Small Shell and Tube Heat Exchanger

Foundations of Chemical Engineering Lab 101

Thursday B-1

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Nomenclature 3

1.0 Introduction 4

2.0 Experimental Methodology 5

2.1 *Equipment and Apparatus* 5

2.2 *Experimental Procedures* 7

3.0 Results 8

4.0 Analysis and Discussion of Results 14

5.0 Summary and Conclusions 20

6.0 References 21

Appendix A-1 22

Appendix A-2 34

Nomenclature

Variables	Description	Units
Q_c	Heat duty for cold fluid	W
Q_h	Heat duty for hot fluid	W
Q_l	Heat loss	W
m_c	Mass flow rate for cold fluid	g/s
m_h	Mass flow rate for hot fluid	g/s
C_p	Heat capacity of fluid	J/kg
ΔTlm	Log mean temperature difference $(\Delta T2-\Delta T1)/\ln(\Delta T2/\Delta T1)$	ºC
U	Overall heat transfer coefficient	$W/(m^2\ ºC)$
A	Heat transfer surface area	m^2

1.0 Introduction - Shell and tube heat exchangers are the most widely used industrial heat exchanger. The purpose of a shell and tube heat exchanger is to facilitate the transfer of heat between two liquids of differing temperatures. Their large ratio of area available for heat transfer to overall volume flow makes them a popular choice for engineers [1]. Shell and tube heat exchangers are generally used in large chemical processes for the heating or cooling of water, oil, gas, or other process fluids [2]. They can also serve the same purpose in a variety of smaller scale operations. Small shell and tube heat exchangers are utilized heavily during the scale-up process of reactions at pilot plants [2]. They are versatile tools that can be easily modified to fit specific applications.

In all shell and tube heat exchangers, one fluid flows through the shell and another fluid flows through tubes inside of the shell. Figure 1 shows the small shell and tube heat exchanger used in this experiment. The outer red component is the shell which contains the hot fluid. The tubes containing the cold fluid are located inside of the shell.



Figure 1. Shell and tube heat exchanger used for experiment.

During operation, heat flows from the higher temperature fluid to the lower temperature fluid by conduction through the tube walls. Modeled by the equation

$$Q_h = Q_c + Q_L, \quad (1)$$

the overall heat transfer of this process is composed of the heat input to the cold side flow (Q_c), the heat loss from the hot side flow (Q_h), and the additional heat loss to the environment (Q_L). Because the hot side fluid is at a greater temperature than the surroundings and the shell is not well insulated, a significant amount of heat is lost from the system leading to a considerable Q_L.

The equation that gives the cold side heat duty is

$$Q_c = m_c \cdot C_p \cdot \Delta T, \quad (2)$$

and the equation that gives the hot side heat duty is

$$Q_h = m_h \cdot C_p \cdot \Delta T, \quad (3)$$

where m_c and m_h are the mass flow rates of the cold and hot side fluids respectively, C_p is the specific heat capacity of the fluid, and ΔT is the temperature difference between the inlet and outlet stream for either relevant side. The equations illustrate that the individual heat duties can be manipulated by varying the mass flow rates of the fluids. Ultimately, the process can be analyzed as a whole by computing the overall heat transfer coefficient, U. This value can be calculated using the equation,

$$Q_c = U \cdot A \cdot \Delta Tlm \cdot F \quad (4)$$

where A is the heat transfer area, ΔTlm is the log mean temperature difference, and F is the correction factor. Using these equations, one can study the effects of changing process variables such as the fluid type, the heat transfer surface area, or the mass flow rates of either the hot side of cold side streams on a shell and tube heat exchanger.

This project focuses on analyzing the effects of altering the flow rates of the process fluids on a small shell and tube heat exchanger. In this lab, water was used as the hot, shell-side fluid and the cold, tube-side fluid. Several trials were run where the shell-side flow rate was varied while the tube-side flow rate was kept constant. Trials were also run where the tube-side flow rate was varied and the shell-side flow rate was kept constant. The objectives of this lab were to analyze the effects of these variations on the steady-state heat duties and overall heat transfer coefficient of the heat exchanger for each case.

2.0 Experimental Methodology

2.1 *Equipment and Apparatus* – A small shell and tube heat exchanger was used to carry out the technical objectives in the experiment to determine how varying the tube-side and shell-side flow rates affected the overall heat transfer coefficient of the heat exchanger. The actual heat exchanger equipment is shown in Figure 2.

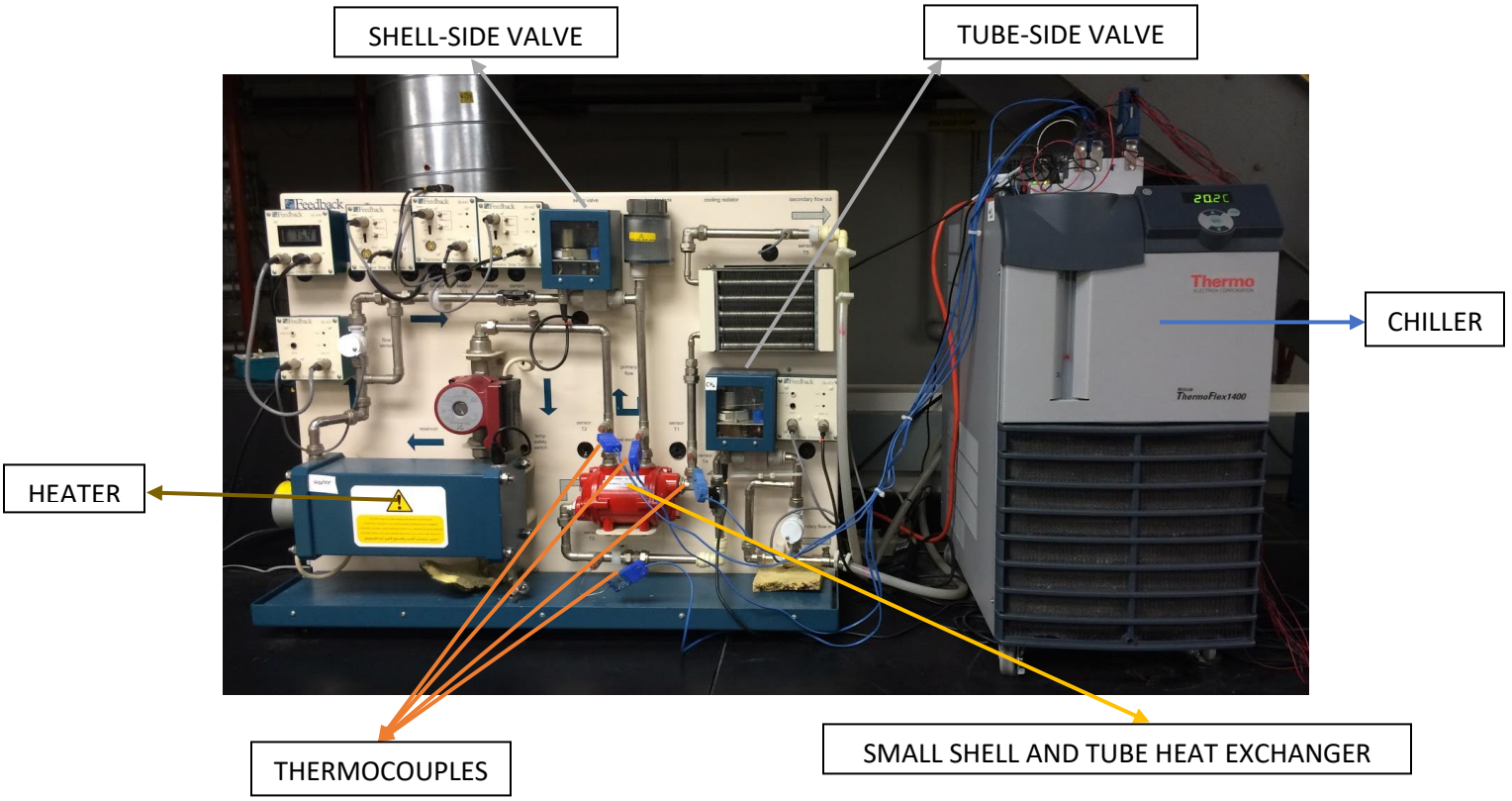


Figure 2. Actual Equipment Used in the Experiment

The main parts of the equipment include a chiller, heater, tube and shell valves, thermocouples, and small shell and tube heat exchanger. The apparatus allows for the control of two variables, tube-side flow and shell-side flow. During the experiment, the tube-side, cold flow moves through the chiller that cools it to 20 degrees Celsius. After the cooling process, the tube-side valve was used to set the tube-side flow to the required flow rate that enters the small shell and tube heat exchanger. The shell-side, hot flow enters a heater that warms the shell-side flow. Like the tube-side flow, the shell-side flow was also controlled by a valve, the shell-side valve, to set its desired flow rate into the small shell and tube heat exchanger. The two flows then enter the heat exchanger, diagrammed in Figure 3, where heat transfer takes place and tube and shell input and output temperatures are measured by thermocouples.

