Double-Pipe Heat Exchanger Worksheet

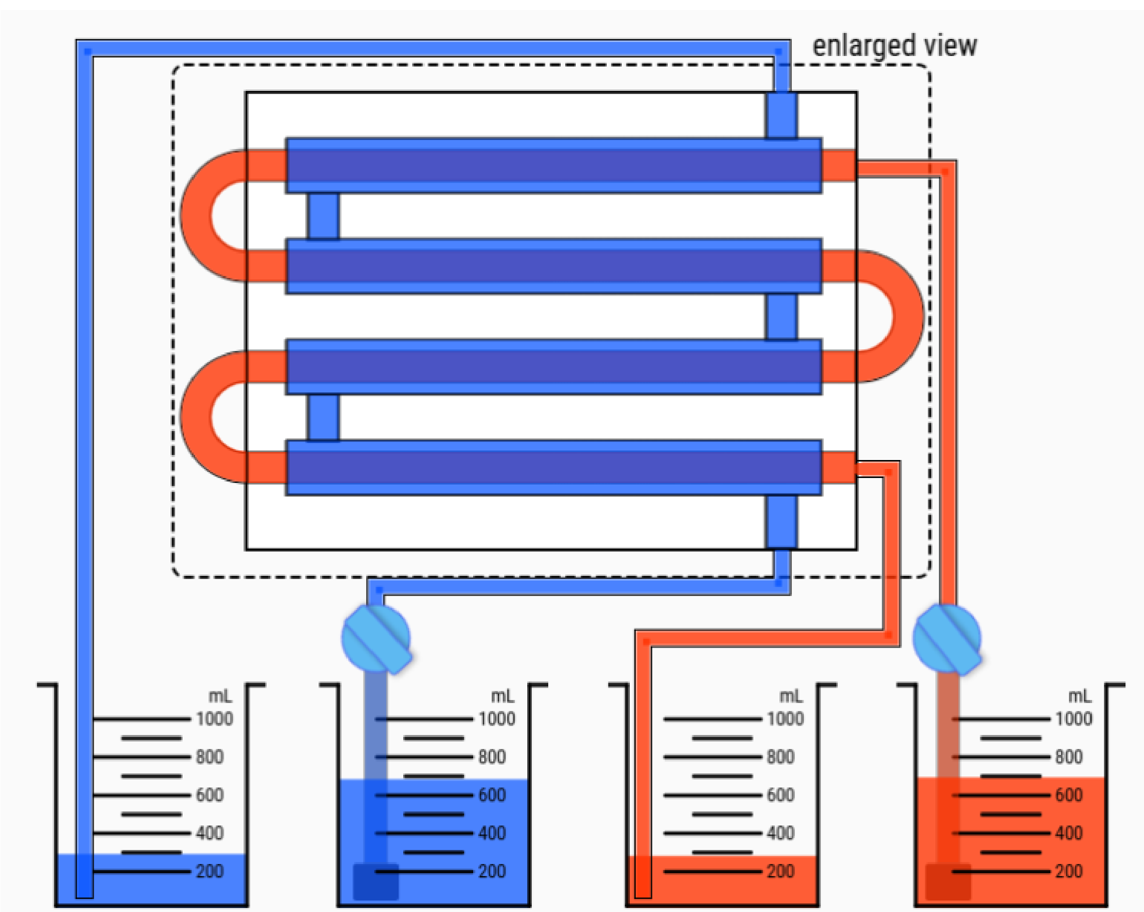
Name(s): ____

This experiment measures water flow rates and temperatures for a countercurrent, double-pipe heat exchanger and then calculates heat transfer rates.

Student Learning Objectives

1. Identify flow patterns and inlets and outlets for hot and cold fluids for countercurrent flow.
2. Identify the energy gains and losses for each fluid in the heat exchanger and how these relate to the energy balance.
3. Perform calculations to determine the rate of heat transfer (heat duty).
4. Understand the difference between flow area and heat transfer area.
5. Identify geometric parameters such as the hydraulic diameter and cross-sectional area for the annular side.
6. Understand the difference between a heat transfer and energy balance temperature difference (ΔT).
7. Determine the log-mean temperature difference and explain why it is used.
8. Explain the effect of flow rate and inlet/outlet temperatures on performance.

