Cross Flow Heat Exchanger

There are many instances involving heat exchange to or from a gas. To compensate for the low thermal conductivity of gases, heat exchanger surface areas on the gas side are increased. These systems are often called extended area heat exchangers. Examples include car radiators, fin cooling of electrical components, and thin handles that readily dissipate heat and enable carrying of hot pots or kettles. The DLMX Cross Flow Heat Exchanger is a radiator in which water flows through flat tubes that have fins attached while air is blown past the fins by a fan. Very large-scale versions of this type of heat exchanger called "fin fan" coolers are used in industry to cool process fluids.

Cross Flow Heat Exchanger cartridge on DLMX Base Unit.

Use of the DLMX Cross Flow Heat Exchanger

1. The DLM-1 cartridge (Cross Flow Heat Exchanger) should be installed in a Base Unit filled with warm water (< 60°C) and the power turned on according to the General Operating Instructions (Section III).
2. Adjust the flow rate using the knob on the Base Unit. Accompanying temperature readings will appear on the output screen.

Preparatory Quiz

A. Learning Objectives/Outcomes

Students will be able to:

1. List the heat transfer resistances present in an extended-area heat exchanger.
2. Explain the concept of a controlling resistance.
3. Explain how fins compensate for the heat transfer resistance on the air side.
4. Explain why a fin effectiveness factor is needed.

B. Reading

C. Quiz Exercises

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

2. Explain the concept of a controlling resistance. How might this relate to the design of an extended-area heat exchanger?

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

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Activity Worksheet

A. Learning Objectives/Outcomes

Students will be able to:

1. Explain the unique design features of an extended-area heat exchanger.
2. Label the dimensions, areas, and films through which heat is transferred and explain how they are used in calculations.
3. Experimentally measure the heat duty of an extended area heat exchanger.
4. Explain how to determine the heat transfer coefficient of the extended area heat exchanger from measurements.
5. Discuss the meaning, determination of, and implications surrounding the fin effectiveness factor.

B. Experimental Procedure

1. Have a plastic ruler ready for measuring water depth and a handheld digital thermometer, if available, for measuring the air temperature entering and leaving the heat exchanger.
2. Turn on power for the Base Unit.
3. Install the DLM-1 cartridge (Cross Flow Heat Exchanger) into a Base Unit filled with hot water (< 60°C).
4. Measure and record the depth of water in the Base Unit reservoir with a ruler.
5. Scroll down to display the flow rate and temperatures registered on the Base Unit.
6. Set the flow rate to a medium value and record it.
7. Record flow rates, water inlet and outlet temperatures, from Base Unit readout, and air inlet and outlet temperatures measured with the handheld digital thermometer.

