Worksheet: Shell and Tube Heat Exchanger

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Name(s):____

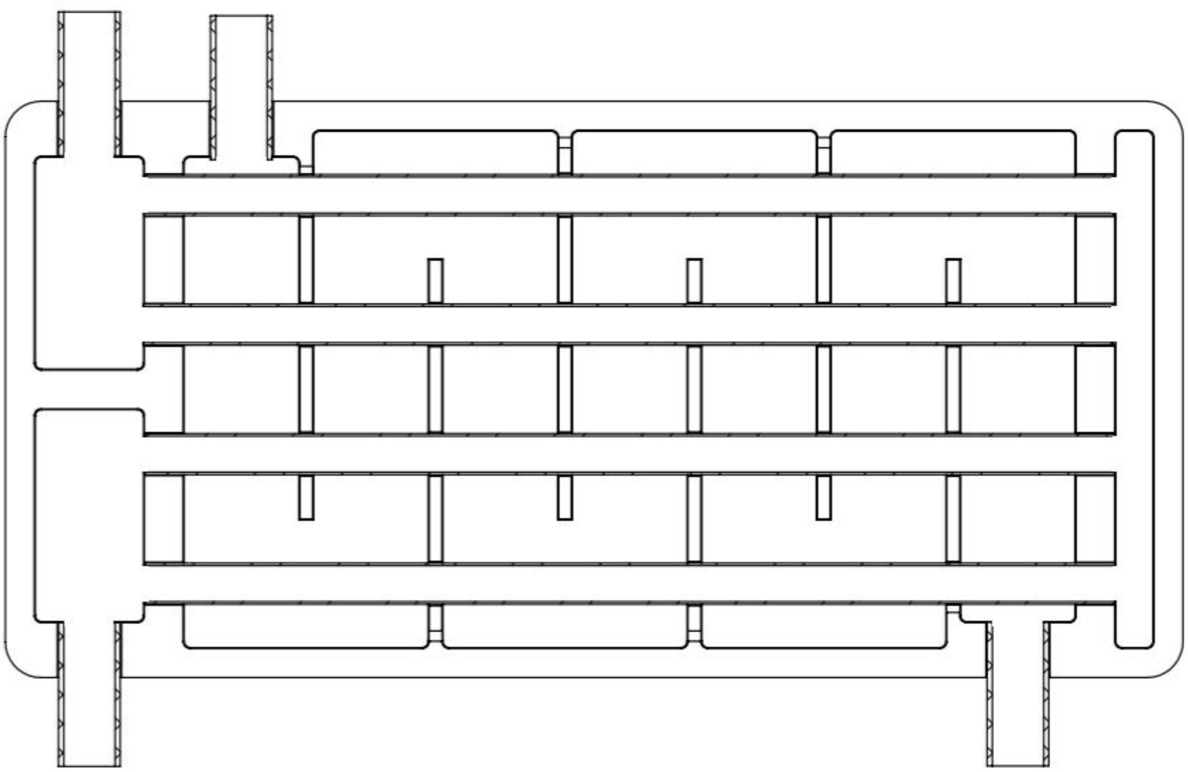
This digital experiment uses a shell and tube exchanger in countercurrent flow. Hot water is fed to the tube side and cold water is fed to the shell side, and heat transfer rates are calculated.

Student Learning Objectives

1. Identify flow patterns, inlets and outlets, and regions of counter, cross, and parallel flow.
2. Understand the difference between flow area and heat transfer area.
3. Determine experimental heat transfer rates.
4. Identify geometrical parameters used in heat-transfer correlations.
5. Determine the Reynolds number for the tube and shell sides.
6. Understand competing effects of design parameters on performance, including baffle spacing.
7. Calculate a correlated heat transfer coefficient and understand why it differs from a measured value.

Before Starting the Digital Experiment

Assuming hot fluid on the tube side and cold on the shell side, draw the expected flow patterns on onto the schematic labeling inlets and outlets of hot and cold fluids.