Equipment

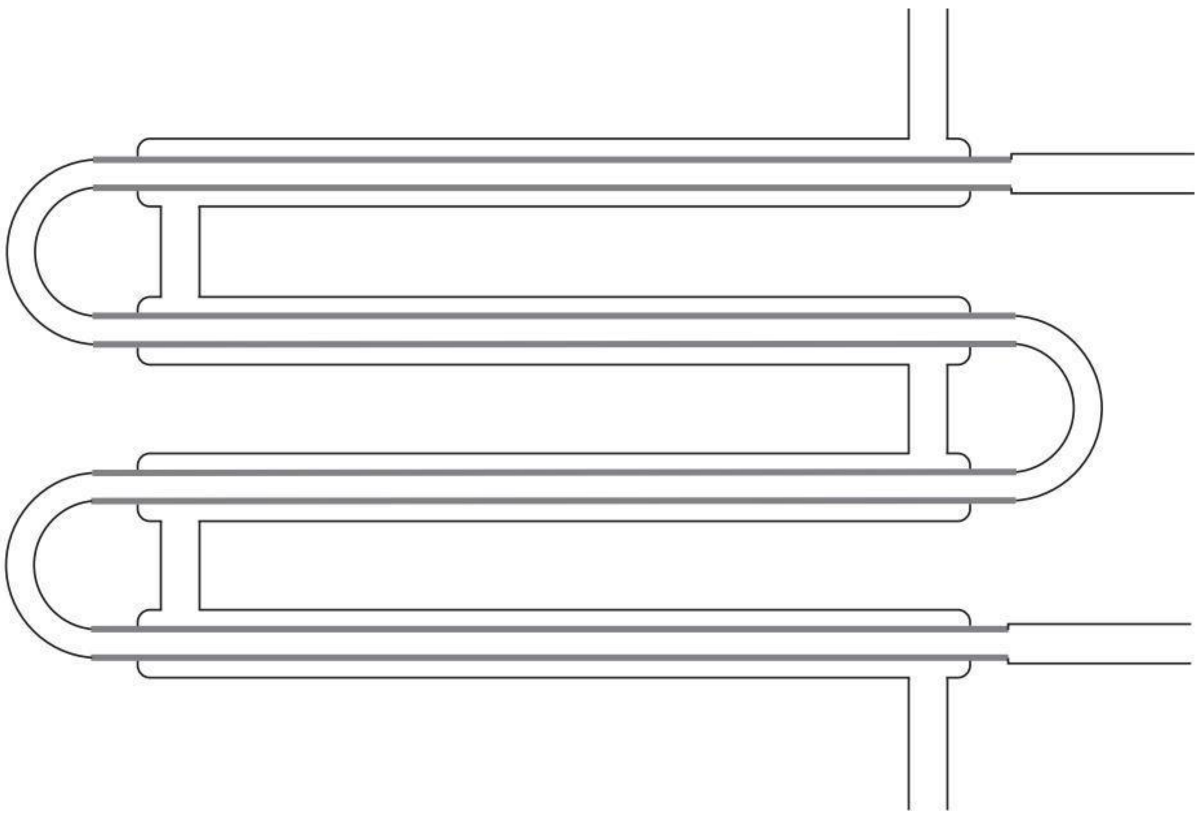


The experiment consists of feed beakers with hot (blue) and cold (red) water and outlet beakers that collect the water after it flows through the heat exchanger. Pumps are located in the feed beakers, and the pumps turn off when either beaker reaches 100 mL. The size of the heat exchanger is enlarged relative to the size of the beakers to make it easier to view the flows inside the heat exchanger.

