T_{m,2}$ for case A be greater than, equal to, or less than $T_{m,2}$ for case B? Briefly explain why.

log mean temperature difference to the arithmetic mean temperature difference.

$\boxed{\text{(b)}}$ For $5 \leq L \leq 100$ m, compute and plot the average Nusselt number $\overline{Nu}_D$ and the oil outlet temperature as a function of L.

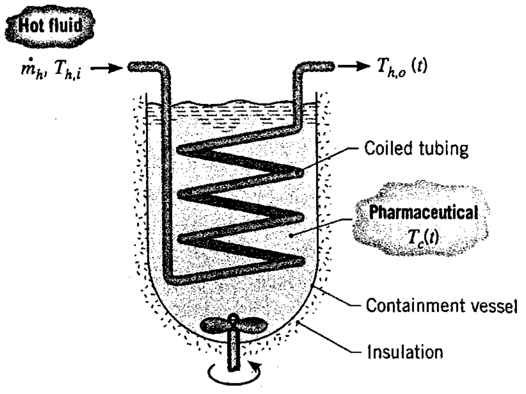
8.24 An oil preheater consists of a single tube of 10 mm diameter and 5 m length, with its surface maintained at 175°C by swirling combustion gases. The engine oil (new) enters at 75°C. What flow rate must be supplied to maintain an oil outlet temperature of 100°C ? What is the corresponding heat transfer rate ?

8.25 Engine oil flows at a rate of 1 kg/s through a 5-mm-diameter straight tube. The oil has an inlet temperature of 45°C and it is desired to heat the oil to a mean temperature of 80°C at the exit of the tube. The surface of the tube is maintained at 150°C. Determine the required length of the tube. *Hint*: Calculate the Reynolds numbers at the entrance and exit of the tube before proceeding with your analysis.

8.26 Ethylene glycol flows at 0.01 kg/s through a 3-mm-diameter, thin-walled tube. The tube is coiled and submerged in a well-stirred water bath maintained at 25°C. If the fluid enters the tube at 85°C, what heat rate and tube length are required for the fluid to leave at 35°C? Neglect heat transfer enhancement associated with the coiling.

8.27 In the final stages of production, a pharmaceutical is sterilized by heating it from 25 to 75°C as it moves at 0.2 m/s through a straight thin-walled stainless steel tube of 12.7-mm diameter. A uniform heat flux is maintained by an electric resistance heater wrapped around the outer surface of the tube. If the tube is 10 m long, what is the required heat flux? If fluid enters the tube with a fully developed velocity profile and a uniform temperature profile, what is the surface temperature at the tube exit and at a distance of 0.5 m from the entrance? Fluid properties may be approximated as $\rho = 1000\ \mathrm{kg/m^3}$, $c_p = 4000\ \mathrm{J/kg \cdot K}$, $\mu = 2 \times 10^{-3}\ \mathrm{kg/s \cdot m}$, $k = 0.8\ \mathrm{W/m \cdot K}$, and $Pr = 10$.

8.28 *Batch processes* are often used in chemical and pharmaceutical operations to achieve a desired chemical composition for the final product. Related heat transfer processes are typically transient, involving a liquid of fixed volume that may be heated from room temperature to a desired process temperature, or cooled from the process temperature to room temperature. Consider a batch process for which a pharmaceutical (the cold fluid, *c*) is poured into an insulated, highly agitated vessel (a *stirred reactor*) and heated by passing a hot fluid (*h*) through a submerged heat exchanger coil of thin-walled tubing and surface area A_s. The flow rate, $\dot{m}_h$, mean inlet temperature, $T_{h,i}$, and specific heat, $c_{p,h}$, of the hot fluid are known, as are the initial temperature, $T_{c,i} < T_{h,i}$, the volume, V_c, mass density, ρ_c, and specific heat, $c_{v,c}$, of the pharmaceutical. Heat transfer from the hot fluid to the pharmaceutical is governed by an overall heat transfer coefficient U.



