Cross-Flow Heat Exchanger

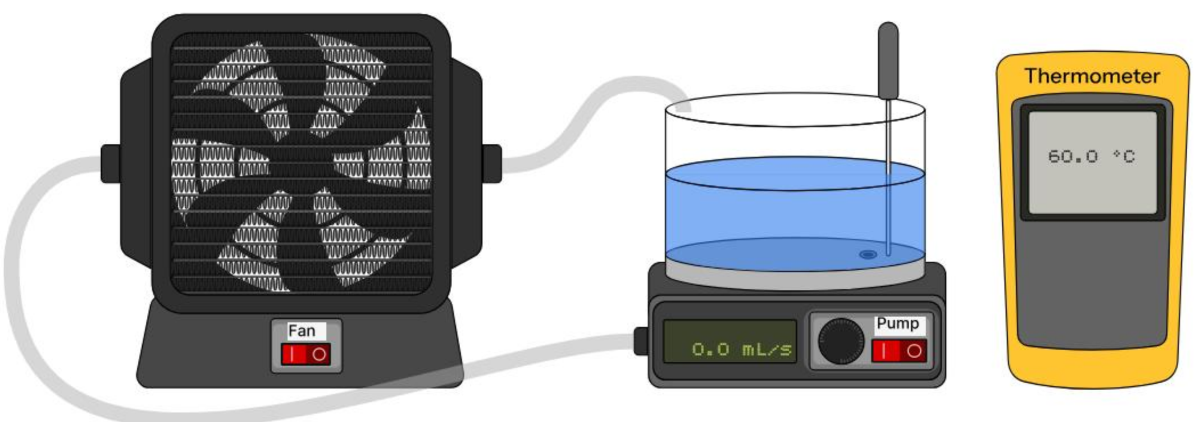
The cross-flow heat exchanger is a radiator in which water flows through flat tubes that have fins attached while a fan blows air past the fins. This is like a car radiator, and large-scale versions cool process fluids.

Name(s): ____

Student Learning Objectives

1. List the heat transfer resistances in an extended-area heat exchanger.
2. Explain the concept of controlling resistance.
3. Explain how fins compensate for the heat transfer resistance on the air side.
4. Explain the need for a fin effectiveness factor. Discuss the meaning, determination of, and implications surrounding the fin effectiveness factor.
5. Explain how to determine the heat transfer coefficient of the extended area heat exchanger from measurements.
6. Explain the unique design features of an extended-area heat exchanger.
7. Label the dimensions, areas, and films through which heat transfers and explain how to use them in calculations.
8. Measure the heat duty of an extended area heat exchanger.

Equipment



The system contains a tank whose inside diameter is 22 cm. The tank is filled to a height of 7.0 cm with hot water at 60°C. A hole in the bottom of the tank connects to the pump below the tank. A digital thermometer is inserted into the hot water. **Measure air temperature?**

Dimensions & Constants

Tube Data
material: copper
tube height, $h_{T,\,outer}$ = 2.1 mm (0.0827 in)
tube width, $w_{T,\,outer}$ = 13.3 mm (0.524 in)
tube length, L_T = 11.0 cm (4.33 in)
tube wall thickness, x_w = 0.13 mm (0.0015 in)
number of tubes = 12 (6 per pass)