Before Starting the Digital Experiment

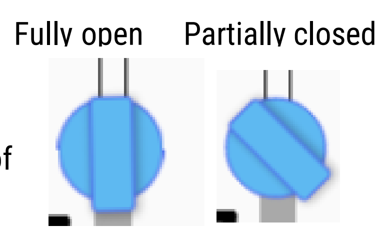
For a **countercurrent** heat exchanger with hot fluid on the tube side and cold fluid on the annular side:

1) Draw the expected flow patterns in the heat exchanger on the schematic below.
2) Identify the inlet and outlet of the hot and cold fluids in the heat exchanger and add labels below.



Experiment 1: Confirming Flow Patterns and Measuring Heat Transfer Rate

a) The tube side beaker contains hot water (red color) and the annular side beaker contains cold water (blue color).
b) Select valve openings for each valve.
c) Click "measure temperature" and record in Table 1 the temperatures of the inlet-beaker cold water and the inlet-beaker hot water.



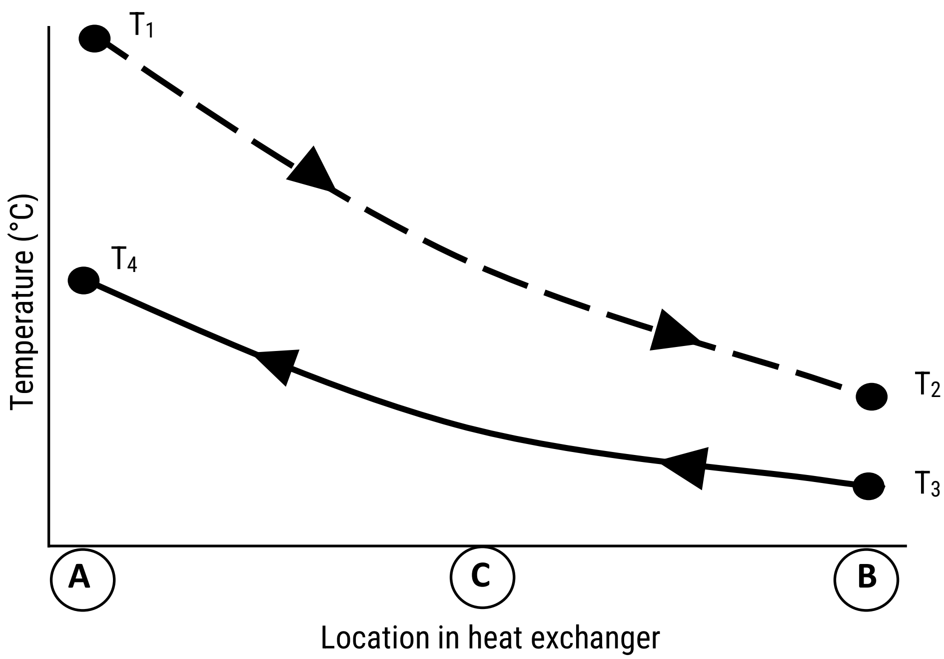
d) Click "start pumps" to turn on both pumps. When the hot and cold water reach the outlet beakers, ***start your phone timer.***
e) Before one of the inlet beakers is empty, record in Table 1 temperatures of hot water and cold water outlet beakers.
f) Then record the time and the hot- and cold-water outlet beaker volumes in Table 1.
g) Make any corrections to the flow patterns hypothesized above.

Table 1. Experimental data

Tube side (hot)			Annular side (cold)			Time (s)
T_{in}	T_{out}	V_{out} (mL)	T_{in}	T_{out}	V_{out} (mL)	

Heat Transfer Driving Mechanism and Log-Mean Temperature Difference

1. In the diagram below each line represents a temperature profile for one fluid along the length of a countercurrent exchanger. Label:
   A) Your experimental temperatures in the appropriate locations
   B) The temperature difference between the hot and cold fluid at both ends of the exchanger (locations A and B) and at a point midway through the exchanger (location C)



2. Which temperature difference (ΔT) drives heat transfer, $T_1 - T_2$; $T_4 - T_3$; or $T_{hot} - T_{cold}$?

3. Based on your answer to (1B), is the driving potential for heat transfer constant throughout the exchanger? What does this tell you about the heat transfer rate throughout the exchanger?