(a) Starting from basic principles, derive expressions that can be used to determine the variation of T_c and $T_{h,o}$ with time during the heating process. *Hint*: Two equations may be written for the rate of heat transfer, *q(t)*, to the pharmaceutical, one based on the log-mean temperature difference and the other on an energy balance for flow of the hot fluid through the tube. Equate these expressions to determine $T_{h,o}(t)$ as a function of $T_c(t)$ and prescribed parameters. Use the expression for $T_{h,o}(t$ and the energy balance for flow through the tube with an energy balance for a control volume containing the pharmaceutical to obtain an expression for $T_c(t)$.

(b) Consider a pharmaceutical of volume $V_c = 1\ \mathrm{m^3}$ density $\rho_c = 1100\ \mathrm{kg/m^3}$, specific heat $c_{v,c} =$ 2000 J/kg · K, and an initial temperature of $T_{c,i} = 25$°C. A coiled tube of length $L = 40$ m, diameter $D = 50$ mm, and coil diameter $C = 500$ mm is submerged in the vessel, and hot fluid enters the tubing at $T_{h,i} = 200$°C and $\dot{m}_h = 2.4$ kg/s. The convection coefficient at the outer surface of the tubing may be approximated as $h_o = 1000\ \mathrm{W/m^2 \cdot K}$, and the fluid properties are $c_{p,h} = 2500\ \mathrm{J/kg \cdot K}$, $\mu_h =$ $0.002\ \mathrm{N \cdot s/m^2}$, $k_h = 0.260\ \mathrm{W/m \cdot K}$, and $Pr_h = 2C$ For the foregoing conditions, compute and plot the pharmaceutical temperature T_c and the outlet temperature $T_{h,o}$ as a function of time over the rang $0 \leq t \leq 3600$ s. How long does it take to reach batch temperature of $T_c = 160$°C? The proces operator may control the heating time by varyin $\dot{m}_h$. For $1 \leq \dot{m}_h \leq 5$ kg/s, explore the effect of th

(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 $T_{m,i} = 90°\text{C}$ 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?

$\boxed{\text{(c)}}$ 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 $R''_{\text{cd}} = 0.002\ \text{m}^2 \cdot \text{K/W}$. The inlet temperature of the process fluid is $T_{m,i} = 20°\text{C}$, 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.

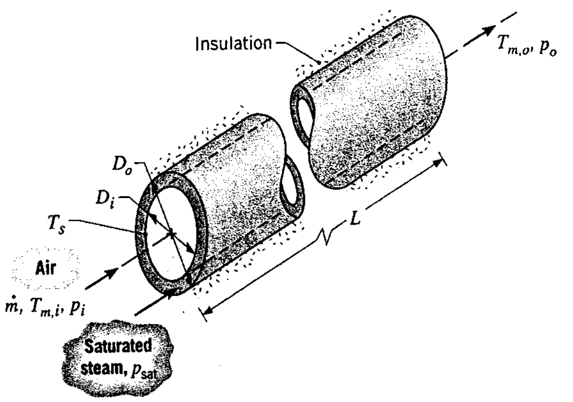
(b) Do you expect $T_{m,o}$ to increase or decrease if combined thermal and hydrodynamic entry conditions exist within the tube? Estimate the outlet temperature of the water for this condition.

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 $T_s = 15°\text{C}$.

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

$\boxed{\text{(b)}}$ 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 $T_{m,i} = 17°\text{C}$, 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 ($k_{\text{ins}} = 0.125\ \text{W/m} \cdot \text{K}$) 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.

Cooling water flows through the 25.4-mm-diameter thin-walled tubes of a steam condenser at 1 m/s, and a surface temperature of 350 K is maintained by the condensing steam. The water inlet temperature is 290 K, and the tubes are 5 m long.

(a) What is the water outlet temperature? Evaluate water properties at an assumed average mean temperature, $\overline{T}_m = 300$ K.

(b) Was the assumed value for $\overline{T}_m$ reasonable? If not, repeat the calculation using properties evaluated at a more appropriate temperature.

(c) A range of tube lengths from 4 to 7 m is available to the engineer designing this condenser. Generate a plot to show what coolant mean velocities are possible if the water outlet temperature is to remain at the value found for part (b). All other conditions remain the same.

