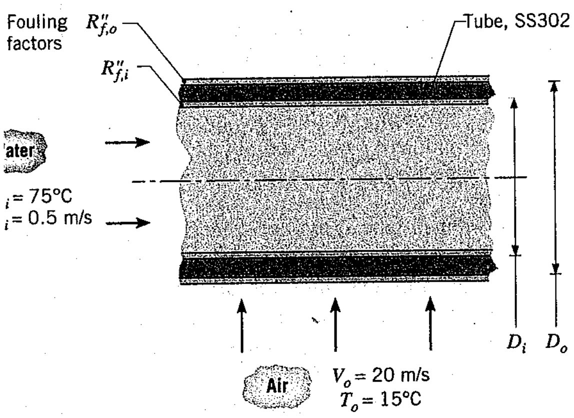
roblems

erall Heat Transfer Coefficient

1 In a fire-tube boiler, hot products of combustion flowing through an array of thin-walled tubes are used to boil water flowing over the tubes. At the time of installation, the overall heat transfer coefficient was 400 $W/m^2 \cdot K$. After 1 year of use, the inner and outer tube surfaces are fouled, with corresponding fouling factors of $R''_{f,i} = 0.0015$ and $R''_{f,o} = 0.0005\ m^2 \cdot K/W$, respectively. Should the boiler be scheduled for cleaning of the tube surfaces?

.2 A type-302 stainless steel tube of inner and outer diameters $D_i = 22$ mm and $D_o = 27$ mm, respectively, is used in a cross-flow heat exchanger. The fouling factors, R''_f, for the inner and outer surfaces are estimated to be 0.0004 and 0.0002 $m^2 \cdot K/W$, respectively.



(a) Determine the overall heat transfer coefficient based on the outside area of the tube, U_o. Compare the thermal resistances due to convection, tube wall conduction, and fouling.

(b) Instead of air flowing over the tube, consider a situation for which the cross-flow fluid is water at 15°C with a velocity of $V_o = 1$ m/s. Determine the overall heat transfer coefficient based on the outside area of the tube, U_o. Compare the thermal resistances due to convection, tube wall conduction, and fouling.

(c) For the water–air conditions of part (a) and mean velocities, $u_{m,i}$, of 0.2, 0.5, and 1.0 m/s, plot the overall heat transfer coefficient as a function of the cross-flow velocity for $5 \le V_o \le 30$ m/s.

(d) For the water–water conditions of part (b) and cross-flow velocities, V_o, of 1, 3, and 8 m/s, plot the overall heat transfer coefficient as a function of the mean velocity for $0.5 \le u_{m,i} \le 2.5$ m/s.

11.3 A shell-and-tube heat exchanger is to heat an acidic liquid that flows in unfinned tubes of inside and outside diameters $D_i = 10$ mm and $D_o = 11$ mm, respectively. A hot gas flows on the shell side. To avoid corrosion of the tube material, the engineer may specify either a Ni-Cr-Mo corrosion-resistant metal alloy ($\rho_m = 8900\ kg/m^3$, $k_m = 8\ W/m \cdot K$) or a polyvinylidene fluoride (PVDF) plastic ($\rho_p = 1780\ kg/m^3$, $k_p = 0.17\ W/m \cdot K$). The inner and outer heat transfer coefficients are $h_i = 1500\ W/m^2 \cdot K$ and $h_o = 200\ W/m^2 \cdot K$, respectively.

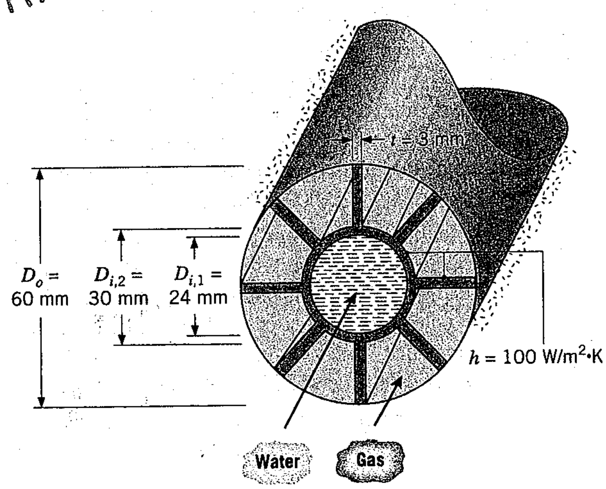
(a) Determine the ratio of plastic to metal tube surface areas needed to transfer the same amount of heat.