4. The predicted heat transfer rate (heat duty) of a heat exchanger is function of the logarithmic mean temperature difference, ΔT_{LMTD}, defined below:

$$\dot{Q} = f\ (\Delta T_{LMTD}) \qquad \Delta T_{LMTD} = \frac{(\Delta T)_A - (\Delta T)_B}{ln\ (\frac{(\Delta T)_A}{(\Delta T)_B})}$$

A) How does ΔT_{LMTD} correct for what you described in question 3?

B) Which temperatures from Table 1 are used to calculate ΔT_{LMTD}; e.g., what does ΔT_A and ΔT_B mean?

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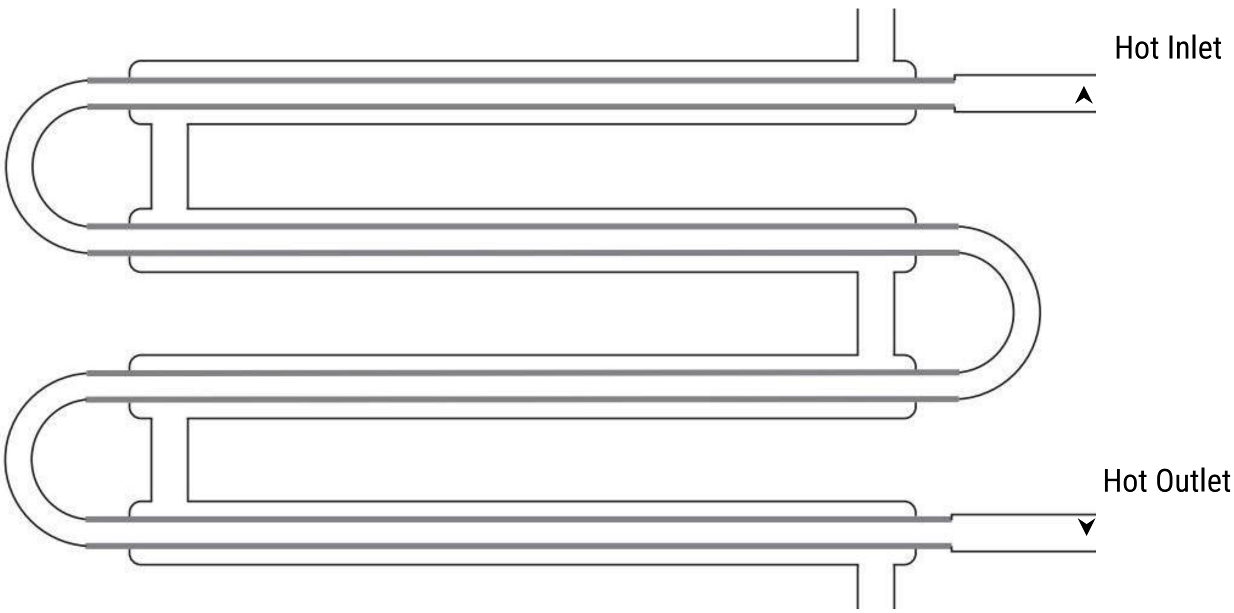
Energy Balances in the Heat Exchanger

5. Considering the hot fluid; indicate on the figure where thermal energy enters and leaves the system.



6. Calculate the heat transfer rate (heat duty) with an energy balance on the hot or cold fluid:

$$\dot{Q}_H = \dot{m}_h C_{p,h} \Delta T_h \qquad \dot{Q}_C = \dot{m}_c C_{p,c} \Delta T_c$$

7. How does the energy balance account for the energy gains and losses you labeled in question 5?

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8. If the hot water (red) inside the heat exchanger is treated as the system (i.e., the mass flow rate and heat capacity of the hot water are used), which of your experimental temperatures are used to calculate ΔT_h in the energy balance? Why?

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9. Considering energy conservation, how should $\dot{Q}_H$ and $\dot{Q}_C$ compare? Why might they differ?