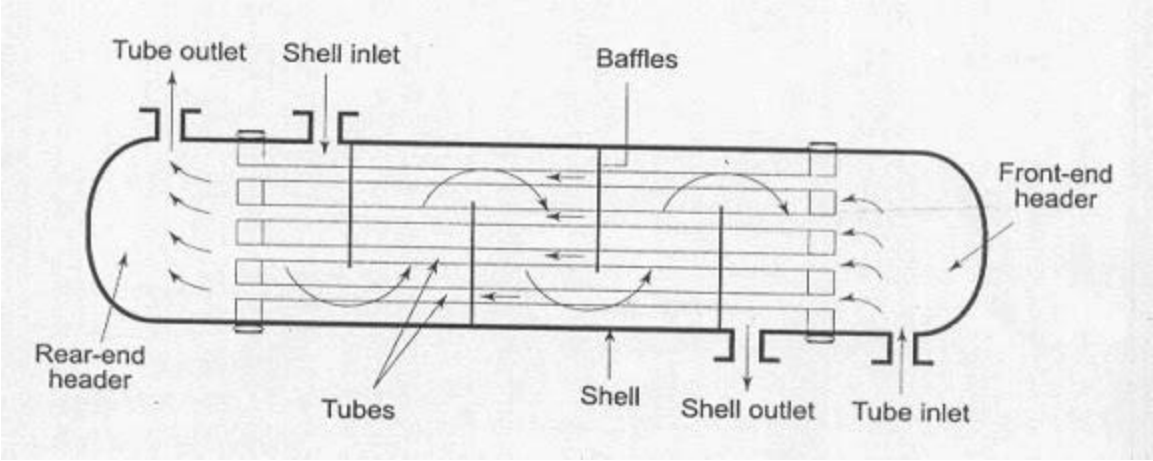


Figure 3 [3]. A Cross Section of a Shell and Tube Heat Exchanger

As shown in Figure 3, there is an inlet and outlet for both the tube, cold side, and the shell, hot side. Water is used as the fluid for both inlets in this experiment. During operation, cold water flows through the tubes while hot water flows outside of the tubes through the shell. The baffles help support the tubes and stabilize them during flow-induced vibrations [1]. They also serve the key function of guiding the shell-side flow, which maximizes heat transfer [1]. Because the fluids are held in separate containers, they never physically mix. Heat transfer results from the contact of the shell flow with the tubes containing the tube flow. The heat from the hot fluid is transferred to the tubes of the cold flow by conduction and then transferred to the water flowing through the tubes.

2.2 *Experimental Procedures* – The first technical objective was to evaluate the effect of the tube-side flow rate on the steady state heat duty and the overall heat transfer coefficient of the heat exchanger. The data needed for this evaluation were found by varying the tube-side flow rate and keeping the shell-side flow rate constant. The tube-side flow rate was varied by changing the percent opening in the tube valve. For the first objective the shell-side valve was held constant at 50% open because only the tube flow was being varied.

For the first trial, the tube-side valve was set to 10% open while the shell-side valve was set to 50% open. The flow rates were held constant until the system reached steady state. Steady state in this experiment was defined as the stabilization of both outlet temperatures.

The temperatures were captured by thermocouples linked to software where they could be monitored to determine when steady state was reached. When the graphed temperature lines of both the shell and tube outlet streams leveled off, it was clear that the system was at steady state. Once steady state was reached, the tube side was set to 30% open until steady state was reached. The tube-side valve was then set to 60% open and 100% open, and in both cases steady state was reached before continuing.

The second technical objective was to analyze the effect of the shell-side flow rate on the steady state heat duty and the overall heat transfer coefficient of the heat exchanger. The same procedure was followed as in the first technical objective, but in this case the tube-side flow rate was held constant and the shell-side flow rate was varied. The tube-side valve opening was held constant at 50% open and the shell side was set initially at 10% open. After outlet temperatures reached steady state for the 10% open shell-side valve flow rate, the shell side was set to 30% open, 50% open, and 70% open, respectively. For each of the varied shell valve openings, outlet temperatures were required to reach steady state before continuing.

For both objectives, data needed to analyze the overall heat transfer coefficient of the heat exchanger was collected by the software program, LabVIEW, which arranged the data in a Microsoft Excel file. The file contained information on the tube and shell flow rates, inlet and outlet temperatures, and the time in seconds. The information was then used to complete the analysis described in the objectives.

3.0 Results – Data was recorded in LabVIEW and exported to Microsoft Excel. Each of the averaged values listed in Tables 1 through 3 were obtained by averaging the last ten data points in each trial. These ten data points for each parameter in each trial can be found in Appendix A-1. Each mass flow rate was found using the average volumetric flow rate of the shell and tube sides, dividing that number by sixty to convert it into liters per second, and multiplying by the density of water. Equations 2 and 3 were used to find the heat duty of the tube side and the hot side, respectively. The heat capacity (Cp) of water, 4.184 J/(g

°C), was used for each trial and each equation. ΔT was found by subtracting the incoming water temperature from the outgoing water temperature for each heat duty.

After the heat duty was found from Equations 2 and 3, Equation 1 was used to find the heat lost to the environment during each trial. Since the shell of the heat exchanger was exposed to the surroundings and the temperature of the shell was greater than the outside temperature, heat from the shell diffused to the surrounding air. This loss in heat was calculated using Equation 1. Equation 4 was then used to find U, the heat transfer coefficient for each trial. All calculated values can be found on Appendix A-1.

Tables 1 through 3 show the results of the collected data. Detailed calculations of the first trial, tube side open 10% and shell side open 50%, can be found in Appendix A-2.

TABLE 1

Results of the First Technical Objective (First Trial)

Tube Side Flow (L/min)	Shell Side Flow (L/min)	Qc (W)	Qh (W)	Ql (W)	U (W/m^2*°C)
1.2835	3.8675	878.317173	-1595.507732	-717.190559	1523.15189
2.8411	3.8553	930.665756	-1708.7656	-778.099844	1863.961747
4.1926	3.8153	918.052113	-1665.575269	-747.523156	2077.83957
4.7978	3.7897	903.062131	-1611.033101	-707.97097	2170.333686

TABLE 2

Results of the Second Technical Objective

Tube Side Flow (L/min)	Shell Side Flow (L/min)	Qc (W)	Qh (W)	Ql (W)	U (W/m^2*K)
3.8661	1.2651	832.323854	-1460.714333	-628.390479	1450.023655
3.8761	2.3434	895.31977	-1585.580903	-690.261133	1820.70128
3.8605	3.8051	903.238405	-1636.153731	-732.915326	2042.886082
3.8657	5.1363	895.613211	-1680.468199	-784.854989	2136.948468

TABLE 3

Results of the First Technical Objective (Second Trial)

Tube Side Flow (L/min)	Shell Side Flow (L/min)	Qc (W)	Qh (W)	Ql (W)	U (W/m^2*°C)
3.8661	1.2651	832.323854	-1460.714333	-628.390479	1450.023655
3.8761	2.3434	895.31977	-1585.580903	-690.261133	1820.70128
3.8605	3.8051	903.238405	-1636.153731	-732.915326	2042.886082
3.8657	5.1363	895.613211	-1680.468199	-784.854989	2136.948468

Figures 4 through 12 describe the information in Tables 1 through 3.