The air passage for cooling a gas turbine vane can be approximated as a tube of 3-mm diameter and 75-mm length. The operating temperature of the vane is 650°C, and air enters the tube at 427°C.

(a) For an air flow rate of 0.18 kg/h, calculate the air outlet temperature and the heat removed from the vane.

(b) Generate a plot of the air outlet temperature as a function of flow rate for $0.1 \le \dot{m} \le 0.6$ kg/h. Compare this result with those for vanes having 2- and 4-mm-diameter tubes, with all other conditions remaining the same.

The core of a high-temperature, gas-cooled nuclear reactor has coolant tubes of 20-mm diameter and 780-mm length. Helium enters at 600 K and exits at 1000 K when the flow rate is 8×10^{-3} kg/s per tube.

(a) Determine the uniform tube wall surface temperature for these conditions.

(b) If the coolant gas is air, determine the required flow rate if the heat removal rate and tube wall surface temperature remain the same. What is the outlet temperature of the air?

Air at 200 kPa enters a 2-m-long, thin-walled tube of 25-mm diameter at 150°C and 6 m/s. Steam at 20 bars condenses on the outer surface.

(a) Determine the outlet temperature and pressure drop of the air, as well as the rate of heat transfer to the air.

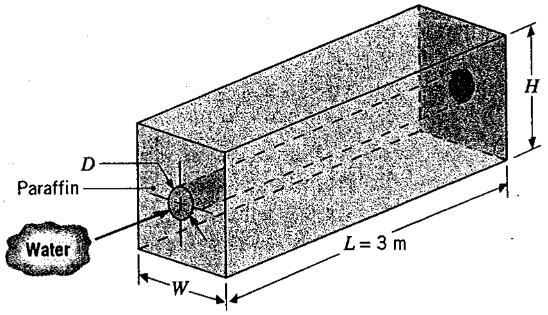
(b) Calculate the parameters of part (a) if the pressure of the air is doubled.

Heated air required for a food-drying process is generated by passing ambient air at 20°C through long, circular tubes ($D = 50$ mm, $L = 5$ m) housed in a steam condenser. Saturated steam at atmospheric pressure condenses on the outer surface of the tubes, maintaining a uniform surface temperature of 100°C.

(a) If an air flow rate of 0.01 kg/s is maintained in each tube, determine the air outlet temperature $T_{m,o}$ and the total heat rate q for the tube.

(b) The air outlet temperature may be controlled by adjusting the tube mass flow rate. Compute and plot $T_{m,o}$ as a function of $\dot{m}$ for $0.005 \le \dot{m} \le 0.050$ kg/s. If a particular drying process requires approximately 1 kg/s of air at 75°C, what design and operating conditions should be prescribed for the air heater, subject to the constraint that the tube diameter and length be fixed at 50 mm and 5 m, respectively?

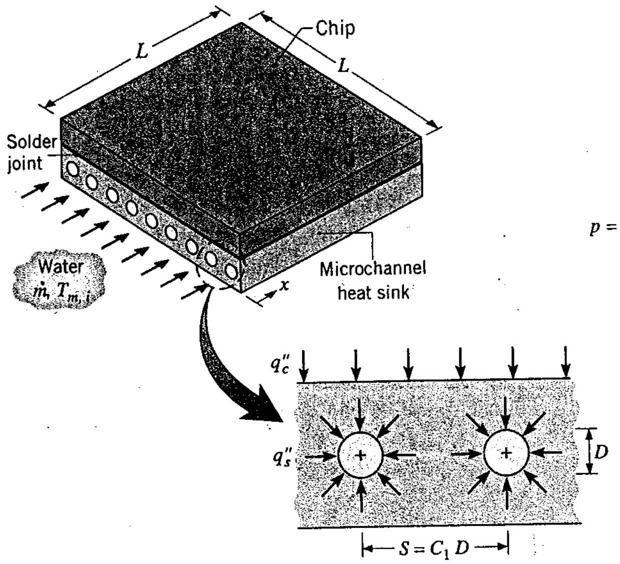
8.47 Consider a horizontal, thin-walled circular tube of diameter $D = 0.025$ m submerged in a container of n-octadecane (paraffin), which is used to store thermal energy. As hot water flows through the tube, heat is transferred to the paraffin, converting it from the solid to liquid state at the phase change temperature of $T_\infty = 27.4°\text{C}$. The latent heat of fusion and density of paraffin are $h_{sf} = 244$ kJ/kg and $\rho = 770$ kg/m^3, respectively, and thermophysical properties of the water may be taken as $c_p = 4.185$ kJ/kg · K, $k = 0.653$ W/m · K, $\mu = 467 \times 10^{-6}$ kg/s · m, and $Pr = 2.99$.