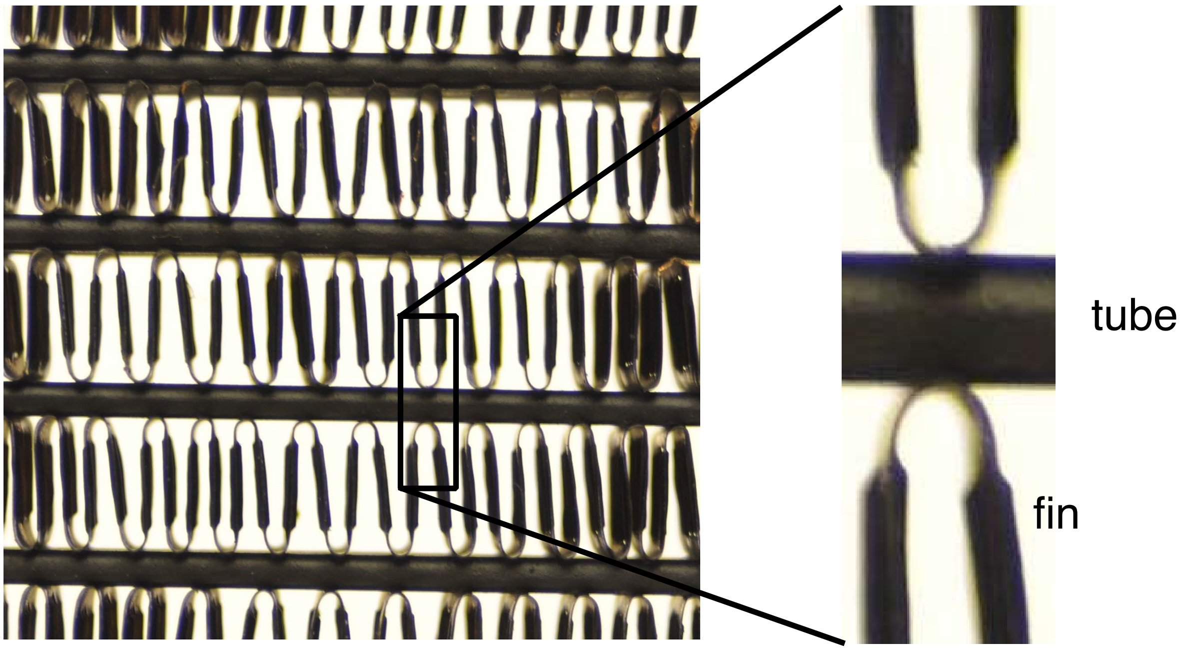
Dimensions & Constants

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/m^3
specific heat, $C_{p,\mathrm{air}}$ = 1005 J/kg·K

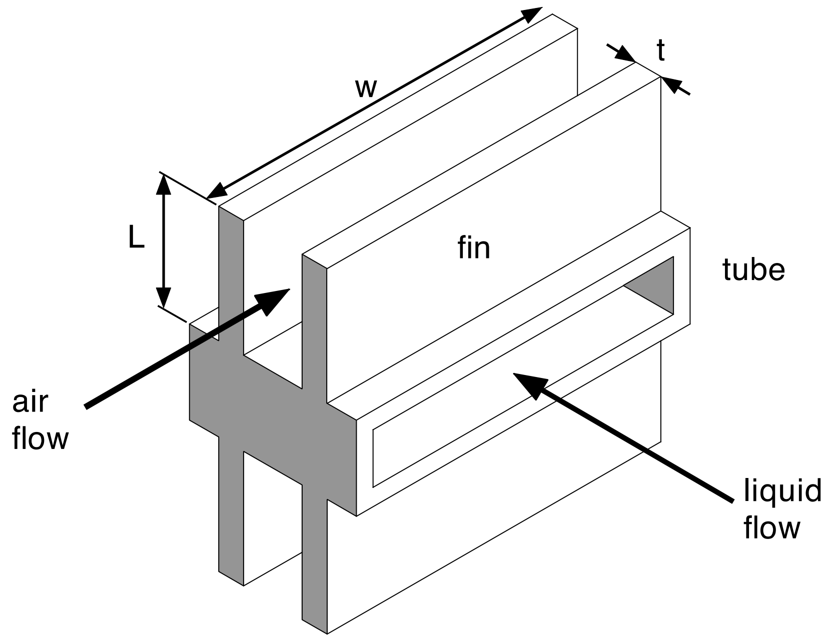
Fin Data
material: copper
fin spacing, x_f = 1.6 mm (0.063 in)
fin thickness, t = 0.11 mm (0.0043 in)
fin width, w = 16.1 mm (0.634 in)
fin length, L = 3.72 mm (0.146 in)
(1/2 of distance between tubes)

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



Photograph of a section of the radiator looking in the direction of airflow. Four of the horizontal flat tubes are seen with vertical fins connecting between them. The section in the rectangle that is blown up on the right is a pattern that is repeated throughout the exchanger. Note fins appear thicker than they really are because the 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.

Cross Flow Heat Exchanger



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 fin thickness is exaggerated.