Determine and record the following quantities:

Number of tubes: ___________________ Number of baffles: ____________

Number of tube passes: _________________ Number of shell passes: ____________

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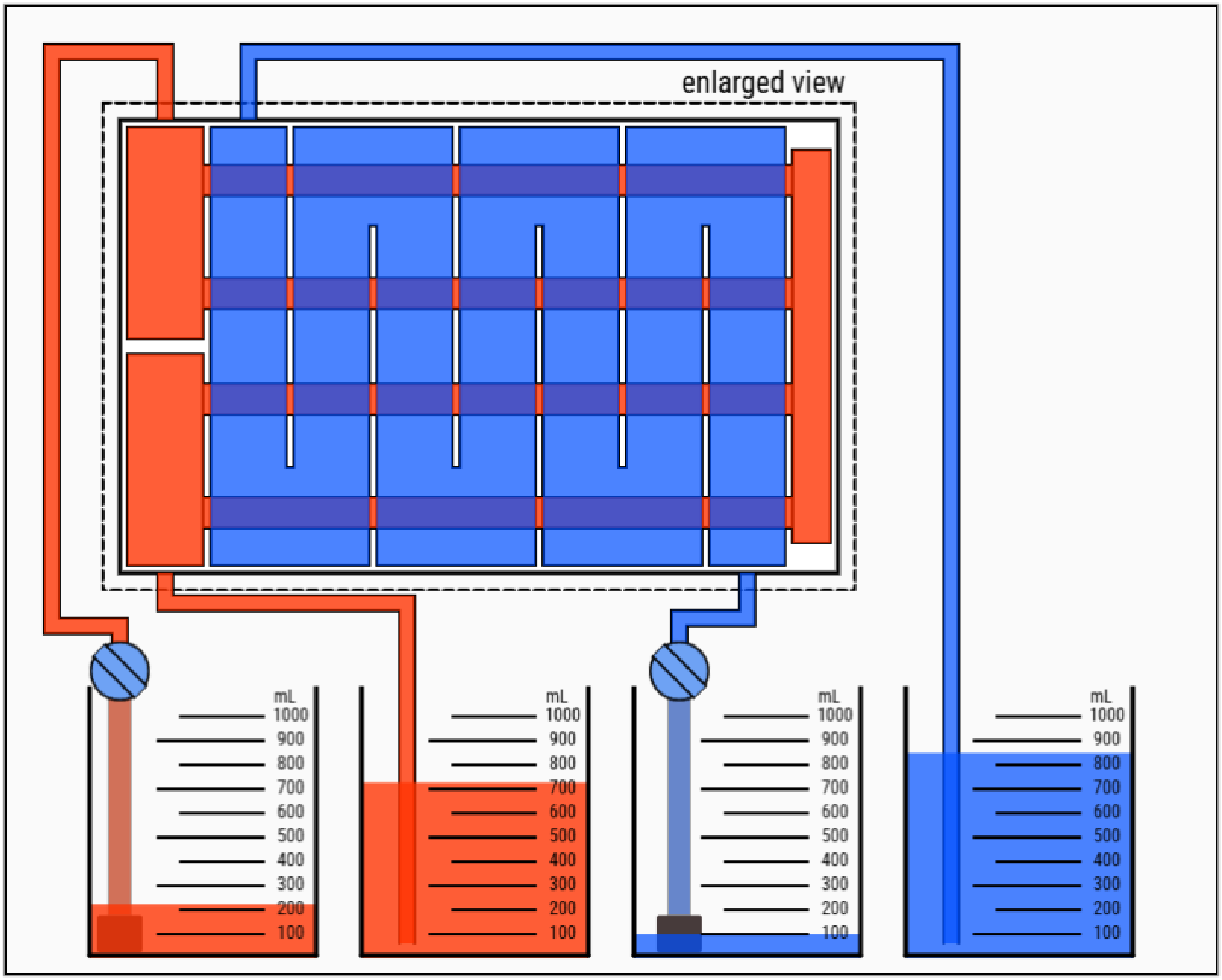
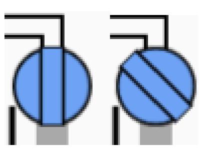
Equipment