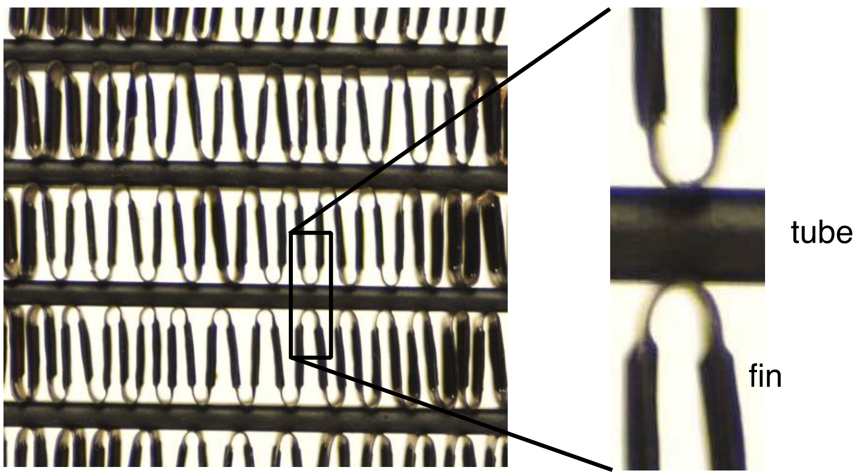
Air Properties

density, ρ_{air} = 1.18 kg/m3
specific heat, $C_{p,\mathrm{air}}$ = 1005 J/kg·K

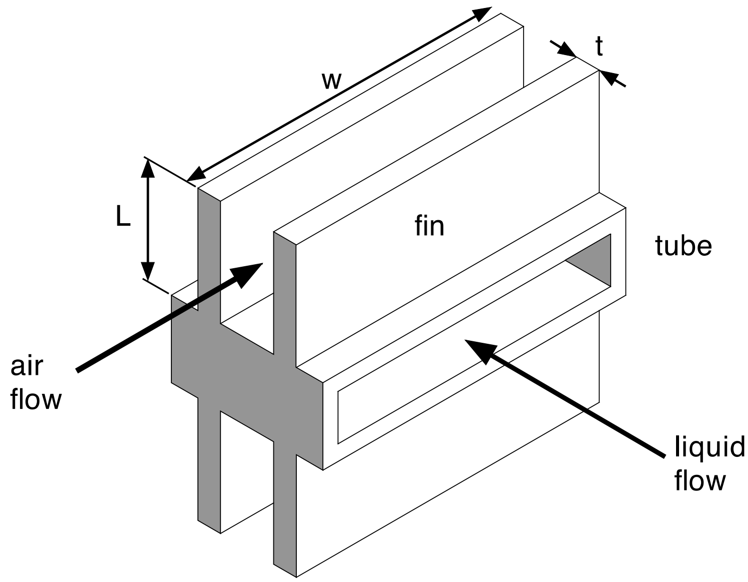
Fin Data
material: copper
fin spacing, x_f = 1.6 mm (0.063 in)
fin thickness, t = 0.11 mm (0.0043 in)
fin width, w = 16.1 mm (0.634 in)
fin length, L = 3.72 mm (0.146 in)
(1/2 of distance between tubes)

Copper Properties

thermal conductivity, k_{copper} = 401 W/m·K



Photograph of a section of the radiator looking in the direction of airflow. Vertical fins connect the four horizontal flat tubes. The section blown up on the right is a pattern repeated throughout the exchanger. Fins appear thicker than they really are because fins are cut into thin strips that are twisted at an angle. The edges of these strips disturb full development of a boundary layer, keeping the boundary layer thinner and thereby decreasing the resistance to heat transfer on the air side.



Schematic of a section of flat tube with attached fins. This represents an idealization of the small section of the radiator in the photograph above. Note that the figure exaggerates the fin thickness.

Questions to answer before starting the experiment

1. List the heat transfer resistances present in an air-cooled, cross-flow heat exchanger (also called an extended-area heat exchanger). Which do you think would be largest? Why?

2. Explain the concept of controlling resistance. How might this relate to the design of a cross-flow heat exchanger?

3. Explain the physical meaning of the fin effectiveness factor, η.

Experimental Procedure

1. Click the switch to turn on the fan.
2. Click the switch to turn on the pump.
3. Set the flow rate to a medium value. Record the flow rate below.
4. Let the system run for ~1 min to warm up the tubing and fittings before collecting data.
5. Record in Table 1 the water and air inlet and outlet temperatures measured with the digital thermometer.

Calculate the mass of water in tank from the water volume ___________

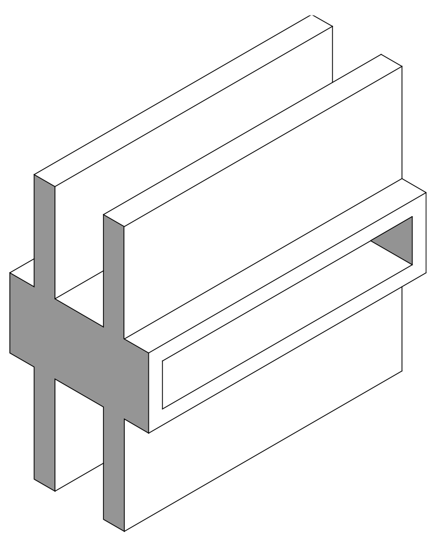
Flow rate _________

Table 1

Time [s]	$T_{in,water}$ [°C]	$T_{out,\ water}$ [°C]	$T_{in,\ air}$ [°C]†	$T_{out,\ air}$ [°C]†
0				
30				
60				
90				
120				
150				
180				

Worksheet Exercises

1. Examine the cross-flow heat exchanger and identify the fundamental section seen in the previous photograph and shown schematically below. Sketch on the diagram the paths for heat flow from the hot liquid inside the tube to cool air blowing past the fin.