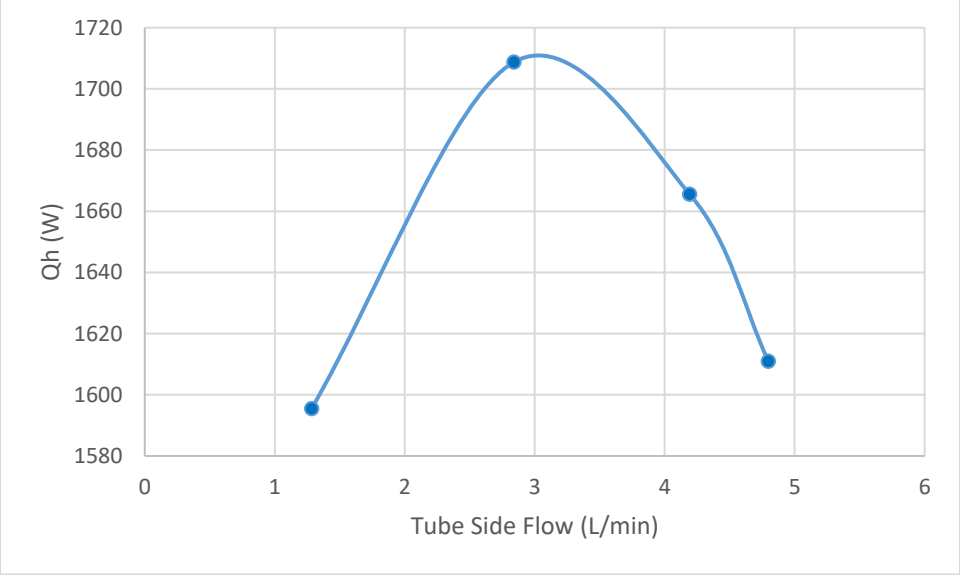


Figure 4. Q_h (W) against Tube-Side Flow Rate (L/min) (From Table 1)

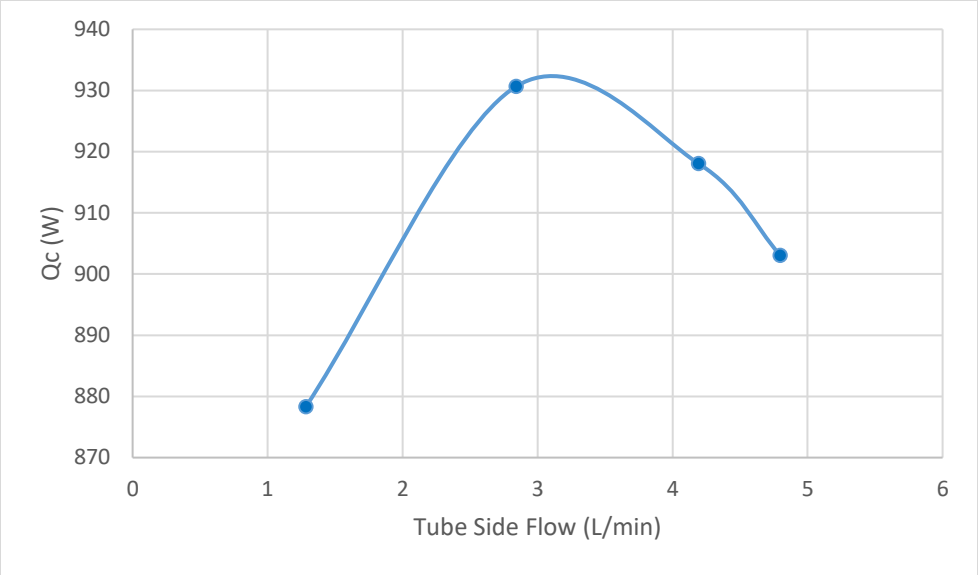


Figure 5. Q_c (W) against Tube Side Flow Rate (L/min) (From Table 1)

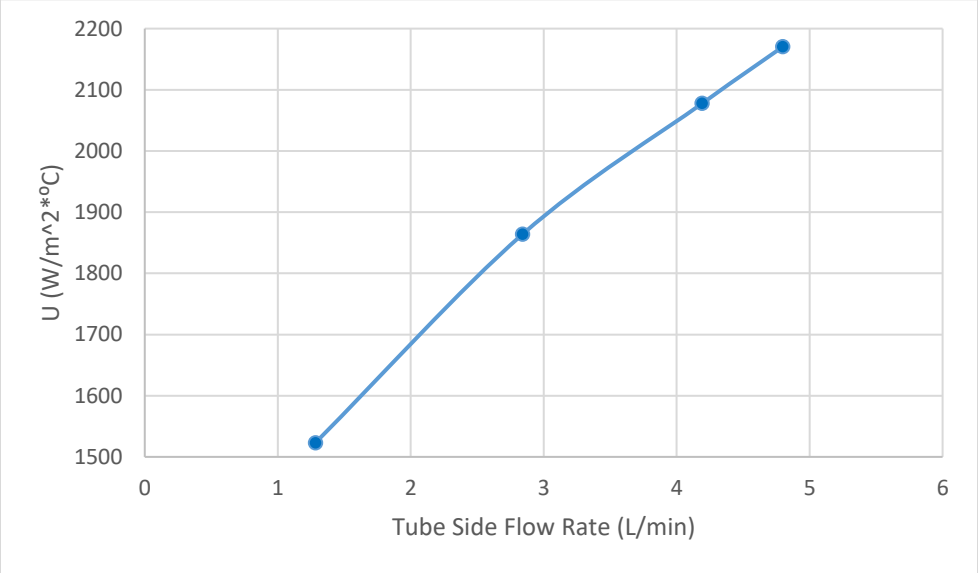


Figure 6. U ($W/m^2 \cdot °C$) against Tube Side Flow Rate (L/min) (From Table 1)

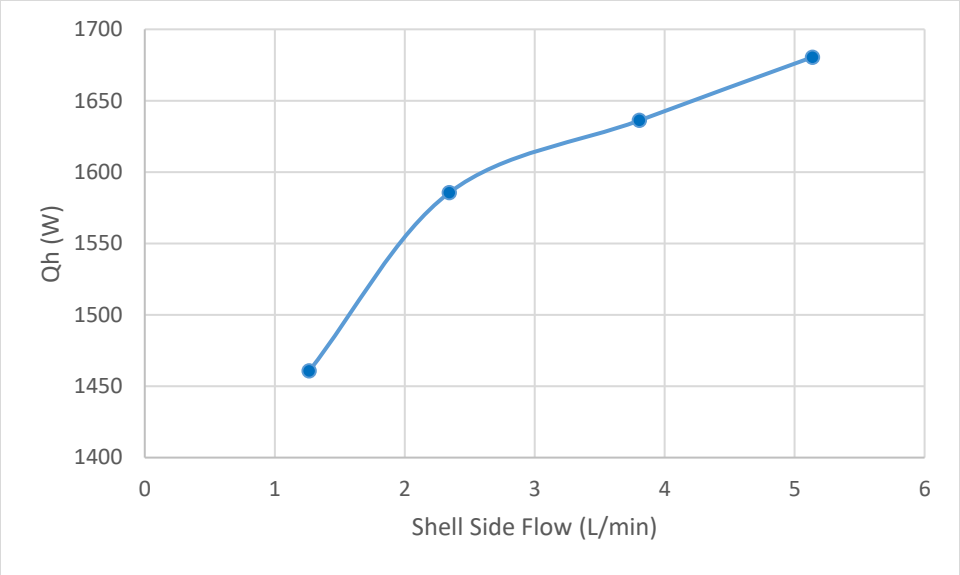


Figure 7. Q_h (W) against Shell Side Flow Rate (L/min) (From Table 2)

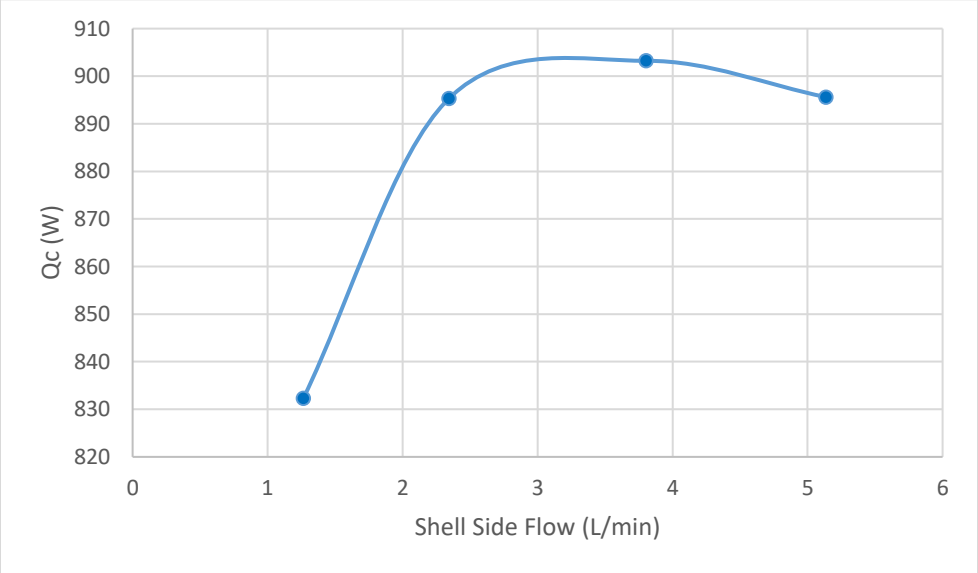


Figure 8. Q_c (W) against Shell Side Flow Rate (L/min) (From Table 2)