The hot water is red, and the cold water is blue. Pumps are in the bottom of the two feed beakers, and flow rates are adjusted with the valves just above the feed tanks. The heat exchanger is enlarged relative to the beakers to make viewing the flow paths easier.

Valve position

Fully open Partially closed



Understanding Flow Paths and Measuring Heat Transfer Rate/Heat Duty

Experiment 1

a) The tube side beaker is filled with hot water (red) and shell side beaker with cold water.

b) Record temperatures (T_{in}) of the hot and cold water in Table 1.

c) Click "start pumps" to turn on both pumps. When *hot and cold water reach the outlet beakers*, ***start a timer.***

d) ***Before*** the inlet beakers are empty, turn off the pumps and ***stop timing*** simultaneously. The pumps turn off when either inlet beaker reaches 100 mL.

e) Measure and record in Table 1 the temperatures of the hot and cold water in the outlet beakers (T_{out}) *immediately after flow stops*.

f) Measure and record in Table 1 the water volumes in the hot and cold outlet beakers.

Table 1. Experimental data

Expt. #	Tube side (hot)			Shell side (cold)			time (s)
	T_{in} (°C)	T_{out} (°C)	V_h (mL)	T_{in} (°C)	T_{out} (°C)	V_c (mL)	
1							

1. If needed, **update your diagram on page 1** with the correct flow patterns for the hot and cold fluid.

Experiment 2: Effect of Temperature Driving Force on Heat Transfer Rate

a) Click "pour back" to pour the water from the outlet beakers back into the corresponding hot and cold inlet beakers.

b) Repeat steps c-g of Experiment 1 and record results in Table 2

Table 2. Experimental data

Expt. #	Tube side (hot)			Shell side (cold)			time (s)
	T_{in} (°C)	T_{out} (°C)	V_h (mL)	T_{in} (°C)	T_{out} (°C)	V_c (mL)	
2							

Driving Force for Heat Exchange

2. The heat transfer rate depends on the ***temperature difference between the hot and cold fluids***. Describe how the temperature difference between the hot and cold fluid changed from Experiment 1 to Experiment 2.

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3. Was the temperature change of the cold fluid (difference between outlet and inlet temperature) higher in Experiment 1 or Experiment 2?

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4. The experimental heat transfer rate can be calculated with an energy balance on the cold fluid, shown below, where $\dot{m}_c$ is the mass flow rate of the cold water, $C_{p,c}$ the heat capacity, and ΔT_c the temperature difference between the cold outlet and inlet fluid.

$$\dot{Q}_c = \dot{m}_c C_{p,c} \Delta T_c$$

5. Based on your answers to Questions 2 and 3 and considering the energy balance equation above, what is the relationship between the heat transfer rate ($\dot{Q}$) and the temperature difference between the hot and cold fluids? Does a higher temperature difference result in a higher or lower heat transfer rate?