Cross Flow Heat Exchanger

Experimental DLMX Data

Depth of water in Base Unit __________ Tank diameter __________

Mass of water in Base Unit __________ (estimate from water volume in reservoir)

Flow rate __________

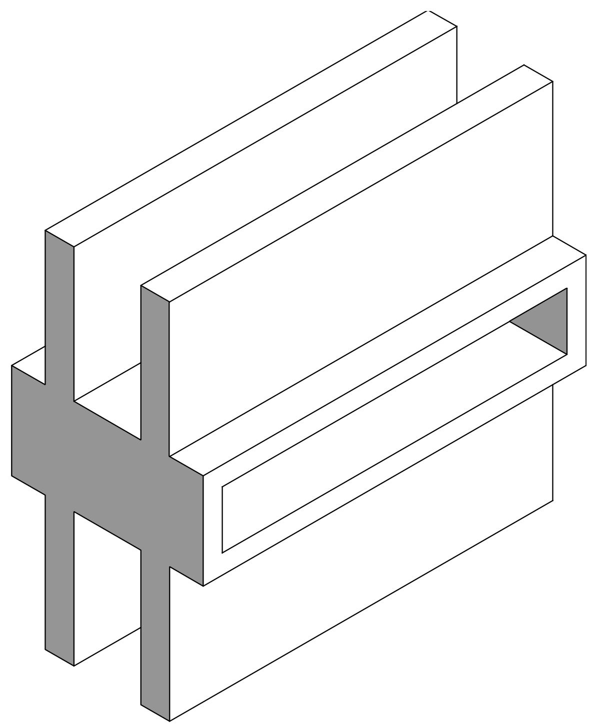
After turning on the pump and setting it to a medium flow rate, let it run for about ~1 min to warm up the tubing and fittings before starting to collect data.

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				

†Air temperatures are not measured by the Base Unit. If no handheld thermometer is available to measure air temperatures these columns should be left blank.

C. Worksheet Exercises

1. Examine the DLMX Cross Flow (extended area) 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 on the next page, label which areas contribute to the areas A_i, A_F, and A_b that appear in the formula above. Using a pen tip also identify these areas on the DLMX Cross Flow cartridge. Also label the tube wall thickness and the inner and outer films through which heat is transferred. Use $\mathrm{k_m}$, h_i, and h_o to correspond to the material of thin films through which energy is transferred.

Cross Flow Heat Exchanger

$A_i =$ inside tube area

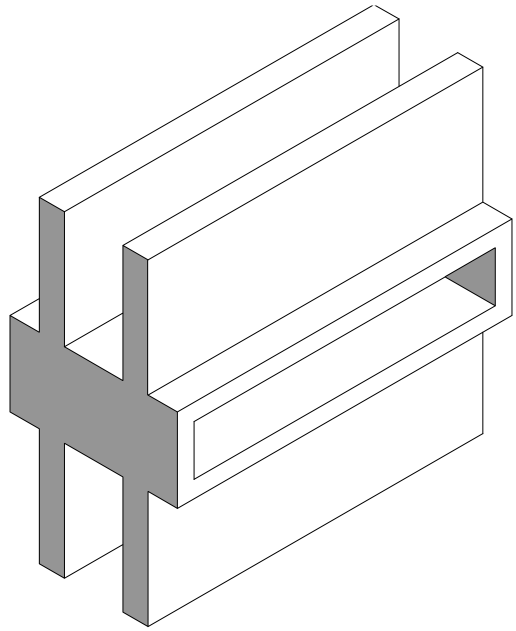
$A_F =$ fin area

$A_b =$ bare outer tube area

$x_W =$ tube wall thickness

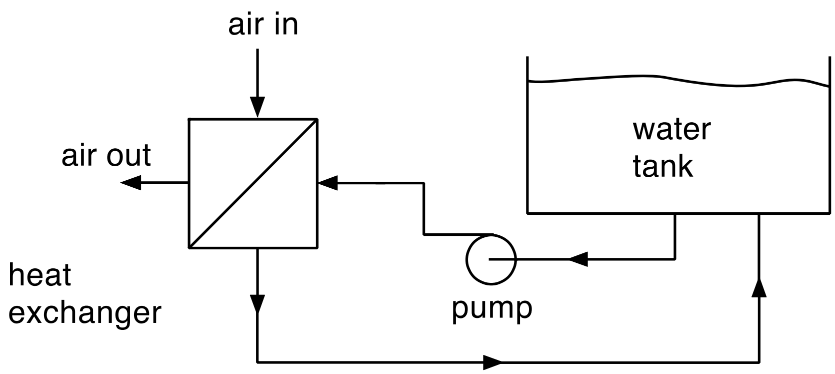
$k_m =$ thermal conductivity of tube wall

$h_i, h_o =$ 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 DLMX Cross Flow Heat Exchanger is the rate at which heat is transferred 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 0.006 kg/s (0.0013 lb_m/sec). Determine the heat duty using an energy balance on the air side of the exchanger using the data at a time of 60 sec.