(b) Determine the ratio of plastic to metal mass associated with the two heat exchanger designs.

(c) The cost of the metal alloy per unit mass is three times that of the plastic. Determine which tube material should be specified on the basis of cost.

11.4 A steel tube ($k = 50\ W/m \cdot K$) of inner and outer diameters $D_i = 20$ mm and $D_o = 26$ mm, respectively, is used to transfer heat from hot gases flowing over the tube ($h_h = 200\ W/m^2 \cdot K$) to cold water flowing through the tube ($h_c = 8000\ W/m^2 \cdot K$). What is the cold-side overall heat transfer coefficient U_c? To enhance heat transfer, 16 straight fins of rectangular profile are installed longitudinally along the outer surface of the tube. The fins are equally spaced around the circumference of the tube, each having a thickness of 2 mm and a length of 15 mm. What is the corresponding overall heat transfer coefficient U_c?

11.5 A heat recovery device involves transferring energy from the hot flue gases passing through an annular



(e) What would be the effectiveness of this exchanger if its length were made very large?

11.19 For a senior project, a student was given the assignment to design a heat exchanger that meets the following specifications:

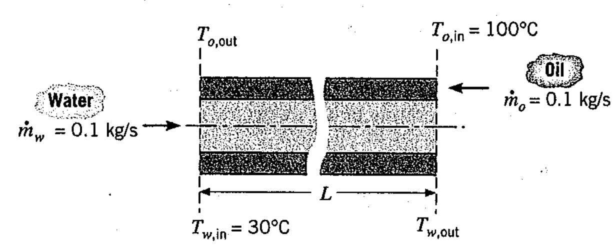
	$\dot{m}$ (kg/s)	$T_{m,i}$ (°C)	$T_{m,o}$ (°C)
Hot water	28	90	—
Cold water	27	34	60

Like many real-world situations, the customer hasn't revealed, or doesn't know, additional requirements that would allow you to proceed directly to a final configuration. At the outset, it is helpful to make a first-cut design based upon simplifying assumptions, which can be evaluated to determine what additional requirements and trade-offs should be considered by the customer.

(a) Design a heat exchanger to meet the foregoing specifications. List and explain your assumptions. *Hint:* Begin by finding the required value for *UA* and using representative values of *U* to determine *A*.

(b) Evaluate your design by identifying what features and configurations could be explored with your customer in order to develop more complete specifications.

11.20 A concentric tube heat exchanger for cooling lubricating oil is comprised of a thin-walled inner tube of 25-mm diameter carrying water and an outer tube of 45-mm diameter carrying the oil. The exchanger operates in counterflow with an overall heat transfer coefficient of 60 W/m² · K and the tabulated average properties.



Properties	Water	Oil
ρ (kg/m³)	1000	800
c_p (J/kg · K)	4200	1900
ν (m²/s)	7×10^{-7}	1×10^{-5}
k (W/m · K)	0.64	0.134
Pr	4.7	140

(a) If the outlet temperature of the oil is 60°C, determine the total heat transfer and the outlet temperature of the water.

(b) Determine the length required for the heat exchanger.

11.21 A counterflow, concentric tube heat exchanger used for engine cooling has been in service for an extended period of time. The heat transfer surface area of the exchanger is 5 m², and the *design value* of the overall convection coefficient is 38 W/m² · K. During a test run, engine oil flowing at 0.1 kg/s is cooled from 110°C to 66°C by water supplied at a temperature of 25°C and a flow rate of 0.2 kg/s. Determine whether fouling has occurred during the service period. If so, calculate the fouling factor, R''_f (m² · K/W).