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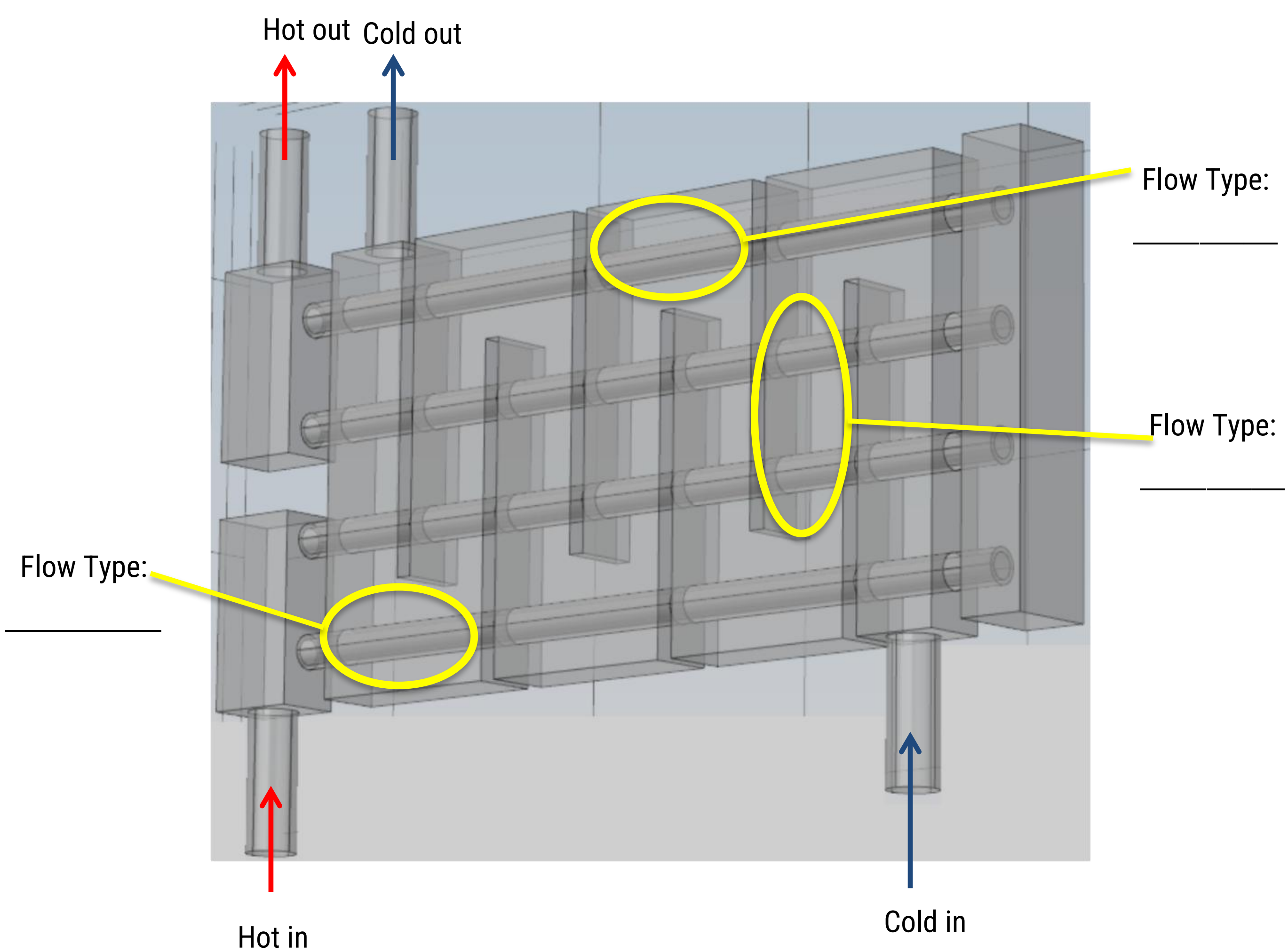
Heat Exchanger Flow Patterns