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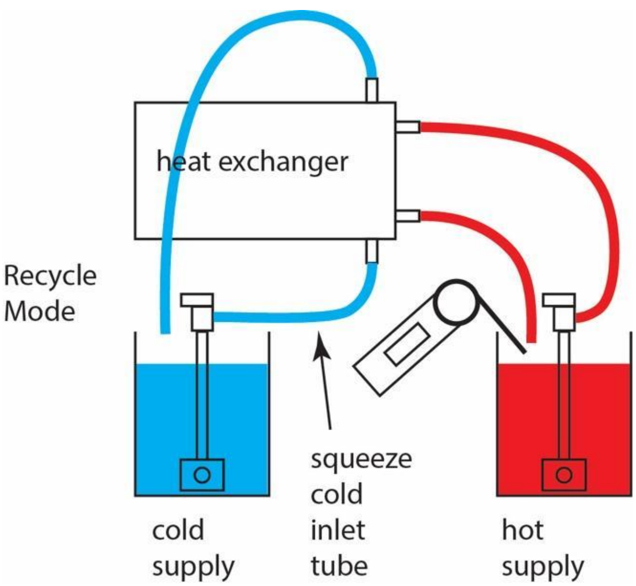
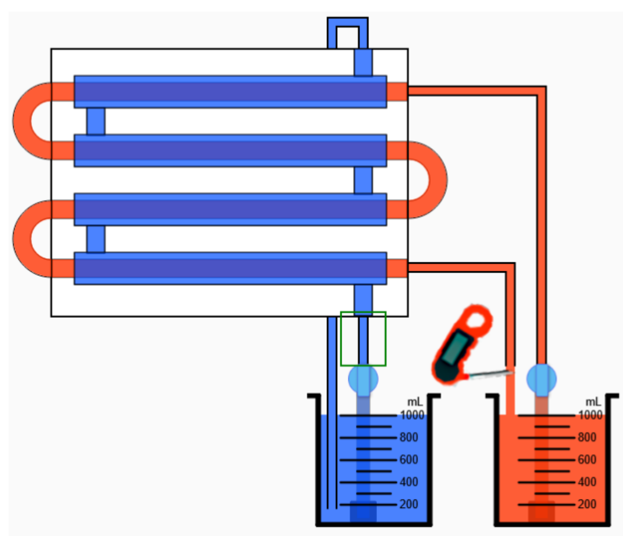
Experiment 2: Effect of Flowrate on Heat Transfer Rate

a) Click on “menu” and the click on Experiment 2.
b) Click “start pumps” to start flow of hot and cold water. The valves are fully open and cannot be adjusted.
c) The thermometer is situated so it reaches ***into the hot water exit stream,*** near the end of the exit tube.
d) ***Note the temperature of the hot stream.***
e) Click on the tubing just above the valve for the cold-water beaker for ~5 s to pinch the cold inlet tubing; this slows the cold-water flowrate. ***Note the temperature of the hot stream.***
f) Move the mouse from the tubing and ***note the temperature change*** after ~5 s.
g) Turn off the pumps.





10. Describe the change in the temperature of the hot water flowing into the outlet beaker.

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11. Did slowing the cold-water flow rate increase or decrease the heat transfer rate? Explain.

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12. Based on your knowledge of laminar and turbulent flow patterns, how does decreasing the velocity towards the laminar regime affect the heat transfer rate? Is heat more easily transferred from the hot to the cold fluid during laminar or turbulent flow? Why?