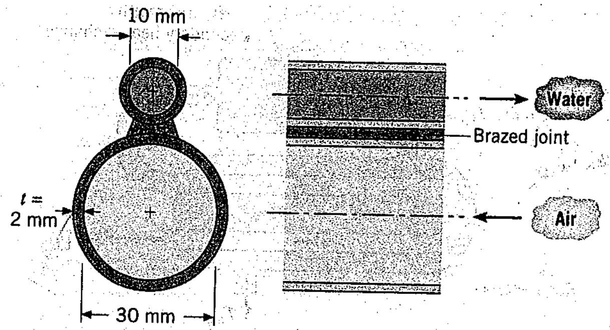
11.22 A shell-and-tube heat exchanger must be designed to heat 2.5 kg/s of water from 15 to 85°C. The heating is to be accomplished by passing hot engine oil, which is available at 160°C, through the shell side of the exchanger. The oil is known to provide an average convection coefficient of h_o = 400 W/m² · K on the outside of the tubes. Ten tubes pass the water through the shell. Each tube is thin walled, of diameter D = 25 mm, and makes eight passes through the shell. If the oil leaves the exchanger at 100°C, what is its flow rate? How long must the tubes be to accomplish the desired heating?

11.23 An automobile radiator may be viewed as a cross-flow heat exchanger with both fluids unmixed. Water, which has a flow rate of 0.05 kg/s, enters the radiator at 400 K and is to leave at 330 K. The water is cooled by air that enters at 0.75 kg/s and 300 K.

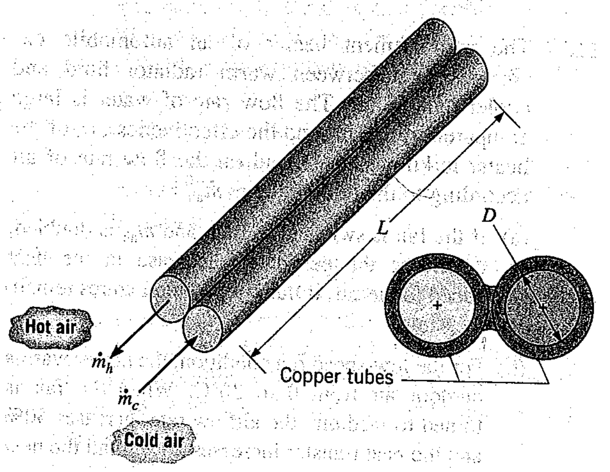
(a) If the overall heat transfer coefficient is 200 W/m² · K, what is the required heat transfer surface area?

(b) A manufacturing engineer claims ridges can be stamped on the finned surface of the exchanger, which could greatly increase the overall heat transfer coefficient. With all other conditions remaining the same and the heat transfer surface area determined from part (a), generate a plot of the air and water outlet temperatures as a function of U for $200 \le U \le 400$ W/m² · K. What benefits result from increasing the overall convection coefficient for this application?

11.24 Hot air for a large-scale drying operation is to be produced by routing the air over a tube bank (unmixed), while products of combustion are routed through the tubes. The surface area of the cross-flow heat exchanger is A = 25 m², and for the proposed operating conditions, the manufacturer specifies an overall heat transfer coefficient of U = 35 W/m² · K. The air



11.29 A twin-tube, counterflow heat exchanger operates with balanced flow rates of 0.003 kg/s for the hot and cold airstreams. The cold stream enters at 280 K and must be heated to 340 K using hot air at 360 K. The average pressure of the airstreams is 1 atm and the maximum allowable pressure drop for the cold air is 10 kPa. The tube walls may be assumed to act as fins, each with an efficiency of 100%.



(a) Determine the tube diameter D and length L that satisfy the prescribed heat transfer and pressure drop requirements.

(b) For the diameter D and length L found in part (a), generate plots of the cold stream outlet temperature, the heat transfer rate, and pressure drop as a function of balanced flow rates in the range from 0.002 to 0.004 kg/s. Comment on your results.

11.30 A 5-m-long, twin-tube, counterflow heat exchanger, such as that illustrated in Problem 11.29, is used to heat air for a drying operation. Each tube is made from plain carbon steel ($k = 60$ W/m · K) and has an inner diameter and wall thickness of 50 mm and 4 mm, respectively. The thermal resistance per unit length of the brazed joint connecting the tubes is $R'_t = 0.01$ m · K/W. Consider conditions for which air enters one tube at a pressure of 5 atm, a temperature of 17°C, and flow rate of 0.030 kg/s, while saturated steam at 2.455 bar condenses in the other tube. The convection coefficient for condensation may be approximated as 5000 W/m² · K. What is the air outlet temperature? What is the mass rate at which condensate leaves the system? *Hint*: Account for the effects of circumferential conduction in the tubes by treating them as extended surfaces.

