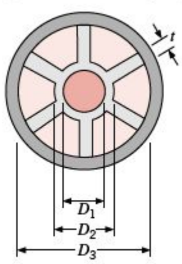
region to pressurized water flowing through the inner tube of the annulus. The inner tube has inner and outer diameters of 24 and 30 mm and is connected by eight struts to an insulated outer tube of 60-mm diameter. Each strut is 3 mm thick and is integrally fabricated with the inner tube from carbon steel ($k = 50\ W/m \cdot K$).

Consider conditions for which water at 300 K flows through the inner tube at 0.161 kg/s while flue gases at 800 K flow through the annulus, maintaining a convection coefficient of $100\ W/m^2 \cdot K$ on both the struts and the outer surface of the inner tube. What is the rate of heat transfer per unit length of tube from gas to the water?

11.6 A novel design for a condenser consists of a tube of thermal conductivity $200\ W/m \cdot K$ with longitudinal fins snugly fitted into a larger tube. Condensing refrigerant at 45°C flows axially through the inner tube, while water at a flow rate of 0.012 kg/s passes through the six channels around the inner tube. The pertinent diameters are $D_1 = 10$ mm, $D_2 = 14$ mm, and $D_3 = 50$ mm, while the fin thickness is $t = 2$ mm. Assume that the convection coefficient associated with the condensing refrigerant is extremely large.



Determine the heat removal rate per unit tube length in a section of the tube for which the water is at 15°C.

11.7 The condenser of a steam power plant contains $N = 1000$ brass tubes ($k_t = 110\ W/m \cdot K$), each of inner and outer diameters, $D_i = 25$ mm and $D_o = 28$ mm, respectively. Steam condensation on the outer surfaces of the tubes is characterized by a convection coefficient of $h_o = 10{,}000\ W/m^2 \cdot K$.

(a) If cooling water from a large lake is pumped through the condenser tubes at $\dot{m}_c = 400$ kg/s, what is the overall heat transfer coefficient U_o based on the outer surface area of a tube? Properties of the water may be approximated as $\mu = 9.60 \times 10^{-4}\ N \cdot s/m^2$, $k = 0.60\ W/m \cdot K$, and $Pr = 6.6$.

(b) If, after extended operation, fouling provides a resistance of $R''_{f,i} = 10^{-4}\ m^2 \cdot K/W$, at the inner surface, what is the value of U_o?

(c) If water is extracted from the lake at 15°C and 10 kg/s of steam at 0.0622 bars are to be condensed, what is the corresponding temperature of the water leaving the condenser? The specific heat of the water is $4180\ J/kg \cdot K$.

11.8 Thin-walled aluminum tubes of diameter $D = 10$ mm are used in the condenser of an air conditioner. Under normal operating conditions, a convection coefficient of $h_i = 5000\ W/m^2 \cdot K$ is associated with condensation on the inner surface of the tubes, while a coefficient of $h_o = 100\ W/m^2 \cdot K$ is maintained by airflow over the tubes.

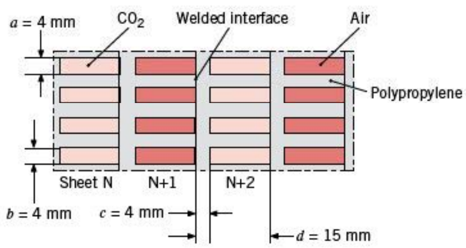
(a) What is the overall heat transfer coefficient if the tubes are unfinned?

(b) What is the overall heat transfer coefficient based on the inner surface, U_i, if aluminum annular fins of thickness $t = 1.5$ mm, outer diameter $D_o = 20$ mm, and pitch $S = 3.5$ mm are added to the outer surface? Base your calculations on a 1-m-long section of tube. Subject to the requirements that $t \geq 1$ mm and $(S - t) \geq 1.5$ mm, explore the effect of variations in t and S on U_i. What combination of t and S would yield the best heat transfer performance?

11.9 A finned-tube, cross-flow heat exchanger is to use the exhaust of a gas turbine to heat pressurized water. Laboratory measurements are performed on a prototype version of the exchanger, which has a surface area of $10\ m^2$, to determine the overall heat transfer coefficient as a function of operating conditions. Measurements made under particular conditions, for which $\dot{m}_h = 2$ kg/s, $T_{h,i} = 325°C$, $\dot{m}_c = 0.5$ kg/s, and $T_{c,i} = 25°C$, reveal a water outlet temperature of $T_{c,o} = 150°C$. What is the overall heat transfer coefficient of the exchanger?

11.10 Water at a rate of 45,500 kg/h is heated from 80 to 150°C in a heat exchanger having two shell passes and eight tube passes with a total surface area of $925\ m^2$. Hot exhaust gases having approximately the same thermophysical properties as air enter at 350°C and exit at 175°C. Determine the overall heat transfer coefficient.

