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Design, Construction, Operation, and Analysis of a Chemical Engineering Unit Operations Laboratory Plate Heat Exchanger Experiment

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Abstract

Unit Operations Laboratory courses are a staple of chemical engineering programs worldwide. In these courses, undergraduate students operate and analyze the performance of equipment and instruments commonly used in chemical processing and other industries. Because heat transfer operations are ubiquitous in the chemical processing industry, heat exchanger experiments are often found in Unit Operations Laboratories. At The Ohio State University, a new pilot-scale Plate Heat Exchanger (PHX) experiment was designed and constructed in the Unit Operations Laboratory during the summer of 2021.

A particularly challenging aspect of developing new experimental apparatus for Unit Operations Laboratories is operating pilot-scale or commercial-scale equipment with laboratory-scale utilities and flows. While it is desirable for students to work with authentic industrial equipment, the operation of large-scale units may be unrealistic if the available utilities and flow rates are undersized. As shipped from the manufacturer, the heat exchanger used in the PHX experiment at Ohio State is drastically oversized relative to the available flows. In addition, the flow path in the PHX results in a mix of co-current and counter-current flows. For these reasons, the PHX was modified internally to reduce the effective surface area and maintain a consistent flow configuration without affecting the physical size or appearance of the heat exchanger.

The apparatus features co-current and counter-current flow configurations, two electromagnetic flow meters, four T-type thermocouples, a pressure relief valve, an expansion tank, and an automatic data acquisition system. Construction was completed at a total cost of approximately \$3,900 for flow components, \$900 for data acquisition, and \$1,500 for support structure. This does not include the cost of flowmeters.

The system was operated throughout Autumn 2021 and Spring 2022 semesters, and no safety issues or operational problems were encountered. In testing, results agreed closely with those predicted from heat transfer theory. Typical heat transfer rates were 4–30 kW with overall heat transfer coefficients of approximately 1,800–5,700 $W/(m^2K)$. The number of transfer units ranged from 1.5–7, and the effectiveness ranged from 0.48-0.94. This paper describes the design, specification, testing, and performance of the PHX experiment, along with an analysis of data collected from the experiment. A comprehensive parts list and detailed construction drawings are also included, and other Unit Operations Labs are encouraged to “steal this experiment.”

1 Introduction

Unit Operations Laboratory (Unit Ops Lab) courses are ubiquitous in undergraduate chemical engineering degree programs in the United States. In a 2017 survey of 70 chemical engineering programs, every program reported having at least one laboratory course or course with a laboratory component[1], suggesting that the lab experience in Unit Ops is a fundamental part of chemical engineering education. One of the most important aspects of the lab course is for students to gain hands-on experience operating equipment that is commonly used in the chemical processing industry. For example, the equipment in the Unit Ops Lab at Ohio State is typical of Unit Ops Labs in general and includes: Absorption, Adsorption, Bioreactor, Continuous Stirred-Tank Reactor, Distillation, 2-Phase and 3-Phase Fluidization, Hydrogen Fuel Cell, Liquid-Liquid Extraction, Mixing, Plate Heat Exchanger, Plug Flow Reactor, Pumping, Reverse Osmosis, and Shell and Tube Heat Exchanger.

Providing these hands-on, industrially-relevant lab experiences requires chemical engineering departments to invest considerable resources in constructing, operating, and maintaining the necessary laboratory apparatus. Many programs employ one or more full-time faculty and/or staff members to oversee the operation of the Unit Operations Laboratory. Even so, the size, complexity, and cost of the lab equipment makes it challenging for lab supervisors to design and build new equipment while also maintaining and upgrading existing equipment.

Another challenge associated with providing laboratory apparatus for student experiments is to ensure proper design and sizing of the equipment so that it operates as intended and demonstrates the trends and behavior predicted from theory. This requires familiarity with a wide range of chemical engineering concepts, and may be outside of the knowledge and skill set of many non-engineers, including staff lab managers.

Furthermore, even with careful design, it can be difficult to operate authentic pilot-scale or commercial-scale equipment with lab-scale flow rates e.g. of water, compressed air, steam, etc. typically available. The equipment may be significantly oversized for the available streams, resulting in a small effect size or apparently insignificant effect of the factors in the experiment. However, designing for proper operation is a necessary step if the intention is for students to see classroom principles demonstrated in the laboratory.