11.31 Hot water for an industrial washing operation is produced by recovering heat from the flue gases of a furnace. A cross-flow heat exchanger is used, with the gases passing over the tubes and the water making a single pass through the tubes. The steel tubes ($k = 60$ W/m · K) have inner and outer diameters of $D_i = 15$ mm and $D_o = 20$ mm, while the staggered tube array has longitudinal and transverse pitches of $S_T = S_L = 40$ mm. The plenum in which the array is installed has a width (corresponding to the tube length) of $W = 2$ m and a height (normal to the tube axis) of $H = 1.2$ m. The number of tubes in the transverse plane is therefore $N_T \approx H/S_T = 30$. The gas properties may be approximated as those of atmospheric air, and the convection coefficient associated with water flow in the tubes may be approximated as 3000 W/m² · K.

(a) If 50 kg/s of water are to be heated from 290 to 350 K by 40 kg/s of flue gases entering the exchanger at 700 K, what is the gas outlet temperature and how many tube rows N_L are required?

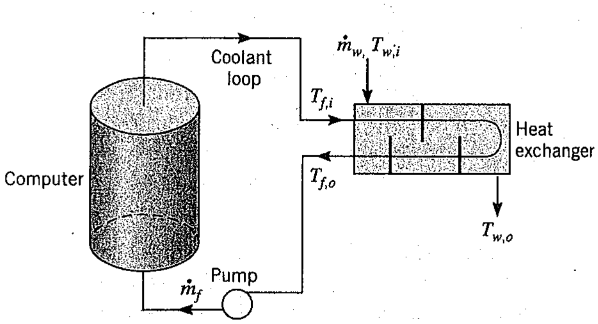
(b) The water outlet temperature may be controlled by varying the gas flow rate and/or inlet temperature. For the value of N_L determined in part (a) and the prescribed values of H, W, S_T, $\dot{m}_c$, and $T_{c,i}$, compute and plot $T_{c,o}$ as a function of $\dot{m}_h$ over the range $20 \le \dot{m}_h \le 40$ kg/s for values of $T_{h,i} = 500$, 600, and 700 K. Also plot the corresponding variations of $T_{h,o}$. If $T_{h,o}$ must not drop below 400 K to prevent condensation of corrosive vapors on the heat exchanger surfaces, are there any constraints on $\dot{m}_h$ and $T_{h,i}$?

11.32 A single-pass, cross-flow heat exchanger uses hot exhaust gases (mixed) to heat water (unmixed) from 30 to 80°C at a rate of 3 kg/s. The exhaust gases, having thermophysical properties similar to air, enter and exit the exchanger at 225 and 100°C, respectively. If the overall heat transfer coefficient is 200 W/m² · K, estimate the required surface area.

11.33 Consider the fluid conditions and overall heat transfer coefficient of Problem 11.32 for a concentric tube heat exchanger operating in parallel flow. The thin-walled separator tube has a diameter of 100 mm.

flow rate for $5000 \leq \dot{m}_c \leq 15{,}000$ kg/h, with all other conditions remaining the same.

11.45 In a supercomputer, signal propagation delays are reduced by resorting to high-density circuit arrangements which are cooled by immersing them in a special dielectric liquid. The fluid is pumped in a closed loop through the computer and an adjoining shell-and-tube heat exchanger having one shell and two tube passes.



During normal operation, heat generated within the computer is transferred to the dielectric fluid passing through the computer at a flow rate of $\dot{m}_f = 4.81$ kg/s. In turn, the fluid passes through the tubes of the heat exchanger and the heat is transferred to water passing over the tubes. The dielectric fluid may be assumed to have constant properties of $c_p = 1040$ J/kg · K, $\mu = 7.65 \times 10^{-4}$ kg/s · m, $k = 0.058$ W/m · K, and $Pr = 14$. During normal operation, chilled water at a flow rate of $\dot{m}_w = 2.5$ kg/s and an inlet temperature of $T_{w,i} = 5°C$ passes over the tubes. The water has a specific heat of 4200 J/kg · K and provides an average convection coefficient of 10,000 W/m^2 · K over the outer surface of the tubes.