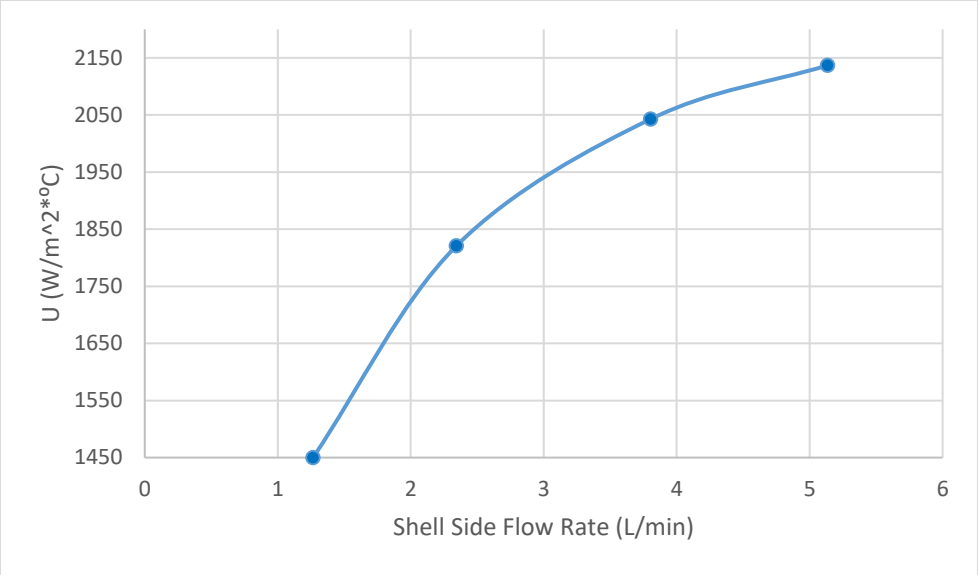


Figure 9. U (W/m^{2}·°C) against Shell Side Flow Rate (L/min) (From Table 2)

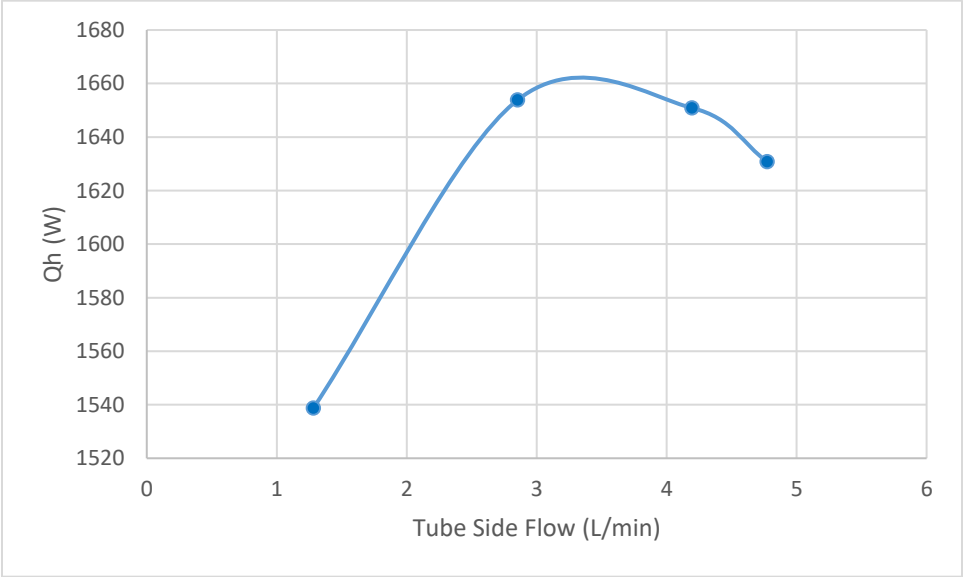


Figure 10. Q_h (W) against Tube Side Flow Rate (L/min) (From Table 3)

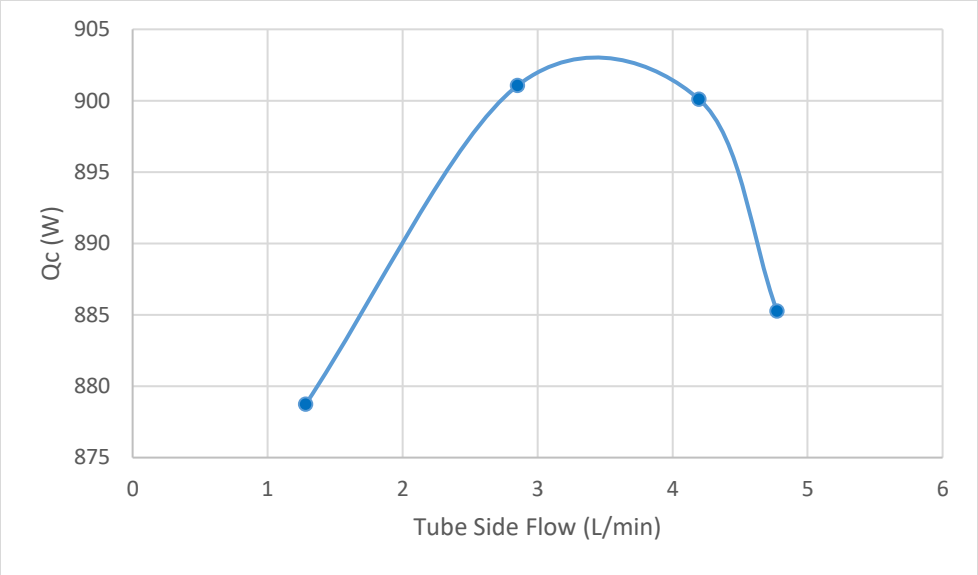


Figure 11. Q_c (W) against Tube Side Flow Rate (L/min) (From Table 3)

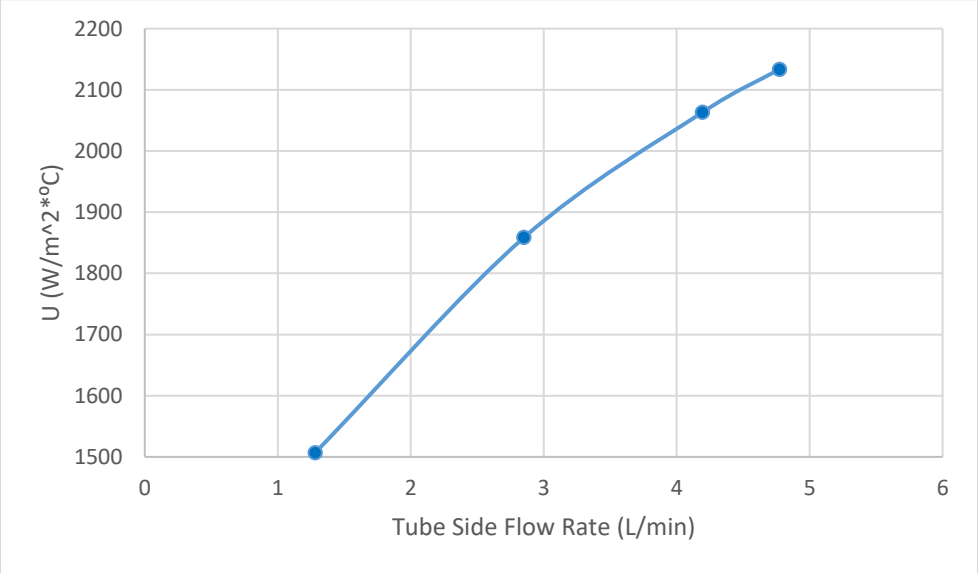


Figure 12. U ($W/m^2 \cdot {}^oC$) against Tube Side Flow Rate (L/min) (From Table 3)

4.0 Analysis and Discussion of Results - The first technical objective involved changing the percentage opening of the tube-side valve (10%, 30%, 60% and 100%) while holding the shell-side flow rate constant at 50%. This varied the rate at which cold water entered the small shell and tube heat exchanger. Each time the valve in the tube side was opened, the flow rate of water was expected to increase because more water was able to pass through. The collected data in Table 1 showed that the flow rate indeed changed as the valve opened.