In Summer 2021, the plate heat exchanger apparatus at Ohio State was completely redesigned and rebuilt. In order to operate with bench-scale flow rates, the pilot-scale heat exchanger was modified internally to reduce the effective area without changing its dimensions or external appearance. The purpose of this paper is provide a detailed description of the design and construction of the plate heat exchanger experiment, including a list of parts and costs, so that other Unit Ops Labs can “steal this experiment.” This paper will also present sample data generated from the plate heat exchanger along with typical values for overall heat transfer coefficient, individual heat transfer coefficients, effectiveness, and number of transfer units (NTU) in order to demonstrate that the apparatus is capable of producing data which follow the expected trends.

2 Design of Plate Heat Exchanger Apparatus

2.1 Design Criteria

The primary goals identified for the design of the plate heat exchanger experiment were for students to be able to learn the principle of operation of a plate heat exchanger, and for them to be able to analyze the effect of flow rate and flow configuration (co-current vs counter-current) on the performance of the heat exchanger. To achieve these goals, several design criteria were identified:

- The heat exchanger apparatus should have an easy-to-understand flow path. Students should be able to easily identify the heat exchanger itself and see where streams enter and exit the heat exchanger and which valves are used to stop, start, and control flow rate and flow direction.
- It should be possible to easily adjust and control the flow rate for the hot and cold streams. The flow control valves should be of a type suitable for throttling flow and should be positioned such that students can comfortably read the flowmeters when adjusting the valves.
- The flow direction should be reversible to allow co-current and counter-current operation, and it should be easy for students to determine the flow configuration at any time by checking the position of the valve handles.
- The data generated and trends observed in the experiment should be consistent with heat transer theory, and students should be able to measure statistically significant effects of the independent variables on the dependent variables.

Logistical considerations led to additional design criteria:

- The heat exchanger should be a commercially available, off-the-shelf unit to ensure authenticity and the availability of replacement parts.
- The heat exchanger should be of the plate-and-frame type, to allow for the addition or removal of plates, and so that students can see the construction of the heat exchanger and the design of the plates.
- The system should incorporate automatic data acquisition for collection of temperature and flow rate measurements.
- The operation of the experiment should not consume any water.
- The apparatus should be constructed primarily of stainless steel and aluminum for corrosion resistance and to ensure a long service life.

Existing utilities in the Unit Ops Lab at Ohio State included city water, process chilled water (PCW), heating hot water (HHW), and 120VAC electrical receptacles. These utilities were available on an overhead service carrier.

2.2 System Design

A process flow diagram showing the preliminary design of the Plate Heat Exchanger experiment is shown in Figure 1. In this design, HHW and PCW are contacted in the heat exchanger. Four thermocouples (TC) are used to measure water temperature at the heat exchanger inlets and outlets, and two flowmeters are included for flow rate measurement. Two three-way valves allow the flow direction of the cold stream to be reversed so that the heat exchanger can be operated in co-current or counter-current configuration.

2.3 Safety Considerations

The primary safety concern in this heat transfer experiment was potential overpressure caused by thermal expansion of water. To mitigate this risk, the design includes an expansion tank and pressure relief valve located upstream of the heat exchanger on the HHW stream.