2. The overall heat transfer coefficient for extended area heat exchangers is typically based on inside tube area and given by

$$U_i = \frac{1}{\frac{A_i}{[h_o(\eta_F A_F + A_b)]} + \frac{x_W}{\mathrm{k_m}} + \frac{1}{h_i}}$$

On the diagram below, label which areas contribute to the areas A_i, A_F, and A_b that appear in the formula above. Label the tube wall thickness and the inner and outer films through which heat transfers. Use k_m, h_i, and h_o to correspond to the material of thin films through which energy transfers.

$A_i =$ inside tube area

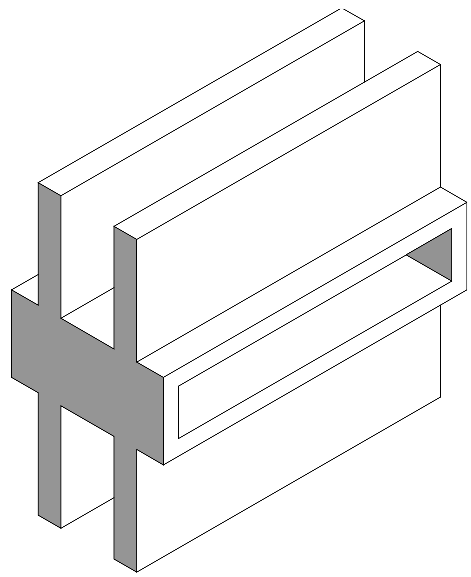
$A_F =$ fin area

$A_b =$ bare outer tube area

$x_W =$ tube wall thickness

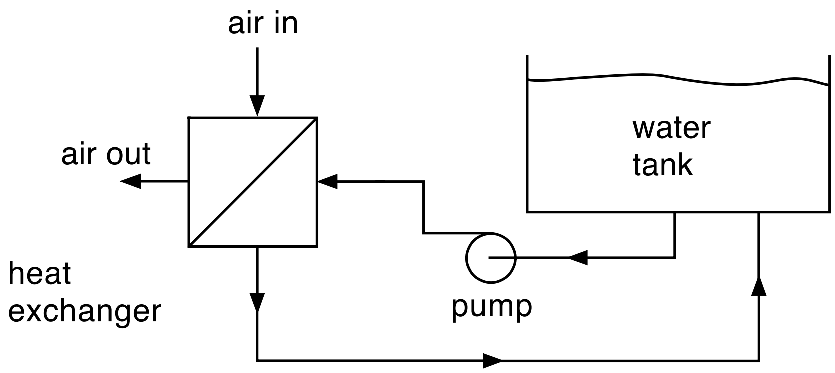
$k_m =$ thermal conductivity of tube wall

$h_i, h_o =$ inner and outer film coefficients



3. Notice the expression for U_i can be written in a way that the areas appear only as the ratios A_F/A_i and A_b/A_i. These ratios can be found knowing only the dimensions of the fundamental section seen above (or an even smaller section). Explain why this is the case.

4. The heat duty of the cross-flow heat exchanger is the rate at which heat transfers from the water to the air. This duty can be obtained from your temperature and flow rate measurements in several ways. Each of these involves an energy balance on some part of the overall system (heat exchanger plus tank). On the diagram below, circle with a dashed line the systems/subsystems on which you could perform an energy balance to determine the heat duty from your data.



5. If you were able to measure the air inlet and outlet temperature you can estimate the heat duty of the exchanger from these temperatures and the fact that the air flow rate through this exchanger is approximately 6 g/s. Determine the heat duty using an energy balance on the air side of the exchanger using the data at a time of 60 s.

6. The heat duty can also be measured by an energy balance on the water side of the heat exchanger. Determine the heat duty using the flow rate and temperature data for the water at 60 s. How does this compare to what you obtained in question 5? Why might this measurement not be accurate?

7. The air side of a radiator is typically the controlling thermal resistance. Explain how you would estimate the air-side individual heat transfer coefficient h_o using standard correlations. How would you determine it from your experiment?