For each trial, the temperatures at each water entry and exit point were recorded using thermocouples. As the amount of cold water entering the heat exchanger increased, the temperature of the hot water leaving decreased. This was because the additional cold water was able to absorb more of the heat from the shell-side inlet stream. The temperature of the hot water entering the exchanger also decreased as the tube-side valve was opened. Because the flow rate was continuous and the water of the shell side was recycled, the heater for the shell side was not able to raise the temperature of the recycled water to the initial entry temperature. Since the flow rate of the tube side was increasing, it was expected that the temperature of the stream exiting the cold side would decrease. Because the tube-side flow rate was increased, the exchanged heat was dispersed through more water.

One of the goals of the technical objectives was to analyze the effects of varying the respective flow rates on the heat duty of the hot and cold sides as well as the heat lost. The heat duties for the hot and cold sides refer to the transfer of heat for each respective side. Shown in Equation 3, the heat duty of the hot side depended on the temperature difference between the shell-side inlet and outlet, which was due to the exchange of heat, the mass flow rate, and the specific heat capacity of water. As the tube-side flow rate was increased for each trial, Q_h and Q_c both initially increased. After reaching an optimum point, the heat duties decreased. This is shown in Figures 4 and 5, respectively. The heat duties reached a maximum measured value at 30% open. Equation 2 was used to solve for the heat duty of the cold side and was also dependent on the same parameters as Equation 3. Since the same heat exchange occurred between the shell side and tube side, it was expected to see this same trend.

This result was unexpected. It was expected that the heat duties would continuously increase with the increasing flow rate. This may suggest that there is an ideal state in which the heat duties are the most effective in response to the flow rates. Since there was more water flowing through the system as the valve opening was increased, there was more heat flowing through the system, but the water was not flowing slow enough to allow an adequate amount of time for the heat to be transferred from the hot to the cold.

In an ideal situation, the heat entering the system needs to be equal to the heat leaving the system. As observed in the data, Q_c and Q_h were different. This was because of heat loss in the shell side due to lack of insulation. Therefore, Equation 1 was used to calculate heat loss (Q_L). When heat (Q) is lost from a system, the value of Q is negative, which explains why Q_L from the calculations is negative as shown in Table 1. These values were based upon Q_h and Q_c, which was why there was once again an increase when the valve was opened to 30% and a decrease afterwards.

The second technical objective was to keep the tube-side valves at a constant opening while varying the shell-side valves of the heat exchanger. This analysis offers a perspective on the effects of changing the flow rates of the hot side of a heat exchanger instead of varying the cold side. As the valves of the shell side expanded to let more hot water through the small shell and tube heat exchanger, the flow rate increased as shown in Table 2. This is because the valves were less restricted and the water could flow at a higher rate.

At the outlet of the shell-side flow, the temperature increased very slightly as the valve expanded. According to the results, the temperature increased only by about 0.1 ^{0}C for each trial. This happened because when volumetric flow rate increased, the mass flow rate also increased. Since more mass flows through the shell side when the valves open up, the tube side has to cool down more hot water, which increases the temperature at the end of the shell side. The temperature of the inlet shell-side stream decreased for each trial. This is most likely because the heater that the hot water runs through was not able to increase the temperature to the initial temperature before cooling. The same water was recycled for each trial, so this was an apparent issue. The temperature of the tube-side inlet stayed about the same for each trial because the valve was not changed for the tube side during these experiments, and the chiller cooled at a constant rate throughout the trials. The outlet temperature for the tube side, on the other hand, increased as the shell-side valve increased. This was because as more hot water went through the heat exchanger, more heat was transferred to the cold water, thereby increasing the temperature of the cold water in the tube side.

The heat duties for each trial were also calculated. As the shell-side valves expanded, Q_h increased in magnitude. According to Equation 3, if the mass flow rate of the hot water, m_h, increases, the heat duty (Q_h) of the shell side is also going to increase, as shown in Figure 7. When the valve opened, more hot water flowed through the heat exchanger, causing this effect. The value of Q_h was negative because the temperature of the hot water decreased as it moved through the heat exchanger, creating a negative ΔT value. Q_c also generally increased as the shell-side valve expanded, as shown in Figure 8. This is because ΔT for the tube side increased in value for each trial except for the last. These increases in ΔT, therefore, increased Q_c according to Equation 2. However, the last trial strayed from the others, as ΔT decreased in this case. This could be due to the loss of heat to the surroundings, which would make the temperature at the outlet tube-side stream decrease. Regarding Q_L, the value increased for each trial, as shown in Table 2. This makes sense because as the shell-side valve expands more for each trial, more hot water travels through the heat exchanger. Because of this, the heat from the shell side diffuses into the air through the metal that encloses the heat exchanger at a higher rate, allowing for Q_L to increase as flow rate increases.

When the shell side was left at 50% open, the tube-side heat duty, Q_c, was at a maximum, as shown in Figure 8. This adds to the suspicion that there is a point at which the heat duty is the most effective. The reasoning for this is the same as explained above for the trials in which the tube-side flow rate was varied.

After completing the two technical objectives, the first objective was repeated. The flow rate of the shell side was once again held at 50% open while the tube side varied at 10%, 30%, 60% and 100%. The same results were expected for each trial. Table 3 shows the results of this objective.

The temperature for the tube-side inlet stream was essentially constant for each trial since it was continuously cooled chiller. The tube-side outlet stream temperature decreased, which caused the change in tube-side temperature to decrease. This was the same result as

before. Once again, the change in the shell-side temperature was almost the same for each variance.

The heat duty was calculated for both the tube side and the shell side. The largest heat exchange occurred when the valve was opened to 30% giving a peak in the heat duties, as seen in Figures 10 and 11. After that point, both heat duties decreased. After performing this objective for the second time, the trends remained the same. This means that there must be a maximum value for each heat duty. Although the data showed a maximum heat transfer at 30% open, this does not mean that this point is the optimum point. There may have been a value in between 30% open and 60% open that showed a max, as shown in Figures 10 and 11. One trial that was not performed during this first objective was when the tube and shell side were both open to 50%. The results from the second objective when both valves were 50% open showed a greater heat duty value. Therefore, a maximum heat duty could occur when the tube side and shell side flow rates are both equal. This explains why there was not a consistent increase in heat duties. Overall, the heat duties and the heat loss were similar for both trials of the first technical objective.

To complete the technical objectives for this experiment, the overall heat transfer coefficient, U, was calculated and analyzed. The heat transfer coefficient provides a quick and easy way to visualize how changing the flow rates impacts the heat transferred between the hot and cold water in the small shell and tube heat exchanger. The overall heat transfer coefficient depends on properties of both the tube material and the liquid flow. This experiment was completed without changing the liquid medium or the shell and tube material, so the heat transfer coefficient can be calculated easily using the cold-side heat duty, the heat transfer area for the tubes (50 square inches), the log mean temperature difference, and a correction factor of 0.96 since the system was not completely insulated. The log mean temperature can be calculated by dividing the difference between ΔT_2 and ΔT_1 by the natural log of the quotient of dividing ΔT_2 by ΔT_1. The equation is

$$\Delta Tlm = (\Delta T_2 - \Delta T_1)/\ln(\Delta T_2/\Delta T_1), \quad (5)$$

where ΔT_2 is the difference between the temperature of the shell-side inlet and the tube-side outlet, and ΔT_1 is the difference between the temperature of the shell-side outlet and the tube-side inlet.