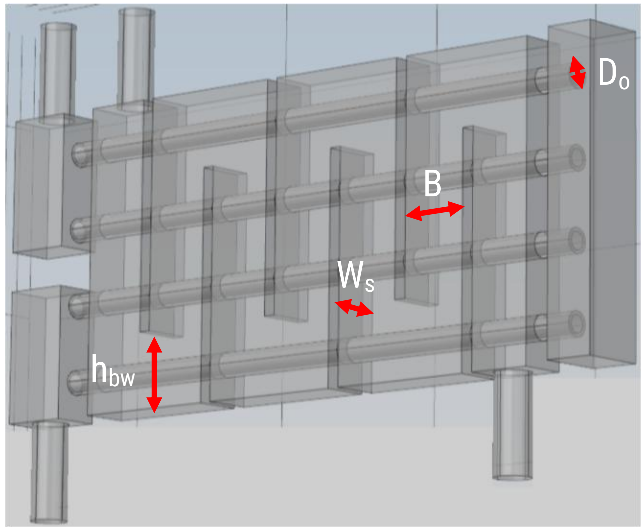
In the shell and tube heat exchanger, three types of flow occur:

a. Parallel flow: hot and cold fluids flow in ***the same*** direction.
b. Counter flow: hot and cold fluid flow in ***opposite*** direction.
c. Cross flow: cold fluid flows ***perpendicular*** to hot fluid.

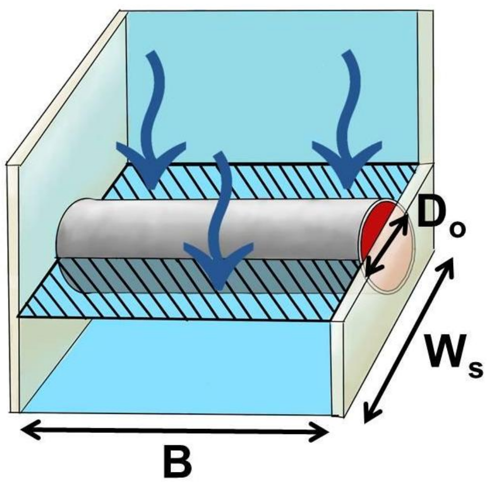
6. In the image below, for each circled region, identify whether parallel, counter, or cross flow is occurring. *Hint: trace the paths of the hot and cold fluid through the exchanger.*



Flow Areas in the Heat Exchanger



7. Referencing the schematic above and the diagram below, write a formula for the *cross-flow area*, A_c (represented by diagonal lines in the figure below), on the shell side. Blue arrows represent cold water flow direction.



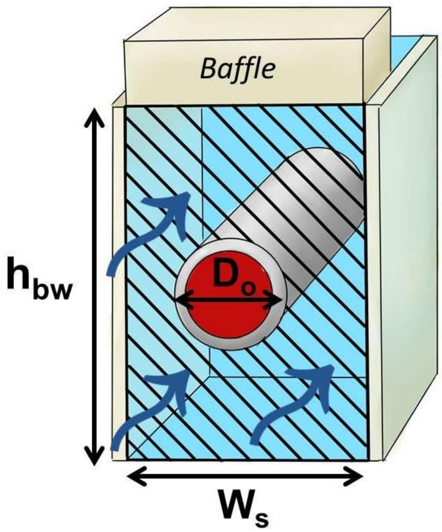
B = baffle spacing

W_s = width of shell

D_o = outer diameter of tube

A_c = ______________________

8. Referencing the schematic below, write a formula for *baffle window flow area, A_b* (represented by diagonal lines), on the shell side.



h_{bw} = height of baffle window

D_s = width of shell

D_o = outer diameter of tube

A_b = ______________________

Determining the Theoretical Heat Transfer Rate

We can calculate the ***theoretical*** overall heat transfer rate using a correlated heat transfer coefficient (U_o), the area available for heat transfer (A_o), the log mean temperature difference (ΔT_{LMTD}), and a correction factor (F).

$$\dot{Q} = U_o A_o \Delta T_{LMTD} F$$

9. Why must we include a correction factor, F, for the log mean temperature difference. Hint: consider how changing flow patterns in Question 6 affect heat transfer. Also, look at the equipment and consider how cold fluid on the shell side passes tubes containing differing temperature hot fluid as the cold fluid flows across the two passes of tubes.