(a) Assuming the tube surface to have a uniform temperature corresponding to that of the phase change, determine the water outlet temperature and total heat transfer rate for a water flow rate of 0.1 kg/s and an inlet temperature of 60°C. If $H = W = 0.25$ m, how long would it take to completely liquefy the paraffin, from an initial state for which all the paraffin is solid and at 27.4°C?

(b) The liquefaction process can be accelerated by increasing the flow rate of the water. Compute and plot the heat rate and outlet temperature as a function of flow rate for $0.1 \le \dot{m} \le 0.5$ kg/s. How long would it take to melt the paraffin for $\dot{m} = 0.5$ kg/s?

8.48 A common procedure for cooling a high-performance computer chip involves joining the chip to a heat sink within which circular microchannels are machined. During operation, the chip produces a uniform heat flux q''_c at its interface with the heat sink, while a liquid coolant (water) is routed through the channels. Consider a square chip and heat sink, each $L \times L$ on a side, with microchannels of diameter D and pitch $S = C_1 D$, where the constant C_1 is greater than unity. Water is supplied at an inlet temperature $T_{m,i}$ and a total mass flow rate $\dot{m}$ (for the entire heat sink).

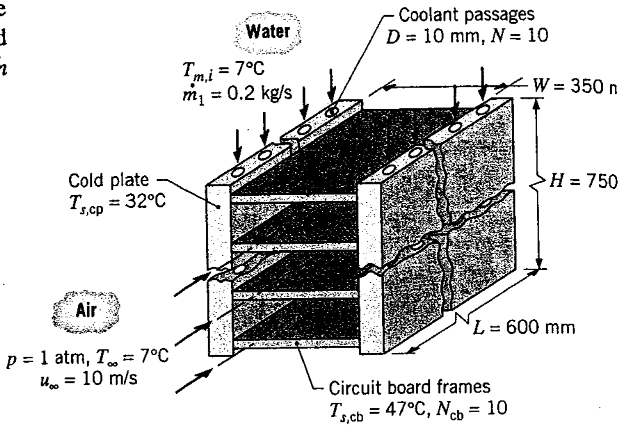


(a) Assuming that q''_c is dispersed in the heat sink such that a uniform heat flux q''_s is maintained at the surface of each channel, obtain expressions for the longitudinal distributions of the mean fluid, $T_m(x)$, and surface, $T_s(x)$, temperatures in each channel. Assume laminar, fully developed flow throughout each channel, and express your results in terms of $\dot{m}$, q''_c, C_1, D, and/or L, as well as appropriate thermophysical properties.

(b) For $L = 12$ mm, $D = 1$ mm, $C_1 = 2$, $q''_c = 20$ W/cm², $\dot{m} = 0.010$ kg/s, and $T_{m,i} = 290$ K, compute and plot the temperature distributions $T_m(x)$ and $T_s(x)$.

(c) A common objective in designing such heat sinks is to maximize q''_c while maintaining the heat sink at an acceptable temperature. Subject to prescribed values of $L = 12$ mm and $T_{m,i} = 290$ K and the constraint that $T_{s,\max} \leq 50°C$, explore the effect on q''_c of variations in heat sink design and operating conditions.

8.49 One way to cool chips mounted on the circuit boards of a computer is to encapsulate the boards in metal frames that provide efficient pathways for conduction to supporting *cold plates*. Heat generated by the chips is then dissipated by transfer to water flowing through passages drilled in the plates. Because the plates are made from a metal of large thermal conductivity (typically aluminium or copper), they may be assumed to be at a temperature, $T_{s,\text{cp}}$.