Equation 4 is used to solve for variable U, the overall heat transfer coefficient. The heat transfer coefficient essentially represents how effectively heat is transferred from one substance to another. In this experiment, it represents how effectively heat was transferred between the hot shell side and the cold tube side. Generally, higher values for U indicate that heat was transferred more effectively while lower values of U indicate that the heat transfer is not as efficient or effective. Figures 6, 9, and 12 show how U changed for each objective as flow rate increased. To support what was previously stated, generally, increasing the flow rate of either the shell side or the tube side causes a larger change of temperature for both hot and cold streams, until a certain point. After this optimum point, if you increase the flow rate any more, the temperature change will decrease. If the fluid is flowing through the system very quickly, having a large flow rate, then the time that the fluid has in contact with the shell and tube is significantly less. This equates to a smaller timeframe to transfer the heat, which results in a smaller temperature change. Until this optimum point, increasing the flow rate directly relates to an increase in the change in temperature. After the optimum point, change in temperature will decrease.

For the first technical objective, the lowest overall heat transfer coefficient, 1523.15 $W/(m^2 \cdot ^oC)$, was found when the tube side was 10% open and the shell side was 50%. The largest overall heat transfer coefficient, 2170.33 $W/(m^2 \cdot ^oC)$, was found when the tube side was 100% open and the shell side was 50% open. Again, this supports that increasing the flow rate allows more heat transfer to occur, since more mass is flowing through the system in a given time. This allows for more heat to be transferred, which increases the overall heat transfer coefficient. Similar results were found for the second technical objective. The smallest heat transfer coefficient, 1450.02 $W/(m^2 \cdot ^oC)$, was found when the tube side was 50% open and the shell side was 10% open. The largest heat transfer coefficient, 2136.94 $W/(m^2 \cdot ^oC)$, was found when the tube side was 50% open and the shell side was 70% open.

Figures 6, 9, and 12 show that the overall heat transfer coefficient (U) seems to begin to level off as the flow rate of the shell and tube sides increase. This is because the pipes have limits to how much water can flow through them. For instance, the valves cannot be opened to 200%. So as the valves were opened, the heat transfer coefficient began to reach its threshold for the specific heat exchanger that was used. To increase heat transfer, one could either increase surface area or change the fluid to something denser than water in order to increase the mass flow rate, because the exchanger can only feed so much liquid (100% open valves).

5.0 Summary and Conclusions - In these experiments, the effects of flow rates on heat transfer in a small shell and tube heat exchanger were examined. The two technical objectives of this procedure were to evaluate the effect of the tube-side flow rate on the steady state heat duty and the heat transfer coefficient and to evaluate the effect of the shell-side flow rate on the steady state heat duty and the heat transfer coefficient.

A small shell and tube heat exchanger was used with water as both the hot shell side and cold tube-side fluid. To achieve the first objective, the flow rate of the tube side was varied while the flow rate of the shell side was kept constant at 50% open. A trial was performed with the tube side at 10% open, 30% open, 60% open, and 100% open. For the next objective, the flow rate of the hot shell side was varied while the flow rate of the cold shell side was kept constant at 50% open. A trial was performed with the shell side set at 10% open, 30% open, 50% open, and 70% open.

When the tube-side flow rate was varied, the heat duty for the cold side and hot side reached highest magnitudes at 30% open. This was also where the magnitude of heat loss was the highest. When the shell-side flow rate was varied, the heat duty for the hot side and the heat loss increased in magnitude as flow rate of the shell side increased. The heat duty for the cold side reached a maximum when the shell side was 50% open. Heat loss was large when heat duty for the hot side was large in both experiments.

As the tube-side flow rate increased, the overall heat transfer coefficient also increased. The same trend occurred as the shell-side flow rate increased. The heat transfer coefficient measures the effectiveness of heat transfer. It appears that increasing the flow rate of either fluid will increase the effectiveness of heat transfer.

On a larger scale, these trends may be different for a number of reasons. One reason for a difference in the effectiveness of heat transfer is better insulation, which would minimize the heat loss. Another difference could come from a greater surface area for heat transfer in the tubes. Differences might also be observed for different fluids or for a small shell and tube heat exchanger made of different materials. However, on the scale of the small shell tube and heat exchanger that was used in this lab, it can be concluded that higher flow rates in the tube side and in the shell side will lead to the most effective heat transfer.

6.0 References

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[3] "Types of Heat Exchangers." (2011, June 7). *Chemical Engineering Blog Spot.* (online article). http://chemicalengineeringdata.blogspot.com/2011/06/types-of-heat-exchangers.html

Appendix A-1
Experimental Data

As stated in the "Results" section, the each averaged value in the Microsoft Excel charts was obtained using the last ten data points in each trial run to ensure that the system was at equilibrium. The data used for each trial are displayed in Tables A-1.1 through A-1.12.

Table A-1.1

Tube Side: 10% Open, Shell Side: 50% Open (First Trial)

L/min(cold)	L/min(hot)	Hot In (deg.	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
1.284	3.886	47.432	41.541	20.961	30.738
1.289	3.897	47.568	41.589	20.98	30.768
1.274	3.847	47.662	41.641	20.993	30.806
1.288	3.868	47.491	41.602	20.941	30.817
1.258	3.804	47.518	41.598	21	30.794
1.278	3.877	47.532	41.59	20.972	30.795
1.282	3.881	47.542	41.635	21.004	30.825
1.296	3.881	47.403	41.561	20.944	30.781
1.305	3.854	47.437	41.536	20.964	30.748
1.281	3.88	47.432	41.564	20.965	30.785

Table A-1.2

Tube Side: 30% Open, Shell Side: 50% Open (First Trial)

L/min(cold)	L/min(hot)	Hot In (deg.	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
2.834	3.838	42.185	35.979	20.631	25.339
2.854	3.849	42.242	35.935	20.65	25.375
2.812	3.766	42.148	35.895	20.679	25.342
2.837	3.937	42.139	35.86	20.64	25.294
2.843	3.858	42.298	35.905	20.654	25.349
2.796	3.856	42.342	35.941	20.638	25.303
2.809	3.9	42.31	35.941	20.637	25.366
2.88	3.884	42.459	35.948	20.635	25.353
2.88	3.79	42.433	35.966	20.646	25.343
2.866	3.875	42.323	35.949	20.638	25.359

Table A-1.3

Tube Side: 60% Open, Shell Side: 50% Open (First Trial)

L/min(cold)	L/min(hot)	Hot In (deg.	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
4.26	3.769	39.839	33.605	20.844	23.994
4.179	3.846	39.875	33.582	20.844	23.974
4.16	3.747	39.78	33.575	20.816	23.953
4.145	3.842	39.784	33.547	20.821	23.938
4.245	3.799	39.862	33.566	20.803	23.945
4.135	3.827	39.806	33.583	20.83	23.981
4.266	3.837	39.786	33.585	20.814	23.952
4.175	3.869	39.752	33.543	20.82	23.945
4.153	3.767	39.91	33.507	20.814	23.966
4.208	3.85	39.873	33.571	20.801	23.96

Table A-1.4

Tube Side: 100% Open, Shell Side: 50% Open (First Trial)

L/min(cold)	L/min(hot)	Hot In (deg.	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
4.785	3.818	38.639	32.611	20.766	23.474
4.836	3.833	38.561	32.561	20.787	23.482
4.815	3.746	38.64	32.524	20.786	23.456
4.722	3.798	38.682	32.531	20.761	23.482
4.739	3.823	38.758	32.582	20.812	23.507
4.763	3.784	38.759	32.601	20.805	23.518
4.861	3.859	38.66	32.589	20.771	23.477
4.822	3.718	38.638	32.573	20.785	23.505
4.804	3.71	38.736	32.597	20.783	23.464
4.831	3.808	38.69	32.632	20.825	23.508

Table A-1.5

Tube Side: 50% Open, Shell Side: 10% Open

L/min(cold)	L/min(hot)	Hot In (deg.	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
3.902	1.277	49.87	33.413	20.834	23.926
3.84	1.267	49.961	33.443	20.882	23.973
3.883	1.299	49.988	33.467	20.884	23.969
3.893	1.231	50.058	33.4	20.864	23.972
3.879	1.24	49.993	33.456	20.872	23.939
3.87	1.292	49.977	33.466	20.834	23.933
3.836	1.25	49.987	33.429	20.854	23.938
3.827	1.293	50.065	33.403	20.854	23.93
3.823	1.254	50.04	33.496	20.838	23.921
3.908	1.248	50.083	33.472	20.868	23.956