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10. What area is used for A_o? How is this different from the areas in Questions 7 and 8? Consider where heat transfer from the hot to cold fluid occurs.

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11. The overall heat transfer coefficient, U_o, depends on individual shell- and tube-side heat transfer coefficients, which ***increase with Reynolds number***. Look at the figures on page 5. How will decreasing the baffle spacing (B) affect the shell-side Reynolds number and heat transfer rate?

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12. From your experimental data, how will you determine the velocity used to calculate the tube-side Reynolds number? Consider that flow splits between two tubes per pass.

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13. In determining the velocity for the shell-side Reynolds number, you divide volumetric flow rate by a cross-sectional area. Considering your answers to questions 7 and 8, why must we use an average velocity? Is the cross-sectional area on the shell side constant?

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Homework Problems Due: ___________

Reference Information for Shell and Tube Heat Exchanger DLM

- Tube length: L = 138 mm
- Tube type: ¼" BWG No. 20
- Tube dia. outer, D_o = 6.35 mm (0.25 in)
- Tube dia. inner, D_i = 4.572 mm (0.18 in)
- Tube material: stainless steel 304
- Number of tube passes, N_p = 2
- Baffle thickness: 2 mm
- Number of tubes per pass, N_t = 2
- Baffle spacing: B = 18 mm
- Shell width: W_s = 10 mm
- Shell height: 82 mm
- Baffle window height: h_{bw} = 21

Experimental Heat Duty

1. Calculate the rate of heat rejection for the hot fluid ($\dot{Q}_h$) and the rate at which the cold fluid receives heat ($\dot{Q}_c$) using your experimental data for Experiments 1 and 2. All physical properties should be calculated at the average fluid temperature.

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

$$\Delta T_c = \left(T_{c,out} - T_{c,in}\right) \quad \Delta T_h = \left(T_{h,in} - T_{h,out}\right) \quad \dot{m}_i = \rho \dot{V}_i \quad \dot{V}_i = \frac{V}{t}$$

Expt. #	$\dot{Q}_h$ [W]	$\dot{Q}_c$ [W]
1		
2		

2. Compare the heat rejection rates of the hot fluid for Experiments 1 and 2. Which is higher and why?

Predicted Heat Transfer Rate

3. Calculate the tube-side heat transfer coefficients for your experimental conditions. The velocity, $\underline{v}$ of the fluid through tube is:

$$\underline{v} = \frac{\dot{V}}{A \cdot N_t} = \frac{\dot{V}}{(\frac{\pi}{4} \cdot D_i^2) \cdot N_t}$$

The Reynolds number is:

$$Re = \frac{\rho \underline{v} D_i}{\mu}$$

The tube-side heat transfer coefficient can be found using the Sieder-Tate correlation for the Nusselt number (neglecting viscosity differences between the fluid at the wall and the bulk fluid):

$$\frac{h_i D_i}{k} = Nu_i = 0.023 Re^{0.8} Pr^{1/3}$$

Expt. #	Tube side		
	$\underline{v}\left[\frac{m}{s}\right]$	Re	$h_i\left[\frac{W}{m^2 {}^\circ C}\right]$
1			
2			

4. Calculate the shell-side heat transfer coefficients for your experimental conditions.

$$\frac{h_o D_o}{k} = Nu_o = 0.2 Re^{0.6} Pr^{1/3} \qquad \text{where: } Re = \frac{D_o G_{avg}}{\mu}$$

The weighted average mass velocity, defined below, is used in the shell-side Reynolds number:

$$G_{avg} = \sqrt{G_c \cdot G_b}$$

$$G_c = \frac{\dot{m}_c}{A_c} \qquad G_b = \frac{\dot{m}_c}{A_b}$$

$$A_c = B(W_s - D_o) \qquad A_b = h_{bw} W_s - \frac{\pi}{4} D_o^2$$

Expt. #	Shell side		
	$G_{avg}\left[\frac{kg}{m^2 s}\right]$	Re	$h_o\left[\frac{W}{m^2 {}^\circ C}\right]$
1			
2			