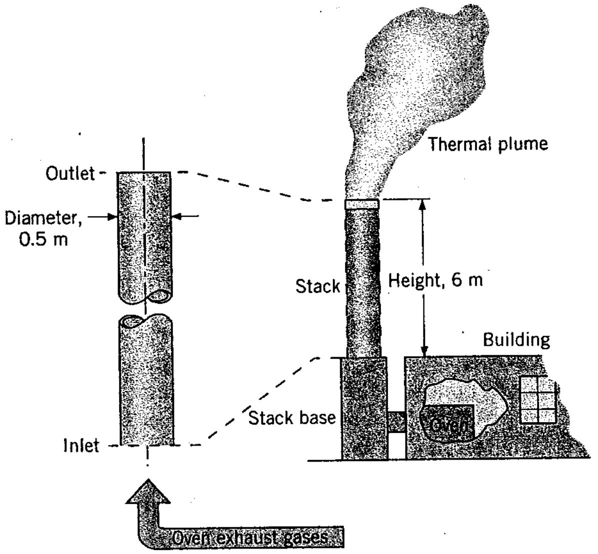
(a) Consider circuit boards attached to cold plates of height $H = 750$ mm and width $L = 600$ mm, each with $N = 10$ holes of diameter $D = 10$ mm. If operating conditions maintain plate temperatures of $T_{s,\text{cp}} = 32°C$ with water flow at $\dot{m}_1 = 0.2$ kg/s per passage and $T_{m,i} = 7°C$, how much heat may be dissipated by the circuit boards?

(b) To enhance cooling, thereby allowing increased power generation without an attendant increase in system temperatures, a hybrid cooling scheme may be used. The scheme involves forced air flow ove the encapsulated circuit boards, as well as wate flow through the cold plates. Consider condition for which $N_{\text{cb}} = 10$ circuit boards of widt $W = 350$ mm are attached to the cold plates and their average surface temperature is $T_{s,\text{cb}} = 47°C$ when $T_{s,\text{cp}} = 32°C$. If air is in parallel flow over the plates with $u_\infty = 10$ m/s and $T_\infty = 7°C$, how muc of the heat generated by the circuit boards is transferred to the air?

8.50 Refrigerant-134a is being transported at 0.1 kg/ through a Teflon tube of inside diameter $D_i = 25$ m and outside diameter $D_o = 28$ mm, while atmospheri air at $V = 25$ m/s and 300 K is in cross flow over th tube. What is the heat transfer per unit length of tube t Refrigerant-134a at 240 K?

8.51 Oil at 150°C flows *slowly* through a long, thin-walle pipe of 30-mm inner diameter. The pipe is suspende in a room for which the air temperature is 20°C an the convection coefficient at the outer tube surface is 1 W/m² · K. Estimate the heat loss per unit length of tube.

8.52 Exhaust gases from a wire processing oven are discharged into a tall stack, and the gas and stack surface temperatures at the outlet of the stack must be estimated. Knowledge of the outlet gas temperature $T_{m,o}$ is useful for predicting the dispersion of effluents in the thermal plume, while knowledge of the outlet stack surface temperature $T_{s,o}$ indicates whether condensation of the gas products will occur. The thin-walled, cylindrical stack is 0.5 m in diameter and 6.0 m high. The exhaust gas flow rate is 0.5 kg/s, and the inlet temperature is 600°C.

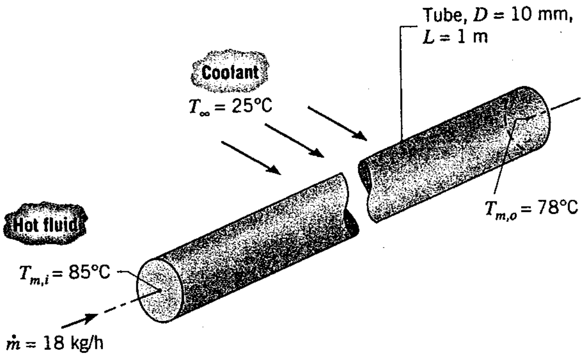


(a) Consider conditions for which the ambient air temperature and wind velocity are 4°C and 5 m/s, respectively. Approximating the thermophysical properties of the gas as those of atmospheric air, estimate the outlet gas and stack surface temperatures for the given conditions.