11.11 A novel heat exchanger concept consists of a large number of extruded polypropylene sheets ($k = 0.17\ W/m \cdot K$), each having a fin-like geometry, that are subsequently stacked and melted together to form the heat exchanger core. Besides being inexpensive, the heat exchanger can be easily recycled at the end of its life. Carbon dioxide at a mean temperature of 10°C and pressure of 2 atm flows in the cool channels at a mean velocity of $u_m = 0.1$ m/s. Air at 30°C and 2 atm flows at 0.2 m/s in the warm channels. Neglecting the thermal contact resistance at the welded interface, determine the product of the overall heat transfer coefficient and heat transfer area, *UA*, for a heat exchanger core consisting of 200 cool channels and 200 warm channels.



Design and Performance Calculations

11.12 The properties and flow rates for the hot and cold fluids of a heat exchanger are shown in the following table. Which fluid limits the heat transfer rate of the exchanger? Explain your choice.

	Hot fluid	Cold fluid
Density, kg/m^3	997	1247
Specific heat, J/kg · K	4179	2564
Thermal conductivity, W/m · K	0.613	0.287
Viscosity, N · s/m^2	8.55×10^{-4}	1.68×10^{-4}
Flow rate, m^3/h	14	16

11.13 A process fluid having a specific heat of 3500 J/kg · K and flowing at 2 kg/s is to be cooled from 80°C to 50°C with chilled water, which is supplied at a temperature of 15°C and a flow rate of 2.5 kg/s. Assuming an overall heat transfer coefficient of 2000 W/m^2 · K, calculate the required heat transfer areas for the following exchanger configurations: (a) parallel flow, (b) counterflow, (c) shell-and-tube, one shell pass and 2 tube passes, and (d) cross-flow, single pass, both fluids unmixed. Compare the results of your analysis. Your work can be reduced by using the *Tools/Heat Exchanger* models of *IHT*.

11.14 A shell-and-tube exchanger (two shells, four tube passes) is used to heat 10,000 kg/h of pressurized water from 35 to 120°C with 5000 kg/h pressurized water entering the exchanger at 300°C. If the overall heat transfer coefficient is 1500 W/m^2 · K, determine the required heat exchanger area.

11.15 Consider the heat exchanger of Problem 11.14. After several years of operation, it is observed that the outlet temperature of the cold water reaches only 95°C rather than the desired 120°C for the same flow rates and inlet temperatures of the fluids. Determine the cumulative (inner and outer surface) fouling factor that is the cause of the poorer performance.

11.16 A counterflow, concentric tube heat exchanger is designed to heat water from 20 to 80°C using hot oil, which is supplied to the annulus at 160°C and discharged at 140°C. The thin-walled inner tube has a diameter of $D_i = 20$ mm, and the overall heat transfer coefficient is 500 W/m^2 · K. The design condition calls for a total heat transfer rate of 3000 W.

(a) What is the length of the heat exchanger?

(b) After 3 years of operation, performance is degraded by fouling on the water side of the exchanger, and the water outlet temperature is only 65°C for the same fluid flow rates and inlet temperatures. What are the corresponding values of the heat transfer rate, the outlet temperature of the oil, the overall heat transfer coefficient, and the water-side fouling factor, $R''_{f,c}$?

11.17 Consider the counterflow, concentric tube heat exchanger of Example 11.1. The designer wishes to consider the effect of the cooling water flow rate on the tube length. All other conditions, including the outlet oil temperature of 60°C, remain the same.

(a) From the analysis of Example 11.1, we saw that the overall coefficient *U* is dominated by the hot-side convection coefficient. Assuming the water properties are independent of temperature, calculate *U* as a function of the water flow rate. Justify a constant value of *U* in the calculations of part (b).

(b) Calculate and plot the required exchanger tube length *L* and the water outlet temperature $T_{c,o}$ as a function of the cooling water flow rate for $0.15 \le \dot{m}_c \le 0.30$ kg/s.

11.18 Consider a concentric tube heat exchanger with an area of 50 m^2 operating under the following conditions:

	Hot fluid	Cold fluid
Heat capacity rate, kW/K	6	3
Inlet temperature, °C	60	30
Outlet temperature, °C	—	54

(a) Determine the outlet temperature of the hot fluid.

(b) Is the heat exchanger operating in counterflow or parallel flow, or can't you tell from the available information?

(c) Calculate the overall heat transfer coefficient.

(d) Calculate the effectiveness of this exchanger.