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 sec. How does this compare to what you obtained in question 5? Why might this measurement not be very 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

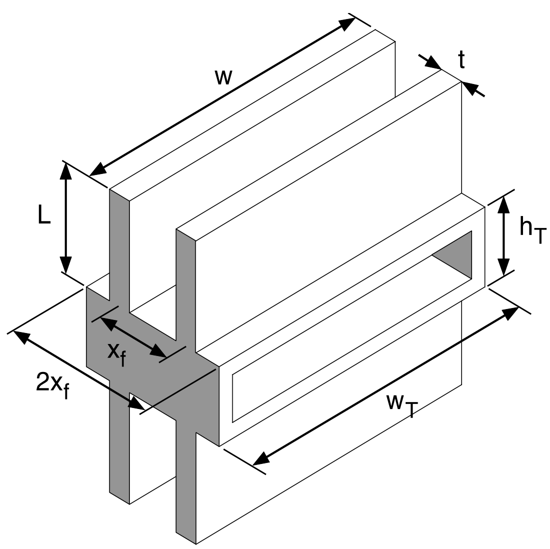
A. Learning Objectives/Outcomes

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.

B. 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). If one assumes 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), calculate the average heat duty of the exchanger from the average rate of change of temperature during the 3 minute period of the experiment. Note that you need to estimate the total mass of water in the system from the measured depth in the tank (tank inside diameter is 22 cm). Compare this duty to the ones obtained by air-side and water-side balances. Comment on how valid you think the assumptions are.

3. If you were able to acquire air temperature data, calculate the log mean temperature difference, $(\Delta T)_{LM}$, for the data from the experiment at 60 sec. 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).

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

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/sec.
5. Heat transfer is enhanced by the fins. The effectiveness of the fins depends on the fin effectiveness factor, η_F, as can be seen by the expression given in the worksheet for the overall heat transfer coefficient. Determine the fin effectiveness factor from the chart below by first finding

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

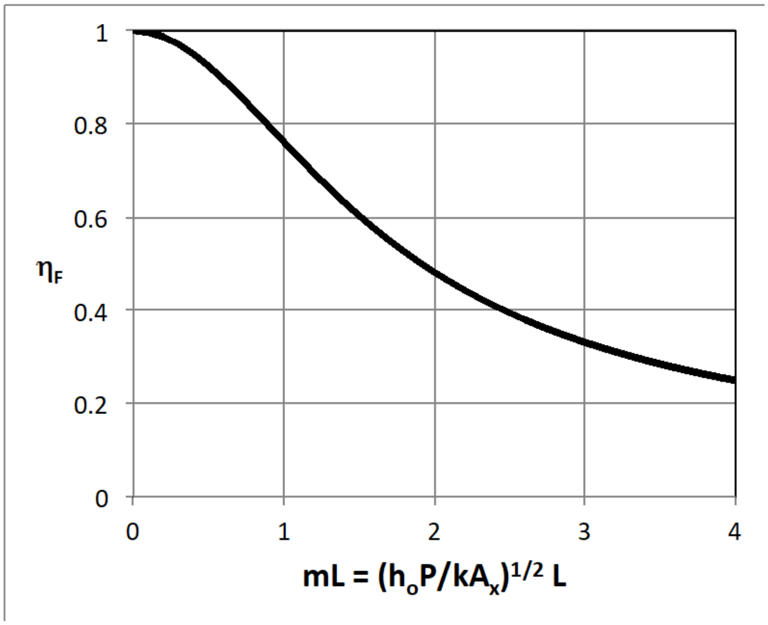
h_o = air side heat transfer coefficient

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. Anafi, 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.