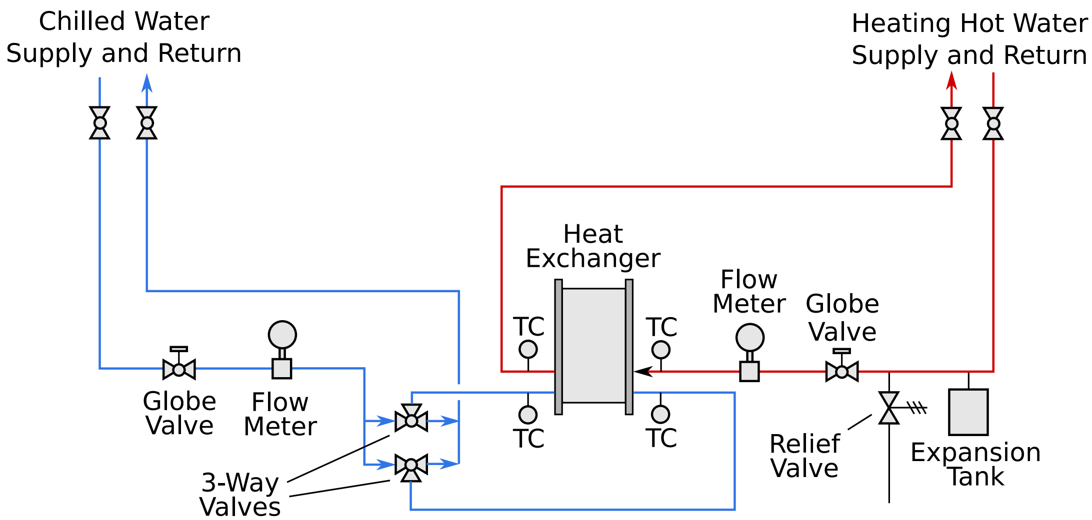

Figure 1: Initial Process Flow Diagram of PHX

2.4 System Specification and Assembly

With a basic design for the system completed, parts were then sized and specified. With the knowledge that the heat exchanger would be oversized relative to the available flow rates in the lab, the primary consideration with respect to sizing was to minimize pressure drop through the system to ensure the highest possible flow rates with the provided supply pressures of PCW and HHW. For this reason, the system was sized with 3/4" tubing and fittings throughout. In addition, tube bending was used when possible to avoid pressure drops through elbows and tees. With a few exceptions, stainless steel was used throughout the system to ensure a long service life.

When possible, parts were sourced from major industrial suppliers. However, plate-and-frame type heat exchangers from those vendors were expensive, typically costing $2,500 or more. A less expensive option was sought, and the SABCO PlatePro Sanitary Wort Chiller was found to meet the design criteria. With a plate-and-frame construction and costing under $1,000, the SABCO plate heat exchanger is constructed with 41 stainless steel, chevron-pattern plates. Intended and marketed for use in the brewing industry, the beer-themed branding of the SABCO heat exchanger (see Figure 2) tends to pique the interest of students and prompts lively discussions about applications of plate heat exchangers in brewing.

The brass relief valve was sized to open at 150 psi, the maximum allowable working pressure of the heat exchanger.

Table 1 shows a list of the primary flow components specified for the PHX experiment, along with their vendors, part numbers, and prices. A detailed drawing showing the location where each part was used is shown in Figure 3.

Figure 2: SABCO PlatePro Wort Chiller

Label	Description	Qty	Price	Cost	Model #	Supplier
A	PlatePro Sanitary Wort Chiller	1	925	925	PTP-041-101	SABCO
B	3/4 in. Seamless Stainless Steel Tubing (per foot)	40	9.70	388	667135	Ferguson
C	Tylok 3/4 in. OD x MNPT Stainless Steel Male Connector	24	24.35	584.40	1596548	Ferguson
D	3/4 in. 316LSS NPT Rising Valve Stem Globe Valve	2	89.24	178.48	1227233	Ferguson
E	Ball Valve, 316SS, 3-Way, 3-Piece, Pipe Size 3/4 in	2	217.34	434.68	46CE57	Grainger
F	Tylok CBC-Lok 3/4 in. OD Stainless Steel Union Tee	2	65.31	130.62	1598083	Ferguson
G	CBC-Lok 3/4 in. OD Tube Double Ferrule 316SS 90 Degree Elbow	6	58.28	349.68	1597173	Ferguson
H	3/4 in. FNPT x MNPT 150# Street Global 304SS 90 Degree Elbow	2	6.79	13.58	1289529	Ferguson
I	Yor-Lok Fitting for Stainless Steel Tubing Straight Adapter for 3/4” Tube OD x 3/4 NPT Female	2	43.45	86.90	5182K803	McMaster
J	303SS Adapter, 3/4 GHT Female x 3/4 NPT Male	2	30.48	60.96	6224T19	McMaster
K	Fast-Acting Pressure-Relief for Hot Water, 3/4 NPT Female	1	100.22	100.22	4702K49	McMaster
L	PROFLO 2 gal Thermal Expansion Tank	1	31.29	31.29	3883444	Ferguson
M	316SS Threaded Pipe Fitting Low-Pressure, Cross Connector, 3/4 NPT Female	5	48.74	243.7	4452K485	McMaster
N	High-Polish Quick-Clamp Sanitary Tube Fitting	2	59.02	118.04	45195K794	McMaster
O	Quick-Clamp Tube Fitting, Sanitary, Wing Nut Clamp for 1/2” and 3/4” Tube OD	2	19.23	38.46	4759K61	McMaster
P	Water- and Steam-Resistant EPDM Gasket for Quick-Clamp Fittings, for 3/4” Tube OD	2	1.53	3.06	1100N12	McMaster
Q	316 Stainless Steel Threaded Pipe Fitting Low-Pressure, Bushing Adapter, 3/4 Male x 1/4 Female	8	7.22	57.76	4452K168	McMaster
R	Yor-Lok Fitting for Stainless Steel Tubing Straight Adapter for /16” Tube OD 1x 1/4 NPT Male	4	26.18	104.72	5182K179	McMaster
S	Dual Scale Pressure Gauge with Steel Case 1/4 NPT Male Bottom Connection, 3-1/2” Dial	4	16.27	65.08	4000K713	McMaster
	Total			3914.63		