(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:

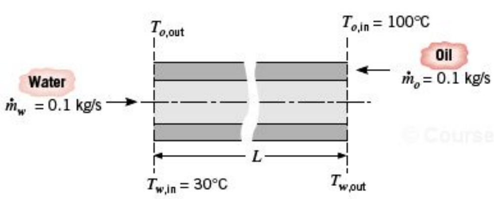
	$\dot{m}$ (kg/s)	$T_{m,i}$ (°C)	$T_{m,o}$ (°C)
Hot water	28	90	—
Cold water	27	34	60

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 $200 \leq U \leq 400$ 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 and the combustion gases may each be assumed to have a specific heat of c_p = 1040 J/kg · K. Consider conditions for which combustion gases flowing at 1 kg/s enter the heat exchanger at 800 K, while air at 5 kg/s has an inlet temperature of 300 K.

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

(b) After extended operation, deposits on the inner tube surfaces are expected to provide a fouling resistance of $R''_f = 0.004$ m² · K/W. Should operation be suspended in order to clean the tubes?

(c) The heat exchanger performance may be improved by increasing the surface area and/or the overall heat transfer coefficient. Explore the effect of such changes on the air outlet temperature for $500 \le UA \le 2500$ W/K.

11.25 In a dairy operation, milk at a flow rate of 250 liter/hour and a *cow-body* temperature of 38.6°C must be chilled to a safe-to-store temperature of 13°C or less. Ground water at 10°C is available at a flow rate of 0.72 m³/h. The density and specific heat of milk are 1030 kg/m³ and 3860 J/kg · K, respectively.

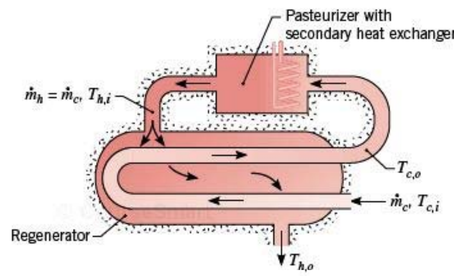
(a) Determine the *UA* product of a counterflow heat exchanger required for the chilling process. Determine the length of the exchanger if the inner pipe has a 50-mm diameter and the overall heat transfer coefficient is U = 1000 W/m² · K.

(b) Determine the outlet temperature of the water.

(c) Using the value of *UA* found in part (a), determine the milk outlet temperature if the water flow rate is doubled. What is the outlet temperature if the flow rate is halved?

11.26 A shell-and-tube heat exchanger with one shell pass and two tube passes is used as a *regenerator,* to preheat milk before it is pasteurized. Cold milk enters the regenerator at $T_{c,i} = 5°C$, while hot milk, which has completed the pasteurization process, enters at $T_{h,i} = 70°C$. After leaving the regenerator, the heated milk enters a second heat exchanger, which raises its temperature from $T_{c,o}$ to 70°C.

(a) A regenerator is to be used in a pasteurization process for which the flow rate of the milk is $\dot{m}_c = \dot{m}_h = 5$ kg/s. For this flow rate, the manufacturer of the regenerator specifies an overall heat transfer coefficient of 2000 W/m² · K. If the desired effectiveness of the regenerator is 0.5, what is the requisite heat transfer area? What are the corresponding rate of heat recovery and the fluid outlet temperatures? Milk may be assumed to have the properties of water.



(b) If the hot fluid in the secondary heat exchanger derives its energy from the combustion of natural gas and the burner has an efficiency of 90%, what would be the annual savings in energy and fuel costs associated with installation of the regenerator? The facility operates continuously throughout the year, and the cost of natural gas is C_{ng} = \$0.0075/MJ.

11.27 The compartment heater of an automobile exchanges heat between warm radiator fluid and cooler outside air. The flow rate of water is large compared to the air, and the effectiveness, ε, of the heater is known to depend on the flow rate of air according to the relation, $\varepsilon \sim \dot{m}_{air}^{-0.2}$.

(a) If the fan is switched to high and $\dot{m}_{air}$ is doubled, determine the percentage increase in the heat added to the car, if fluid inlet temperatures remain the same.

(b) For the low-speed fan condition, the heater warms outdoor air from 0 to 30°C. When the fan is turned to medium, the airflow rate increases 50% and the heat transfer increases 20%. Find the new outlet temperature.

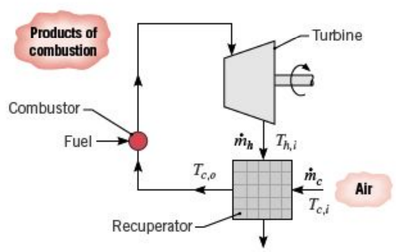
11.28 A counterflow, twin-tube heat exchanger is made by brazing two circular nickel tubes, each 40 m long, together as shown below. Hot water flows through the smaller tube of 10-mm diameter and air at atmospheric pressure flows through the larger tube of 30-mm diameter. Both tubes have a wall thickness of 2 mm. The thermal contact conductance per unit length of the brazed joint is 100 W/m · K. The mass flow rates of the water and air are 0.04 and 0.12 kg/s, respectively. The inlet temperatures of the water and air are 85 and 23°C, respectively.