8. Fin effectiveness
    a. Discuss the meaning of the fin effectiveness factor, η_f, multiplying A_F in the term for the air side resistance in the model for the overall heat transfer coefficient, U_i.

    b. Look at a plot of η_f in a textbook. Discuss the meaning of the x-axis term within the square root.

    c. Using a pen tip identify L; is it the full or half-length of the fin? Why?

Homework

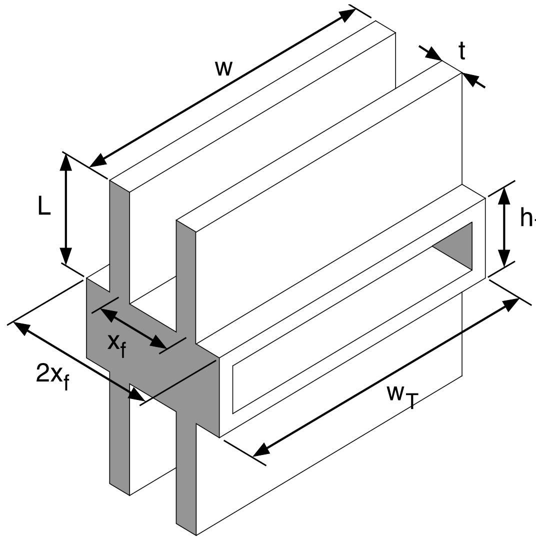
Learning Objectives/Outcomes

Students will be able to:

1. Compute the area ratios for a fundamental section of a cross-flow heat exchanger.
2. Calculate heat duty from experimental measurements using an unsteady state energy balance on the system.
3. Estimate the overall thermal resistance of the cross-flow heat exchanger from experimental measurements.
4. Estimate the airside thermal resistance from correlations.
5. Draw conclusions regarding limiting resistance.
6. Compare correlated and experimental heat losses.

Homework Exercises

1. As noted in the worksheet activity, the expression for U_i can be written in a way that the areas appear only as the ratios A_F/A_i and A_b/A_i. Using only the dimensions of the fundamental section in the diagram below, develop formulas for these area ratios. Then proceed to calculate the area ratios for the DLMX extended area heat exchanger using numbers from the worksheet section "Dimensions and Constants."



2. A third way to measure the heat duty (in addition to those discussed in the worksheet) is by an unsteady balance on all the water in the system (tank, tubing, and exchanger). Assume that heat is lost from the water only in the exchanger, and that the inlet temperature to the exchanger is representative of the temperature of the water in the tank (assuming it is well mixed). Then, calculate the average heat duty of the exchanger from the average rate of change of temperature during the 3-minute period of the experiment. Compare this duty to the ones obtained by air-side and water-side balances. Comment on how valid you think the assumptions are.

3. Calculate the log-mean temperature difference, $(\Delta T)_{LM}$, for the data from the experiment at 60 s. Also determine the overall heat transfer resistance from your measured data (recall that heat transfer resistance is the ratio of driving force to heat transfer rate). In the formula below, the correction factor F accounts for the geometry of the particular cross-flow heat exchanger and can be obtained from standard references [12, 13] (use the correlation or charts for cross-flow with both fluids unmixed).

   heat transfer resistance = $R = \dfrac{1}{U_i A_i} = \dfrac{F(\Delta \mathrm{T})_{LM}}{\dot{Q}}$

4. Estimate the air-side individual heat transfer coefficient h_o using the method you outlined in your worksheet. Note that a typical air speed through the fins is 0.5 m/s.

5. Fins enhance heat transfer. The effectiveness of the fins depends on the fin effectiveness factor, η_F, as can be seen by the expression given in the worksheet on page 5 for the overall

heat transfer coefficient. Determine the fin effectiveness factor from the chart below by first finding mL:

$$mL = \sqrt{\frac{h_o P_W}{k_m A_x}} * L$$

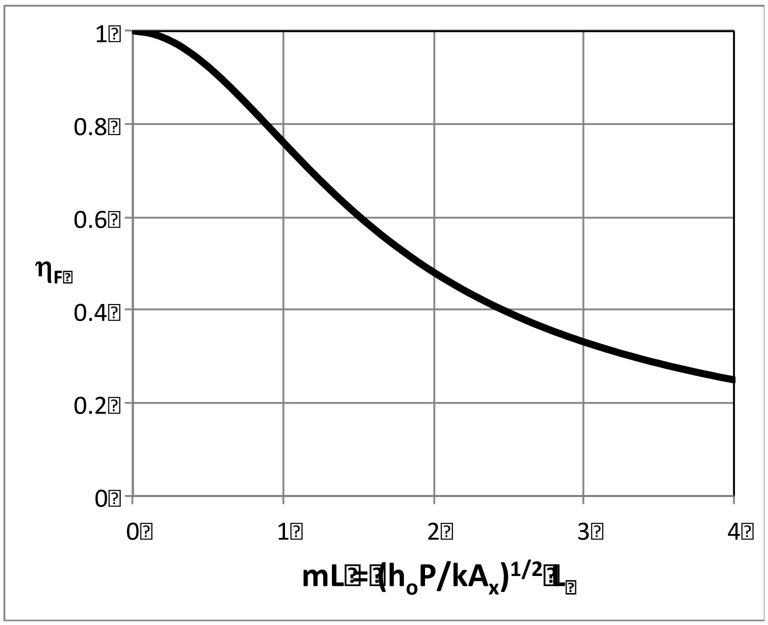
h_o = air side heat transfer coefficient

k_{copper} = thermal conductivity of metal fin

P_W = wetted perimeter of the fin

A_x = cross sectional area of the fin

L = half of fin length between tubes (see worksheet diagram and photo)



6. Compute the air-side thermal resistance from

$$R_{air} = \frac{1}{A_i[h_o(\eta_F(A_F/A_i) + (A_b/A_i)]}$$

using the results for h_o, η_F, (A_F/A_i), and (A_b/A_i) that were determined in previous problems. Note that you also need to determine the total inside area of all the tubes in the heat exchanger, A_i. How does this thermal resistance compare to the overall resistance determined in Problem 3? What conclusions can you draw regarding the controlling thermal resistance for the system?

7. Calculate the rate of heat loss based on a correlation and compare that with the experimental heat duty you determined in Problem 2. Comment on any differences you observe.

References

1. Golter, P.B., B.J. Van Wie, P.V. Scuderi, T.W. Henderson, G.R. Brown, and W.J. Thomson, *Combining Modern Learning Pedagogies in Fluid Mechancis and Heat Transfer.* Chem. Engr. Education, (39): p. 280-287.
2. Sweller, J., *Cognitive Load Theory*, in *Psychology of Learning and Motivation: Cognition in Education*, J.P. Mestre and B.H. Ross, Editors. 2011. p. 37-76.
3. Kalyuga, S., *Cognitive Load Theory: How Many Types of Load Does It Really Need?* Educational Psychology Review, 2011: p. 1-19.
4. Chyung, S.Y., A. Moll, B. Marx, M. Frary, and J. Callahan, *Improving Engineering Students' Cognitive and Affective Preparedness with a Pre-instructional E-learning Strategy.* Advances in Engineering Education, 2010. Spring: p. 1-28.
5. Svinicki, M.D., *A Guidebook on Conceptual Frameworks for Research in Engineering Education*, 2008, NSF.
6. Svinicki, M.D., *Learning and Motivation in the Postsecondary Classroom.* 2004, Bolton, MA: Anker Publishing Co.
7. Jones, M.E., P.D. Antonenko, and C.M. Greenwood, *The Impact of Collaborative and Individualized Student Response System Strategies on Learner Motivation, Metacognition, and Knowledge Transfer.* Journal of Computer Assisted Learning, 2012. 28(5): p. 477-487.
8. Chickering, A.W. and S.C. Ehrmann, *Implementing the Seven Principles: Technology as a Lever.* AAHE Bulletin, 1996.: p. 3-6.
9. Chickering, A.W. and Z.F. Gamson, *Seven Principles for Good Practice in Undergraduate Education.* The Wingspread Journal, 1984.
10. Abdul, B., B.J. Van Wie, J.T. Babauta, P.B. Golter, G.R. Brown, R.B. Bako, A.S. Ahmed, E.G. Shide, F.O. Anafı, and O.O. Olaofe, *Addressing Student Learning Barriers in Developing Nations with a Novel Hands-on Active Pedagogy and Miniaturized Industrial Process Equipment: The Case of Nigeria.* International Journal of Engineering Education, 2011. 27(1): p. 1-19.
11. Palincsar, A.S., *Social Constructivist Perspectives on Teaching and Learning.* Annual Review of Psychology, 1998. 49: p. 345-375.
12. McCabe, W.L., Smith, J.C., and Harriott, P., *Unit Operations of Chemical Engineering.* 7th: p. 327.
13. Perry, R.H., Green, D. , *Perry's Chemical Engineers' Handbook*. 8th ed. 2008, New York: McGraw-Hill Professional.