Table A-1.6

Tube Side: 50% Open, Shell Side: 30% Open

L/min(cold)	L/min(hot)	Hot In (deg.	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
3.832	2.344	43.222	33.555	20.663	23.982
3.925	2.336	43.358	33.519	20.651	23.97
3.869	2.372	43.371	33.542	20.704	24.013
3.908	2.358	43.273	33.545	20.657	23.957
3.901	2.353	43.214	33.524	20.67	23.975
3.912	2.388	43.268	33.591	20.661	23.979
3.799	2.266	43.151	33.54	20.63	23.959
3.808	2.377	43.109	33.552	20.656	23.987
3.876	2.316	43.229	33.529	20.66	23.976
3.931	2.324	43.19	33.459	20.63	23.908

Table A-1.7

Tube Side: 50% Open, Shell Side: 50% Open

L/min(cold)	L/min(hot)	Hot In (deg.	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
3.891	3.719	39.667	33.615	20.699	24.076
3.85	3.802	39.705	33.532	20.67	24.017
3.899	3.831	39.838	33.561	20.711	24.045
3.905	3.802	39.846	33.597	20.702	24.076
3.816	3.774	39.839	33.622	20.692	24.05
3.898	3.8	39.886	33.635	20.698	24.043
3.794	3.809	39.728	33.681	20.698	24.071
3.873	3.855	39.73	33.61	20.724	24.068
3.843	3.851	39.742	33.601	20.715	24.091
3.836	3.808	39.726	33.591	20.741	24.065

Table A-1.8

Tube Side: 50% Open, Shell Side: 70% Open

L/min(cold)	L/min(hot)	Hot In (deg.	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
3.892	5.126	38.518	33.681	20.861	24.158
3.821	5.105	38.371	33.73	20.874	24.215
3.848	5.169	38.254	33.666	20.883	24.205
3.834	5.158	38.275	33.689	20.867	24.155
3.878	5.125	38.369	33.68	20.853	24.148
3.894	5.129	38.48	33.707	20.86	24.176
3.893	5.182	38.4	33.755	20.856	24.192
3.845	5.151	38.411	33.663	20.832	24.177
3.867	5.145	38.474	33.735	20.874	24.213
3.885	5.073	38.398	33.726	20.842	24.187

Table A-1.9

Tube Side: 10% Open, Shell Side: 50% Open (Second Trial)

L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
1.279	3.86	46.026	40.328	20.812	30.035
1.258	3.856	46.02	40.357	20.833	30.073
1.316	3.847	46.118	40.375	20.831	30.094
1.273	3.888	46.087	40.353	20.806	30.086
1.275	3.841	46.106	40.382	20.869	30.114
1.292	3.877	46.102	40.385	20.843	30.092
1.279	3.764	46.28	40.434	20.827	30.112
1.287	3.812	46.243	40.44	20.859	30.164
1.29	3.888	46.238	40.488	20.86	30.17
1.268	3.846	46.141	40.474	20.845	30.168

Table A-1.10

Tube Side: 30% Open, Shell Side: 50% Open (Second Trial)

L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
2.89	3.926	41.655	35.457	20.622	25.139
2.821	3.777	41.694	35.48	20.609	25.159
2.878	3.823	41.67	35.473	20.623	25.174
2.877	3.798	41.55	35.445	20.63	25.175
2.874	3.768	41.614	35.378	20.62	25.127
2.801	3.829	41.792	35.422	20.644	25.144
2.836	3.826	41.641	35.469	20.625	25.171
2.763	3.828	41.578	35.408	20.588	25.159
2.909	3.829	41.588	35.414	20.638	25.138
2.873	3.775	41.66	35.377	20.632	25.149

Table A-1.11

Tube Side: 60% Open, Shell Side: 50% Open (Second Trial)

L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
4.179	3.796	39.684	33.313	20.718	23.787
4.217	3.857	39.653	33.36	20.738	23.834
4.137	3.811	39.563	33.353	20.715	23.815
4.211	3.872	39.547	33.338	20.724	23.807
4.193	3.837	39.506	33.359	20.732	23.812
4.26	3.832	39.448	33.297	20.71	23.805
4.245	3.812	39.357	33.242	20.71	23.802
4.156	3.839	39.375	33.25	20.756	23.799
4.201	3.816	39.322	33.248	20.713	23.788
4.149	3.787	39.401	33.217	20.752	23.79

Table A-1.12

Tube Side: 100% Open, Shell Side: 50% Open (Second Trial)

L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
4.722	3.793	38.821	32.658	20.921	23.588
4.752	3.885	38.811	32.66	20.929	23.59
4.798	3.866	38.7	32.632	20.903	23.549
4.881	3.862	38.659	32.636	20.93	23.569
4.754	3.843	38.839	32.583	20.88	23.535
4.84	3.832	38.818	32.675	20.913	23.585
4.773	3.804	38.809	32.652	20.899	23.578
4.753	3.764	38.763	32.657	20.878	23.556
4.741	3.816	38.675	32.686	20.927	23.573
4.719	3.89	38.554	32.637	20.934	23.587

Tables A-1.13 through A-1.24 show every calculated value that was used to obtain the results.

Table A-1.13

Tube Side: 10% Open, Shell Side: 50% Open (First Trial)

	L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
Average of 10% open:	1.2835	3.8675	47.5017	41.5857	20.9724	30.7857
Hot flow rate (L/s):	0.06445833		Cold flow rate (L/s):	0.021391667		
Hot mass rate (g/s):	64.4583333		Cold mass rate (g/s):	21.39166667		
Density of water (g/L):	1000		Density of water (g/L):	1000		
Temp Diff (cold):	9.8133		Temp Diff (Hot):	-5.916		
Qc (W):	878.317173		Qh (W):	-1595.507732		
		Ql (W):	-717.190559			
		U (W/m^2*°C):	1523.15189			

Table A-1.14

Tube Side: 30% Open, Shell Side: 50% Open (First Trial)

	L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
Average of 30% open:	2.8411	3.8553	42.2879	35.9319	20.6448	25.3423
Hot flow rate (L/s):	0.064255		Cold flow rate (L/s):	0.047351667		
Hot mass rate (g/s):	64.255		Cold mass rate (g/s):	47.35166667		
Density of water (g/L):	1000		Density of water (g/L):	1000		
Temp Diff (cold):	4.6975		Temp Diff (Hot):	-6.356		
Qc (W):	930.665756		Qh (W):	-1708.7656		
		Ql (W):	-778.0998433			
		U (W/m^2*°C):	1863.961747			

Table A-1.15

Tube Side: 60% Open, Shell Side: 50% Open (First Trial)

	L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
Average of 60% open:	4.1926	3.8153	39.8267	33.5664	20.8207	23.9608
Hot flow rate (L/s):	0.06358833		Cold flow rate (L/s):	0.069876667		
Hot mass rate (g/s):	63.5883333		Cold mass rate (g/s):	69.87666667		
Density of water (g/L):	1000		Density of water (g/L):	1000		
Temp Diff (cold):	3.1401		Temp Diff (Hot):	-6.2603		
Qc (W):	918.052113		Qh (W):	-1665.575269		
		Ql (W):	-747.5231559			
		U (W/m^2*°C):	2077.83957			

Table A-1.16

Tube Side: 100% Open, Shell Side: 50% Open (First Trial)

	L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
Average of 100% open:	4.7978	3.7897	38.6763	32.5801	20.7881	23.4873
Hot flow rate (L/s):	0.06316167		Cold flow rate (L/s):	0.079963333		
Hot mass rate (g/s):	63.1616667		Cold mass rate (g/s):	79.96333333		
Density of water (g/L):	1000		Density of water (g/L):	1000		
Temp Diff (cold):	2.6992		Temp Diff (Hot):	-6.0962		
Qc (W):	903.062131		Qh (W):	-1611.033101		
		Ql (W):	-707.9709706			
		U (W/m^2*°C):	2170.333686			

Table A-1.17

Tube Side: 50% Open, Shell Side: 10% Open

	L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
Average of 10% open:	3.8661	1.2651	50.0022	33.4445	20.8584	23.9457
Hot flow rate (L/s):	0.021085		Cold flow rate (L/s):	0.064435		
Hot mass rate (g/s):	21.085		Cold mass rate (g/s):	64.435		
Density of water (g/L):	1000		Density of water (g/L):	1000		
Temp Diff (cold):	3.0873		Temp Diff (Hot):	-16.5577		
Qc (W):	832.3238543		Qh (W):	-1460.714333		
		Ql (W):	-628.3904789			
		U (W/m^2*°C):	1450.023655			