(a) If the heat exchanger consists of 72 thin-walled tubes, each of 10-mm diameter, and fully developed flow is assumed to exist within the tubes, what is the convection coefficient associated with flow through the tubes?

(b) If the dielectric fluid enters the heat exchanger at $T_{f,i} = 25°C$ and is to leave at $T_{f,o} = 15°C$, what is the required tube length per pass?

(c) For the exchanger with the tube length per pass determined in part (b), plot the outlet temperature of the dielectric fluid as a function of its flow rate for $4 \leq \dot{m}_f \leq 6$ kg/s. Account for corresponding changes in the overall heat transfer coefficient, but assume all other conditions to remain the same.

(d) The site specialist for the computer facilities is concerned about changes in the performance of the water chiller supplying the cold water ($\dot{m}_w$, $T_{w,i}$) and their effect on the outlet temperature $T_{f,o}$ of the dielectric fluid. With all other conditions remaining the same, determine the effect of a ±10% change in the cold water flow rate on $T_{f,o}$.

(e) Repeat the performance analysis of part (d) to determine the effect of a ±3°C change in the water inlet temperature on $T_{f,o}$, with all other conditions remaining the same.

11.46 A shell-and-tube heat exchanger consists of 135 thin-walled tubes in a double-pass arrangement, each of 12.5-mm diameter with a total surface area of 47.5 m^2. Water (the tube-side fluid) enters the heat exchanger at 15°C and 6.5 kg/s and is heated by exhaust gas entering at 200°C and 5 kg/s. The gas may be assumed to have the properties of atmospheric air, and the overall heat transfer coefficient is approximately 200 W/m^2 · K.

(a) What are the gas and water outlet temperatures?

(b) Assuming fully developed flow, what is the tube-side convection coefficient?

(c) With all other conditions remaining the same, plot the effectiveness and fluid outlet temperatures as a function of the water flow rate over the range from 6 to 12 kg/s.

(d) What gas inlet temperature is required for the exchanger to supply 10 kg/s of hot water at an outlet temperature of 42°C, all other conditions remaining the same? What is the effectiveness for this operating condition?

11.47 An ocean thermal energy conversion system is being proposed for electric power generation. Such a system is based on the standard power cycle for which the working fluid is evaporated, passed through a turbine, and subsequently condensed. The system is to be used in very special locations for which the oceanic water temperature near the surface is approximately 300 K, while the temperature at reasonable depths is approximately 280 K. The warmer water is used as a heat source to evaporate the working fluid, while the colder water is used as a heat sink for condensation of the fluid. Consider a power plant that is to generate 2 MW of electricity at an efficiency (electric power output per heat input) of 3%. The evaporator is a heat exchanger consisting of a single shell with many tubes executing two passes. If the working fluid is evaporated at its phase change temperature of 290 K, with ocean water entering at 300 K and leaving at 292 K, what is the heat exchanger area required for the evaporator? What flow rate must be maintained for the water passing through the evaporator? The overall heat transfer coefficient may be approximated as 1200 W/m^2 · K.

As UA becomes very large, what are the asymptotic values for $T_{h,o}$ and $T_{c,o}$?

11.65 The floor space of any facility that houses shell-and-tube heat exchangers must be sufficiently large so the tube bundle can be serviced easily. A rule of thumb is that the floor space must be at least 2.5 times the length of the tube bundle so that the bundle can be completely removed from the shell (hence the absolute minimum floor space is twice the tube bundle length) and subsequently cleaned, repaired, or replaced easily (associated with the extra half bundle length floor space). The room in which the heat exchanger of Problem 11.22 is to be installed is 8 m long and, therefore, the 4.7-m-long heat exchanger is too large for the facility. Will a shell-and-tube heat exchanger with two shells, one above the other, be sufficiently small to fit into the facility? Each shell has 10 tubes and 8 tube passes.