(b) The gas outlet temperature is sensitive to variations in the ambient air temperature and wind velocity. For $T_\infty = -25°C$, 5°C, and 35°C, compute and plot the gas outlet temperature as a function of wind velocity for $2 \leq V \leq 10$ m/s.

8.53 A hot fluid passes through a thin-walled tube of 10-mm diameter and 1-m length, and a coolant at $T_\infty = 25°C$ is in cross flow over the tube. When the flow rate is $\dot{m} = 18$ kg/h and the inlet temperature is $T_{m,i} = 85°C$, the outlet temperature is $T_{m,o} = 78°C$.

Assuming fully developed flow and thermal conditions in the tube, determine the outlet temperature, $T_{m,o}$, if the flow rate is increased by a factor of 2. That is, $\dot{m} = 36$ kg/h, with all other conditions the same. The thermophysical properties of the hot fluid are $\rho = 1079$ kg/m^3, $c_p = 2637$ J/kg · K, $\mu = 0.0034$ N · s/m^2, and $k = 0.261$ W/m · K.



8.54 Consider a thin-walled tube of 10-mm diameter and 2-m length. Water enters the tube from a large reservoir at $\dot{m} = 0.2$ kg/s and $T_{m,i} = 47°C$.

(a) If the tube surface is maintained at a uniform temperature of 27°C, what is the outlet temperature of the water, $T_{m,o}$? To obtain the properties of water, assume an average mean temperature of $\overline{T}_m = 300$ K.

(b) What is the exit temperature of the water if it is heated by passing air at $T_\infty = 100°C$ and $V = 10$ m/s in cross flow over the tube? The properties of air may be evaluated at an assumed film temperature of $T_f = 350$ K.

(c) In the foregoing calculations, were the assumed values of $\overline{T}_m$ and T_f appropriate? If not, use properly evaluated properties and recompute $T_{m,o}$ for the conditions of part (b).

8.55 Water at a flow rate of $\dot{m} = 0.215$ kg/s is cooled from 70°C to 30°C by passing it through a thin-walled tube of diameter $D = 50$ mm and maintaining a coolant at $T_\infty = 15°C$ in cross flow over the tube.

(a) What is the required tube length if the coolant is air and its velocity is $V = 20$ m/s?

(b) What is the tube length if the coolant is water and $V = 2$ m/s?

8.56 Consider a thin-walled, metallic tube of length $L = 1$ m and inside diameter $D_i = 3$ mm. Water enters the tube at $\dot{m} = 0.015$ kg/s and $T_{m,i} = 97°C$.

(a) What is the outlet temperature of the water if the tube surface temperature is maintained at 27°C?

(b) If a 0.5-mm-thick layer of insulation of $k = 0.05$ W/m · K is applied to the tube and its outer surface is maintained at 27°C, what is the outlet temperature of the water?

(c) If the outer surface of the insulation is no longer maintained at 27°C but is allowed to exchange heat

3 Fluid enters a thin-walled tube of 5-mm diameter and 2-m length with a flow rate of 0.04 kg/s and a temperature of $T_{m,i} = 85°C$. The tube surface is maintained at a temperature of $T_s = 25°C$, and for this operating condition, the outlet temperature is $T_{m,o} = 31.1°C$. What is the outlet temperature if the flow rate is doubled? Fully developed, turbulent flow may be assumed to exist in both cases, and the fluid properties may be assumed to be independent of temperature.

oncircular Ducts

74 Air at 3×10^{-4} kg/s and 27°C enters a rectangular duct that is 1 m long and 4 mm by 16 mm on a side. A uniform heat flux of 600 W/m^2 is imposed on the duct surface. What is the temperature of the air and of the duct surface at the outlet?