Table 1: Primary Flow Components of Plate Heat Exchanger

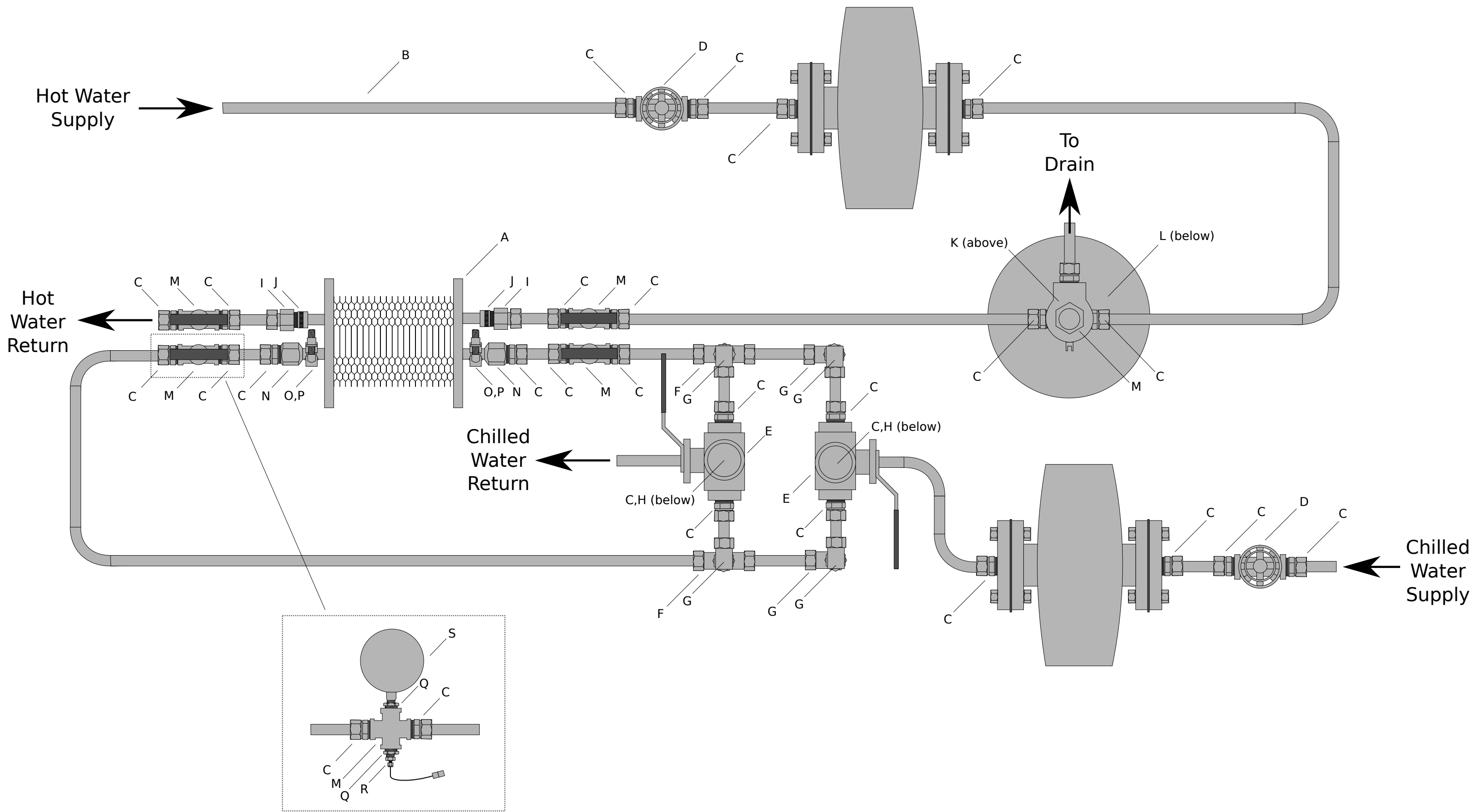

Figure 3: Detail of PHX assembly (top view). Labels reference Table 1.