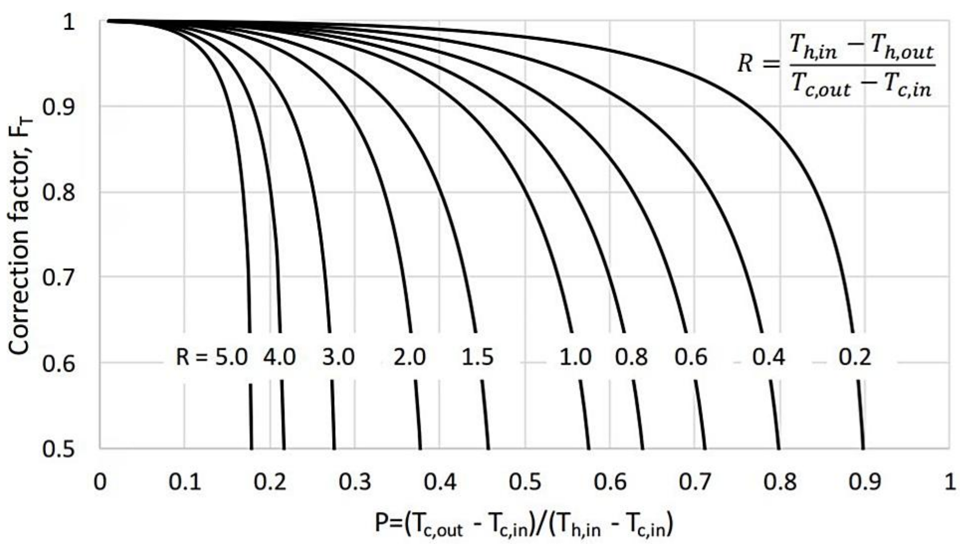
6. Calculate the log-mean temperature difference (ΔT_{LMTD}) and the heat transfer areas using the formulas below:

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

$$A_o = (\pi D_o L)N_t N_p \qquad A_i = (\pi D_i L)N_t N_p$$

Expt. #	ΔT_{LMTD} [°C]	A_o [m^2]	A_i [m^2]
1			
2			

6. Use the figure below and your experimental temperature differences to determine, F (the log-mean temperature difference correction factor) for each experiment.



Expt. #	F
1	
2	

7. Calculate the theoretical and experimental overall heat transfer coefficients for each experiment using the formulas below.

$$\frac{1}{(UA)_{theory}} = \frac{1}{h_o A_o} + \frac{ln\left(\frac{D_o}{D_i}\right)}{2\pi kL} + \frac{1}{h_i A_i} \qquad (UA)_{exp} = \frac{\dot{Q}_{h,measured}}{\Delta T_{LMTD} F}$$

Expt. #	$(UA)_{theory}\left[\frac{W}{°C}\right]$	$(UA)_{exp}\left[\frac{W}{°C}\right]$
1		
2		

8. Compare the predicted heat transfer rate to the measured heat transfer rate for each experiment. If the values do not agree, list possible reasons.

$$\dot{Q}_{h,predicted} = (UA)_{theory} \Delta T_{LMTD} F \qquad \dot{Q}_{h,measured} = \frac{\dot{Q}_{cold} + \dot{Q}_{hot}}{2}$$

Expt. #	$\dot{Q}_{h,predicted}[W]$	$\dot{Q}_{h,mesured}[W]$
1		
2		

What are reasons for difference in predicted vs. measured heat transfer rate? Hint: consider temperature driving force issues and evaporative cooling effects as hot fluid exits the DLM into the beaker.

Conceptual Question

9. What is the purpose of including baffles on the shell side of the heat exchanger? Consider the effects on velocity, Reynolds number, turbulence, and elimination of flow channeling on the shell side in the heat exchanger.