Employ the ε–NTU method to determine the outlet temperature of the air. *Hint:* Account for the effects of circumferential conduction in the walls of the tubes by treating them as extended surfaces.

total heat transfer area is 1 m^2, determine the effectiveness. What is the exit temperature of the oil?

11.54 It is proposed that the exhaust gas from a diesel-powered electric generation plant be used to generate steam in a shell-and-tube heat exchanger with one shell and one tube pass. The steel tubes have a thermal conductivity of 40 W/m · K, an inner diameter of 50 mm, and a wall thickness of 4 mm. The exhaust gas, whose flow rate is 2 kg/s, enters the heat exchanger at 400°C and must leave at 215°C. To limit the pressure drop within the tubes, the tube gas velocity should not exceed 25 m/s. If saturated water at 11.7 bar is supplied to the shell side of the exchanger, determine the required number of tubes and their length. Assume that the properties of the exhaust gas can be approximated as those of atmospheric air and that the water-side thermal resistance is negligible. However, account for fouling on the gas-side of the tubes and use a fouling resistance of 0.0015 $m^2 \cdot K/W$.

11.55 A recuperator is a heat exchanger that heats air used in a combustion process by extracting energy from the products of combustion. It can be used to increase the efficiency of a gas turbine by increasing the temperature of air entering the combustor.



Consider a system for which the recuperator is a cross-flow heat exchanger with both fluids unmixed and the flow rates associated with the turbine exhaust and the air are $\dot{m}_h = 6.5$ kg/s and $\dot{m}_c = 6.2$ kg/s, respectively. The corresponding value of the overall heat transfer coefficient is $U = 100$ $W/m^2 \cdot K$.

(a) If the gas and air inlet temperatures are $T_{h,i} = 700$ K and $T_{c,i} = 300$ K, respectively, what heat transfer surface area is needed to provide an air outlet temperature of $T_{c,o} = 500$ K? Both the air and the products of combustion may be assumed to have a specific heat of 1040 J/kg · K.

(b) For the prescribed conditions, compute and plot the air outlet temperature as a function of the heat transfer surface area.

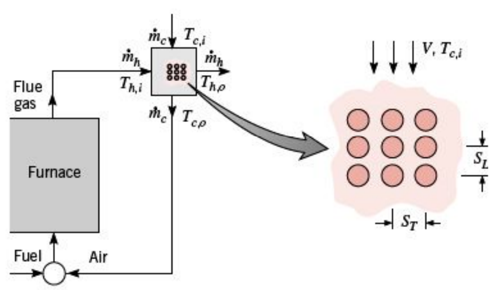
11.56 A concentric tube heat exchanger uses water, which is available at 15°C, to cool ethylene glycol from 100 to 60°C. The water and glycol flow rates are each 0.5 kg/s. What are the maximum possible heat transfer rate and effectiveness of the exchanger? Which is preferred, a parallel-flow or counterflow mode of operation?

11.57 Water is used for both fluids (unmixed) flowing through a single-pass, cross-flow heat exchanger. The hot water enters at 90°C and 10,000 kg/h, while the cold water enters at 10°C and 20,000 kg/h. If the effectiveness of the exchanger is 60%, determine the cold water exit temperature.

11.58 A cross-flow heat exchanger consists of a bundle of 32 tubes in a 0.6-m^2 duct. Hot water at 150°C and a mean velocity of 0.5 m/s enters the tubes having inner and outer diameters of 10.2 and 12.5 mm. Atmospheric air at 10°C enters the exchanger with a volumetric flow rate of 1.0 m^3/s. The convection heat transfer coefficient on the tube outer surfaces is 400 $W/m^2 \cdot K$. Estimate the fluid outlet temperatures.

11.59 Exhaust gas from a furnace is used to preheat the combustion air supplied to the furnace burners. The gas, which has a flow rate of 15 kg/s and an inlet temperature of 1100 K, passes through a bundle of tubes, while the air, which has a flow rate of 10 kg/s and an inlet temperature of 300 K, is in cross flow over the tubes. The tubes are unfinned, and the overall heat transfer coefficient is 100 $W/m^2 \cdot K$. Determine the total tube surface area required to achieve an air outlet temperature of 850 K. The exhaust gas and the air may each be assumed to have a specific heat of 1075 J/kg · K.

11.60 A recuperator is a heat exchanger that heats the air used in a combustion process by extracting energy from the products of combustion (the flue gas). Consider using a single-pass, cross-flow heat exchanger as a recuperator.



Eighty (80) silicon carbide ceramic tubes ($k = 20$ W/m · K) of inner and outer diameters equal to 55 and 80 mm, respectively, and of length $L = 1.4$ m are