3 Testing: Data Collection Procedure

The PHX was tested across the entire available range of hot and cold water flow rates in both co-current and counter-current flow configurations. A single trial of a full factorial design was carried out with six levels of PCW flow rate: 1, 2, 3, 4, 5, and 6 gallons per minute; and six levels of HHW flow rate: 0.5, 1, 1.5, 2, 2.5 and 3 gallons per minute. The first 36 trials were completed in co-current flow configuration while the remaining 36 were completed in counter-current configuration. WINDAQ data acquisition software was used to monitor and record the inlet and outlet temperatures of the hot and cold streams.

The trials were conducted in a random order. After establishing the target flow rates by adjusting the globe valves, the temperatures displayed in the WinDAQ data acquisition software were used to determine when the system had reached steady state. After reaching steady state, the globe valves were adjusted to the flow rates of the next trial. This process was repeated through all levels of hot and cold water flow rate. After changing the flow configuration to counter-current by reversing the position of both three-way valves, the same process was repeated for the second set of 36 trials.

While flow rate data could also be recorded by the data acquisition system, the recorded flow rates fluctuated by ± 0.1 gallons per minute compared to the values reported on the built-in displays on the electromagnetic flowmeters, so the flow rates displayed on the flowmeters' displays were manually entered as "channel event comments" in WINDAQ during testing.

4 Relevant Heat Transfer Theory

As described in Section 2.1, one objective in the design of the Plate Heat Exchanger apparatus was to ensure that data generated in the experiment would exhibit trends predicted by heat transfer theory. Students in Unit Operations who perform the PHX experiment are required to 1) construct Wilson Plots, 2) analyze their data using the NTU-Effectiveness Method, and 3) perform a statistical analysis to determine whether the factors in their experiment had significant effects on the response variables. This section provides an overview of relevant heat transfer theory.

4.1 Calculation of Heat Transfer Rate

Volumetric flow rates can be converted to mass flow rates using Equation 1.

$$\dot{m} = \frac{V}{\rho} \tag{1}$$

where V is the volumetric flow rate in $\frac{m^3}{s}$ and ρ is the fluid density in $\frac{kg}{m^3}$.

The heat transfer rate, q can then be calculated using Equation 2.

$$q = \dot{m} C_p \Delta T \tag{2}$$

where C_p is the specific heat capacity of water at constant pressure in $\frac{J}{kg°C}$ and ΔT is the temperature increase or decrease of a stream in $°C$ as it passes through the heat exchanger.

4.2 Calculation of Overall Heat Transfer Coefficient

The Log Mean Temperature Difference, ΔT_{LM}, can be calculated as follows:

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{ln(\frac{\Delta T_1}{\Delta T_2})} \tag{3}$$

where ΔT_1 is the temperature difference in $°C$ between the hot and cold streams at one end of the heat exchanger and ΔT_2 is the temperature difference in $°C$ at the opposite end of the heat exchanger.

With the heat transfer rate calculated in Equation 2, U can be calculated directly from Equation 4.

$$q = UA\Delta T_{LM} \tag{4}$$

where A is the area of the heat transfer surface in m^2.

4.3 Wilson Plot Method

In the Wilson Plot Method, the flow rate – and therefore the Reynolds number and individual convective heat transfer coefficient – of one stream is held constant, while the other is varied[2].

Using the sum of resistances model, the overall heat transfer coefficient, U, is written as follows:

$$U = \frac{1}{\frac{1}{h_H} + R_w + \frac{1}{h_C}} \tag{5}$$

where h_H and h_C are the individual convective heat transfer coefficients in $\frac{W}{m^2 \cdot °C}$ of the hot and cold streams, respectively, and R_w is the wall resistance.