Table A-1.18

Tube Side: 50% Open, Shell Side: 30% Open

	L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
Average of 30% open:	3.8761	2.3434	43.2385	33.5356	20.6582	23.9706
Hot flow rate (L/s):	0.039056667		Cold flow rate (L/s):	0.064601667		
Hot mass rate (g/s):	39.05666667		Cold mass rate (g/s):	64.60166667		
Density of water (g/L):	1000		Density of water (g/L):	1000		
Temp Diff (cold):	3.3124		Temp Diff (Hot):	-9.7029		
Qc (W):	895.3197698		Qh (W):	-1585.580903		
		Ql (W):	-690.2611335			
		U (W/m^2*°C):	1820.70128			

Table A-1.19

Tube Side: 50% Open, Shell Side: 50% Open

	L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
Average of 50% open:	3.8605	3.8051	39.7707	33.6045	20.705	24.0602
Hot flow rate (L/s):	0.063418333		Cold flow rate (L/s):	0.064341667		
Hot mass rate (g/s):	63.41833333		Cold mass rate (g/s):	64.34166667		
Density of water (g/L):	1000		Density of water (g/L):	1000		
Temp Diff (cold):	3.3552		Temp Diff (Hot):	-6.1662		
Qc (W):	903.2384054		Qh (W):	-1636.153731		
		Ql (W):	-732.9153259			
		U (W/m^2*°C):	2042.886082			

Table A-1.20

Tube Side: 50% Open, Shell Side: 70% Open

	L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
Average of 70% open:	3.8657	5.1363	38.395	33.7032	20.8602	24.1826
Hot flow rate (L/s):	0.085605		Cold flow rate (L/s):	0.064428333		
Hot mass rate (g/s):	85.605		Cold mass rate (g/s):	64.42833333		
Density of water (g/L):	1000		Density of water (g/L):	1000		
Temp Diff (cold):	3.3224		Temp Diff (Hot):	-4.6918		
Qc (W):	895.6132105		Qh (W):	-1680.468199		
		Ql (W):	-784.8549887			
		U (W/m^2*°C):	2136.948468			

Table A-1.21

Tube Side: 10% Open, Shell Side: 50% Open (Second Trial)

	L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
Average of 10% open:	1.2817	3.8479	46.1361	40.4016	20.8385	30.1108
Hot flow rate (L/s):	0.064131667		Cold flow rate (L/s):	0.021361667		
Hot mass rate (g/s):	64.13166667		Cold mass rate (g/s):	21.36166667		
Density of water (g/L):	1000		Density of water (g/L):	1000		
Temp Diff (cold):	9.2723		Temp Diff (Hot):	-5.7345		
Qc (W):	828.7323352		Qh (W):	-1538.72057		
		Ql (W):	-709.9882346			
		U (W/m^2*°C):	1506.949874			

Table A-1.22

Tube Side: 30% Open, Shell Side: 50% Open (Second Trial)

	L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
Average of 30% open:	2.8522	3.8179	41.6442	35.4323	20.6231	25.1535
Hot flow rate (L/s):	0.063631667		Cold flow rate (L/s):	0.047536667		
Hot mass rate (g/s):	63.63166667		Cold mass rate (g/s):	47.53666667		
Density of water (g/L):	1000		Density of water (g/L):	1000		
Temp Diff (cold):	4.5304		Temp Diff (Hot):	-6.2119		
Qc (W):	901.0667198		Qh (W):	-1653.824534		
		Ql (W):	-752.7578141			
		U (W/m^2*°C):	1858.611268			

Table A-1.23

Tube Side: 60% Open, Shell Side: 50% Open (Second Trial)

	L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
Average of 60% open:	4.1948	3.8259	39.4856	33.2977	20.7268	23.8039
Hot flow rate (L/s):	0.063765		Cold flow rate (L/s):	0.069913333		
Hot mass rate (g/s):	63.765		Cold mass rate (g/s):	69.91333333		
Density of water (g/L):	1000		Density of water (g/L):	1000		
Temp Diff (cold):	3.0771		Temp Diff (Hot):	-6.1879		
Qc (W):	900.1052505		Qh (W):	-1650.88692		
		Ql (W):	-750.7816691			
		U (W/m^2*°C):	2063.267121			

Table A-1.24

Tube Side: 100% Open, Shell Side: 50% Open (Second Trial)

	L/min(cold)	L/min(hot)	Hot In (deg. C)	Hot Out (deg. C)	Cold In (deg. C)	Cold Out (deg. C)
Average of 100% open:	4.7733	3.8355	38.7449	32.6476	20.9114	23.571
Hot flow rate (L/s):	0.063925		Cold flow rate (L/s):	0.079555		
Hot mass rate (g/s):	63.925		Cold mass rate (g/s):	79.555		
Density of water (g/L):	1000		Density of water (g/L):	1000		
Temp Diff (cold):	2.6596		Temp Diff (Hot):	-6.0973		
Qc (W):	885.269456		Qh (W):	-1630.797272		
		Ql (W):	-745.5278161			
		U (W/m^2*°C):	2133.515322			

Appendix A-2
Example Calculations

The following calculations were used for the first trial, with the tube-side valve at 10% open and the shell-side valve at 50% open.

The averages of each measured parameter:

$$\bar{X} = \frac{\sum_{i=1}^{n} x_i}{n} \tag{6}$$

$$\overline{Cold\ Flow\ Rate\ (L/min)} = \frac{1.284+1.289+1.274+1.288+1.258+1.278+1.282+1.296+1.305+1.281}{10} \tag{7}$$

$$\overline{Hot\ Flow\ Rate\ (L/min)} = \frac{3.886+3.897+3.847+3.868+3.804+3.877+3.881+3.881+3.854+3.880}{10} \tag{8}$$

$$\overline{Hot\ Inlet\ Temp\ (^0C)} = \frac{47.432+47.568+47.662+47.491+47.518+47.532+47.542+47.403+47.437+47.432}{10} \tag{9}$$

$$\overline{Hot\ Outlet\ Temp\ (^0C)} = \frac{41.541+41.589+41.641+41.602+41.598+41.590+41.635+41.561+41.536+41.564}{10} \tag{10}$$

$$\overline{Cold\ Inlet\ Temp\ (^0C)} = \frac{20.961+20.980+20.993+20.941+21.000+20.972+21.004+20.944+20.964+20.965}{10} \tag{11}$$

$$\overline{Cold\ Outlet\ Temp\ (^0C)} = \frac{30.738+30.768+30.806+30.817+30.794+30.795+30.825+30.781+30.748+30.785}{10} \tag{12}$$

The volumetric flow rates were then converted to mass flow rates in grams per second by

$$\dot{m}_c = \frac{1.2835\ L}{min} * \frac{1\ min}{60\ s} * \frac{1000\ g}{L} = 21.391\ g/s \tag{13}$$

$$\dot{m}_h = \frac{3.8675\ L}{min} * \frac{1\ min}{60\ s} * \frac{1000\ g}{L} = 64.458\ g/s\ . \tag{14}$$

The differences in the inlet and outlet temperatures for the shell and tube sides were then calculated by

$$\Delta T_h = 41.5857 - 47.5017 = -5.916\ ^\circ C \tag{15}$$

$$\Delta T_c = 30.7857 - 20.9724 = 9.813\ ^\circ C. \tag{16}$$

The heat duties for the tube (cold) side and the shell (hot) side were then calculated using

$$\dot{Q}_c = \left(21.392\,\frac{g}{s}\right) * \left(4.184\,\frac{J}{g*^\circ C}\right) * (9.813\ ^\circ C) = 878.317\ W \tag{17}$$

$$\dot{Q}_h = \left(64.458\frac{g}{s}\right) * \left(4.184\frac{J}{g*°C}\right) * (-5.916\,°C) = -1595.508\,W. \quad (18)$$

Using these two values, the heat lost to the environment was calculated using

$$\dot{Q}_L = -1595.508\,W + 878.317\,W = -717.191\,W. \quad (19)$$

Then the log mean temperature difference was calculated by

$$\Delta Tlm = \frac{47.5017-30.7857-41.5857+20.9724}{\ln(\frac{47.5017-30.7857}{41.5857-20.9724})} = 18.600\,°C. \quad (20)$$

Afterwards, the overall heat transfer coefficient, U, was calculated using

$$U = \frac{878.317\,W}{(0.0323\,m^2)*(18.600\,°C)*(0.96)} = 1523.152\,W/(m^2 * °C). \quad (21)$$