11.66 Consider the influence of a finite sheet thickness in Example 11.2, when there are 40 gaps.

(a) Determine the exterior dimension, L, of the heat exchanger core for a sheet thickness of t = 0.8 mm for pure aluminum (k_{al} = 237 W/m · K) and polyvinylidene fluoride (PVDF, k_{pv} = 0.17 W/m · K) sheets. Neglect the thickness of the top and bottom exterior plates.

(b) Plot the heat exchanger core dimension as a function of the sheet thickness for aluminum and PVDF over the range $0 \leq t \leq 1$ mm.

11.67 Hot exhaust gases are used in a shell-and-tube exchanger to heat 2.5 kg/s of water from 35 to 85°C. The gases, assumed to have the properties of air, enter at 200°C and leave at 93°C. The overall heat transfer coefficient is 180 W/m² · K. Using the effectiveness–NTU method, calculate the area of the heat exchanger.

11.68 In open heart surgery under hypothermic conditions, the patient's blood is cooled before the surgery and rewarmed afterward. It is proposed that a concentric tube, counterflow heat exchanger of length 0.5 m be used for this purpose, with the thin-walled inner tube having a diameter of 55 mm. The specific heat of the blood is 3500 J/kg · K.

(a) If water at $T_{h,i}$ = 60°C and $\dot{m}_h$ = 0.10 kg/s is used to heat blood entering the exchanger at $T_{c,i}$ = 18°C and $\dot{m}_c$ = 0.05 kg/s, what is the temperature of the blood leaving the exchanger? The overall heat transfer coefficient is 500 W/m² · K.

(b) The surgeon may wish to control the heat rate q and the outlet temperature $T_{c,o}$ of the blood by altering the flow rate and/or inlet temperature of the water during the rewarming process. To assist in the development of an appropriate controller for the prescribed values of $\dot{m}_c$ and $T_{c,i}$, compute and plot q and $T_{c,o}$ as a function of $\dot{m}_h$ for $0.05 \leq \dot{m}_h \leq 0.20$ kg/s and values of $T_{h,i}$ = 50, 60, and 70°C. Since the dominant influence on the overall heat transfer coefficient is associated with the blood flow conditions, the value of U may be assumed to remain at 500 W/m² · K. Should certain operating conditions be excluded?

11.69 Ethylene glycol and water, at 60 and 10°C, respectively, enter a shell-and-tube heat exchanger for which the total heat transfer area is 15 m². With ethylene glycol and water flow rates of 2 and 5 kg/s, respectively, the overall heat transfer coefficient is 800 W/m² · K.

(a) Determine the rate of heat transfer and the fluid outlet temperatures.

(b) Assuming all other conditions to remain the same, plot the effectiveness and fluid outlet temperatures as a function of the flow rate of ethylene glycol for $0.5 \leq \dot{m}_h \leq 5$ kg/s.

HW

11.70 A boiler used to generate saturated steam is in the form of an unfinned, cross-flow heat exchanger, with water flowing through the tubes and a high-temperature gas in cross flow over the tubes. The gas, which has a specific heat of 1120 J/kg · K and a mass flow rate of 10 kg/s, enters the heat exchanger at 1400 K. The water, which has a flow rate of 3 kg/s, enters as saturated liquid at 450 K and leaves as saturated vapor at the same temperature. If the overall heat transfer coefficient is 50 W/m² · K and there are 500 tubes, each of 0.025-m diameter, what is the required tube length?

11.71 Waste heat from the exhaust gas of an industrial furnace is recovered by mounting a bank of unfinned tubes in the furnace stack. Pressurized water at a flow rate of 0.025 kg/s makes a single pass through *each* of the tubes, while the exhaust gas, which has an upstream velocity of 5.0 m/s, moves in cross flow over the tubes at 2.25 kg/s. The tube bank consists of a square array of 100 thin-walled tubes (10 × 10), each 25 mm in diameter and 4 m long. The tubes are aligned with a transverse pitch of 50 mm. The inlet temperatures of the water and the exhaust gas are 300 and 800 K, respectively. The water flow is fully developed, and the gas properties may be assumed to be those of atmospheric air.

(a) What is the overall heat transfer coefficient?

(b) What are the fluid outlet temperatures?

(c) Operation of the heat exchanger may vary according to the demand for hot water. For the prescribed