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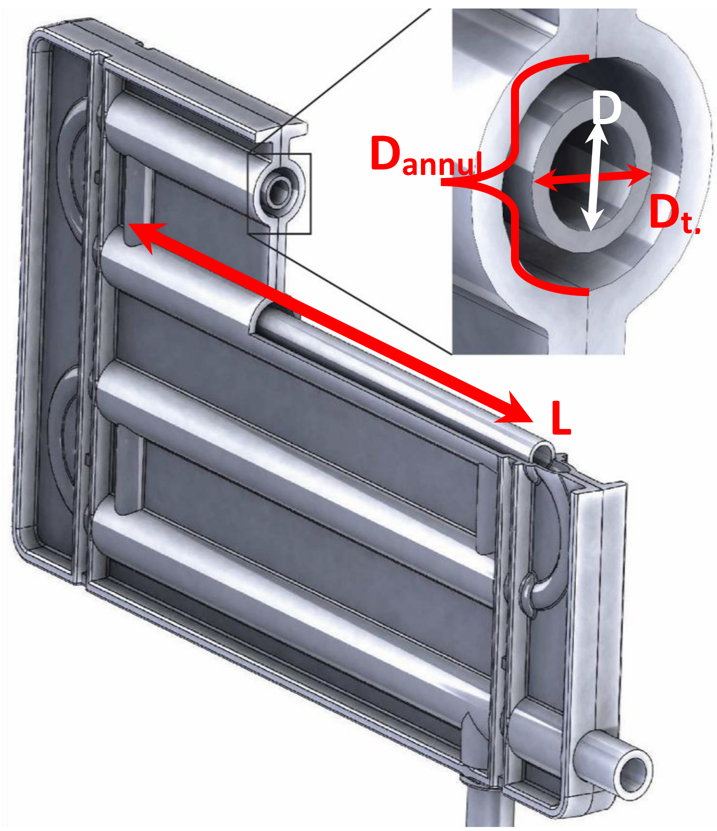
Heat Exchanger Geometry

13. On the diagram of a cross section of the heat exchanger below, label:
    A) The area for cold water flow
    B) The area for hot water flow
    C) The area for heat transfer for a single tube



14. Write a formula for each of the areas listed above.

    A_C: Area for cold water flow = .

    A_H: Area for hot water flow = .

    A_O: Area for heat transfer = .

15. For each of the following, circle which area from above should be used to calculate the term:

A) The velocity of the hot fluid ($\underline{v} = \frac{\dot{V}}{A}$)	A_C	A_H	A_o
B) The velocity of the cold fluid ($\underline{v} = \frac{\dot{V}}{A}$)	A_C	A_H	A_o
C) The heat transfer rate ($\dot{Q} = U_o A \Delta T_{LM}$)	A_C	A_H	A_o

<u>Homework Section</u>: Complete on a separate sheet of paper

Reference information for Double-Pipe Heat Exchanger LCDLM

- Tube length, $L = 155\ mm$
- Number of tubes, $N_t = 4$
- Tube material, 304 stainless steel
- Tube dimensions: Outer diameter, $D_{t,o} = 6.35\ mm$, inner diameter, $D_{t,i} = 4.37\ mm$
- Annulus outer diameter, $D_a = 9.53\ mm$

Experimental Heat Transfer Rate

1. Calculate the heat transfer rate ($\dot{Q}$) using the data you collected in Table 1 and the energy balance equation below for both the annular and tube side. Is the amount of heat released by the hot fluid the same as the amount of heat received by the cold fluid? If not, what are possible reasons?

$$\dot{Q}_C = \dot{m}_C C_{p,C} \Delta T_C \qquad\qquad \dot{Q}_H = \dot{m}_H C_{p,H} \Delta T_H$$

Hydraulic Diameter of the Annular Side

2. Given the definition for the hydraulic diameter (D_h) below, show that for the concentric, circular annulus where cold water flows in the LCDLM, $D_h = \left(D_a - D_{t,o}\right)$

$$D_h = \frac{4 \cdot A_x}{P_w}$$

P_w = wetted perimeter where fluid contacts inner and outer walls of the annulus

A_x = cross-sectional area for flow

Predicted Tube and Annular Heat Transfer Coefficients

3. Using correlations determine the individual heat-transfer coefficients for the tube side (h_i) and annular side (h_o) of the double-pipe heat exchanger using your experimental flowrates. The individual heat transfer coefficients, h_i and h_o, can be determined by rearranging the Nusselt number (Nu or the dimensionless heat transfer coefficient), defined below. Note: use the hydraulic diameter ($D_h = D_a - D_{t,o}$) for the annular side.

$$Nu_i = \frac{h_i D_{t,i}}{k} \qquad Nu_o = \frac{h_o D_h}{k}$$

To determine Nu you will need an empirical correlation defined below.