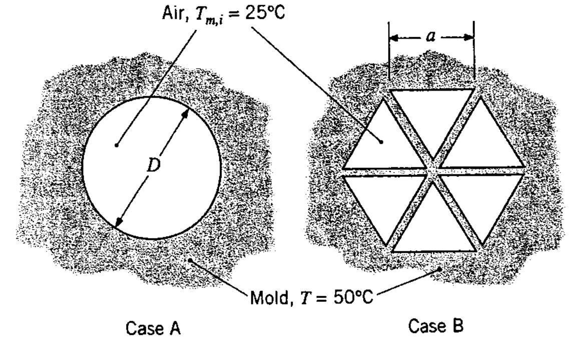
75 Air at 4×10^{-4} kg/s and 27°C enters a triangular duct that is 20 mm on a side and 2 m long. The duct surface is maintained at 100°C. Assuming fully developed flow throughout the duct, determine the air outlet temperature.

76 Air at 25°C flows at 30×10^{-6} kg/s within 100-mm-long channels used to cool a high thermal conductivity metal mold. Assume the flow is hydrodynamically and thermally fully developed.

(a) Determine the heat transferred to the air for a circular channel (D = 10 mm) when the mold temperature is 50°C (case A).

(b) Using new manufacturing methods (see Problem 8.99), channels of complex cross section can be readily fabricated within metal objects, such as molds. Consider air flowing under the same conditions as in case A, except now the channel is segmented into six smaller triangular sections. The flow area of case A is equal to the total flow area of case B. Determine the heat transferred to the air for the segmented channel.

(c) Compare the pressure drops for cases A and B.



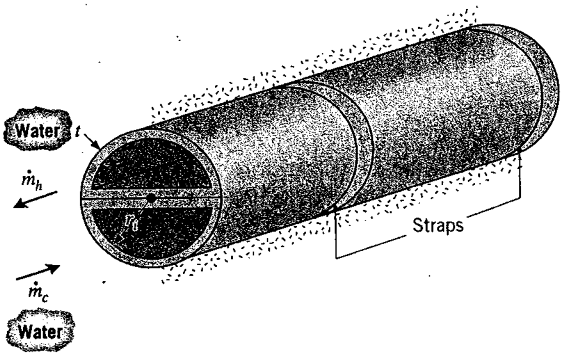
8.77 A device that recovers heat from high-temperature combustion products involves passing the combustion gas between parallel plates, each of which is maintained at 350 K by water flow on the opposite surface. The plate separation is 40 mm, and the gas flow is fully developed. The gas may be assumed to have the properties of atmospheric air, and its mean temperature and velocity are 1000 K and 60 m/s, respectively.

(a) What is the heat flux at the plate surface?

(b) If a third plate, 20 mm thick, is suspended midway between the original plates, what is the surface heat flux for the original plates? Assume the temperature and *flow rate* of the gas to be unchanged and radiation effects to be negligible.

8.78 Air at 1 atm and 285 K enters a 2-m-long rectangular duct with cross section 75 mm by 150 mm. The duct is maintained at a constant surface temperature of 400 K, and the air mass flow rate is 0.10 kg/s. Determine the heat transfer rate from the duct to the air and the air outlet temperature.

8.79 A double-wall heat exchanger is used to transfer heat between liquids flowing through semicircular copper tubes. Each tube has a wall thickness of t = 3 mm and an inner radius of r_i = 20 mm, and good contact is maintained at the plane surfaces by tightly wound straps. The tube outer surfaces are well insulated.



(a) If hot and cold water at mean temperatures of $T_{h,m}$ = 330 K and $T_{c,m}$ = 290 K flow through the adjoining tubes at $\dot{m}_h = \dot{m}_c$ = 0.2 kg/s, what is the rate of heat transfer per unit length of tube? The wall contact resistance is 10^{-5} m$^2 \cdot$ K/W. Approximate the properties of both the hot and cold water as $\mu = 800 \times 10^{-6}$ kg/s $\cdot$ m, k = 0.625 W/m $\cdot$ K, and Pr = 5.35. *Hint*: Heat transfer is enhanced by conduction through the semicircular portions of the tube walls, and each portion may be subdivided into two straight fins with adiabatic tips.

(b) Using the thermal model developed for part (a), determine the heat transfer rate per unit length