For laminar flow (up to Re ≅ 2100), use the following correlation for the Nusselt number. Note, for laminar flow in the annulus the hydraulic diameter, use D_h (defined above) in place of D:

$$Nu = 1.86\left(Re \cdot Pr \cdot \frac{D}{L}\right)^{0.33} \qquad Re = \frac{\rho \underline{v} D}{\mu}$$

For turbulent or transitional flow (Re > 2100), use the following correlation for the Nusselt number:

$$Nu = \frac{\left(\frac{f}{2}\right) Re \cdot Pr}{1 + 8.7\left(\frac{f}{2}\right)^{0.5}(Pr - 1)} \qquad f = (3.64 \cdot ln\,(Re) - 3.28)^{-2}$$

where f = the friction factor.

For the tube side use the inside pipe diameter, $D_{t,i}$, to calculate the Reynolds number. For the annular side, use the hydraulic diameter, D_h. For both sides, evaluate fluid properties at the bulk temperature, defined below:

$$T_b = \frac{T_{in} + T_{out}}{2}$$

Calculate the fluid velocity using your experimentally-measured volumetric flowrate divided by the cross-sectional areas of the tube and annulus, shown respectively below:

$$A_{tube} = \frac{\pi}{4} D_{t,i}^2 \qquad A_{annulus} = \frac{\pi}{4}\left(D_a^2 - D_{t,o}^2\right)$$

Log-Mean Temperature Difference

4. From your experimental data for *countercurrent* flow, compute the log-mean temperature difference.

$$\Delta T_{LMTD} = \frac{\left(T_{h,in} - T_{c,out}\right) - \left(T_{h,out} - T_{c,in}\right)}{ln\left(\frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}\right)}$$

Heat Transfer Resistances

5. Compute the heat transfer resistances for the tube side, the tube wall, and the annular side using the heat transfer coefficients determined above.

$$R_{tube} = \frac{1}{h_i A_i} \qquad R_{wall} = \frac{ln\left(\frac{D_{t.o}}{D_{t.i}}\right)}{2\pi L N_t k_{wall}} \qquad R_{annulus} = \frac{1}{h_o A_o}$$

The inner (A_i) and outer (A_o) surface areas for heat transfer are:

$$A_o = \pi D_{t,o} L N_t \qquad A_i = \pi D_{t,i} L N_t$$

6. Compare the resistances. Is one of them controlling? Why or why not?

Overall Heat Transfer Coefficient and Predicted Heat Transfer Rate

7. Compute the overall heat transfer coefficient based on the sum of the individual resistances and from your experimental data, using the hot-side heat transfer rate calculated in Question 1. How do the values compare?

$$(UA_o)_{\ theory} = \frac{1}{R_{tube} + R_{wall} + R_{annulus}} = \frac{1}{\left(\frac{1}{h_i A_i}\right) + \frac{ln\left(\frac{D_{t.o}}{D_{t.i}}\right)}{2\pi L N_t k_{wall}} + \left(\frac{1}{h_o A_o}\right)}$$

$$(UA_o)_{\ exp} = \frac{\dot{Q}_{H,expermental}}{\Delta T_{LMTD}}$$

8. Using your experimental value for ΔT_{LMTD}, compute the predicted heat transfer rate using $\dot{Q} = (UA_o)_{\ theory} \Delta T_{LMTD}$ and compare it to the measured heat transfer rates calculated in Question 1 based on energy balances. Do the values agree? Explain and list possible reasons for any differences.

9. Using the energy balance equation and the equation for the predicted heat transfer rate $\dot{Q} = U_o A_o \Delta T_{LMTD}$, consider and ***qualitatively*** explain how the heat transfer rate would change if:

   A) You doubled the flowrate of the hot water.

   B) You halved the temperature difference between the hot and cold water.