Taking the inverse of Equation 5,

$$\frac{1}{U} = \frac{1}{h_H} + R_w + \frac{1}{h_C} \tag{6}$$

The Dittus-Boelter correlation is:

$$Nu = \frac{hL}{k} = 0.023Re^{0.8}Pr^n \tag{7}$$

From Equation 7, it is expected that h will change linearly with $Re^{0.8}$, assuming that the Prandtl number is constant with varying flow rate, and that experimental conditions fall within the region where the Dittus-Boelter equation is valid. For example, holding the cold side flow rate constant and assuming a constant wall resistance, the last two terms in Equation 6 will be constants, and $\frac{1}{U}$ will change linearly with $\frac{1}{h_H}$. And since it is expected from Equation 7 that h will change linearly with $Re^{0.8}$, it is expected that $\frac{1}{U}$ will change linearly with $\frac{1}{Re_H^{0.8}}$.

Linear trend lines can be added to groups of data points with the same cold side flow rate but different hot side flow rates. These trend lines are of the form shown in Equation 8:

$$\frac{1}{U} = C_1 \frac{1}{Re_H^{0.8}} + C_2 \tag{8}$$

where C_1 is the slope and C_2 is the intercept.

4.4 NTU-Effectiveness Method

In the NTU-Effectiveness Method, it is first necessary to compute the heat capacity rate of the smaller stream using Equation 9.

$$c_{min} = \{\dot{m}C_p\}_{min} \tag{9}$$

The maximum possible heat transfer rate, q_{max}, is defined as

$$q_{max} = c_{min}(T_{H,in} - T_{C,in}) \tag{10}$$

Using the heat transfer rate from Equation 2, effectiveness (ϵ) is defined as shown in Equation 11.

$$\epsilon = \frac{q}{q_{max}} \tag{11}$$

The Number of Transfer Units (NTUs) can be calculated using the overall heat transfer coefficient, U, from Equation 4.

$$NTU = \frac{UA}{c_{min}} \tag{12}$$

Expected values of ϵ depend on C_R, the ratio of the heat capacity rates of the two streams:

$$C_R = \frac{c_{min}}{c_{max}} \tag{13}$$

5 Results and Discussion

As described in Section 2.1, the design for the PHX included included the following criteria: data generated in the experiment should exhibit trends predicted by heat transfer theory, and students would be able to observe statistically significant effects of the independent variables (factors) on the dependent (response) variables. To validate the newly designed experiment, an analysis of initial data was performed.

Table 2 shows a subset of raw data initially collected from the new Plate Heat Exchanger in co-current flow as received from the manufacturer.

Config	**C flow rate**	**H flow rate**	**C inlet T**	**C outlet T**	**H inlet T**	**H outlet T**
	gpm	**gpm**	**C**	**C**	**C**	**C**
Co-	6.48	3.49	16.43	37.63	76.78	36.87
Co-	6.48	0.99	16.58	24.82	75.79	23.83
Co-	5.53	3.40	16.58	39.47	77.04	38.88
Co-	5.50	0.99	16.43	25.95	76.64	25.11
Co-	4.52	3.50	16.50	43.05	77.51	42.25
Co-	4.50	1.01	16.54	27.71	75.68	26.83
Co-	3.50	3.49	16.50	46.64	76.64	45.69
Co-	3.48	0.98	16.58	30.46	75.76	29.06
Co-	2.48	3.42	16.54	51.33	76.82	50.63
Co-	2.47	1.01	16.58	35.14	77.59	33.72
Co-	1.51	3.50	16.61	60.27	79.16	59.35
Co-	1.51	1.01	16.61	41.81	79.24	41.77

Table 2: Raw Data for Highest and Lowest Flow Rates of Heating Hot Water, Original Configuration

Inspection of these data immediately reveals a problem. In all cases, the cold stream outlet temperature is higher than the hot stream outlet temperature. This should be physically impossible in co-current flow, and it causes various issues with subsequent calculations, such as ΔT_{LM} being undefined because the denominator contains the natural log of a negative number. It also results in impossibly high values for effectiveness. The cause of this issue was twofold. First, the SABCO plate heat exchanger is grossly over-sized relative to the sizes of the streams, resulting in approach temperatures close to zero. Secondly, the plate arrangement of the heat exchanger results in a mix of co-current and counter-current flow. As shipped from the manufacturer, the heat exchanger contains 41 plates arranged in four passes, so that the flow direction of both streams reverses direction three times as shown in Figure 4a.

The four-pass flow configuration means that even in co-current flow there are three counter-current pairs of plates. In particular, between plates 10 and 11, plates 20 and 21, and plates 30 and 31, the hot and cold streams flow in opposite directions. This results in a temperature cross, which should not be possible in co-current flow.

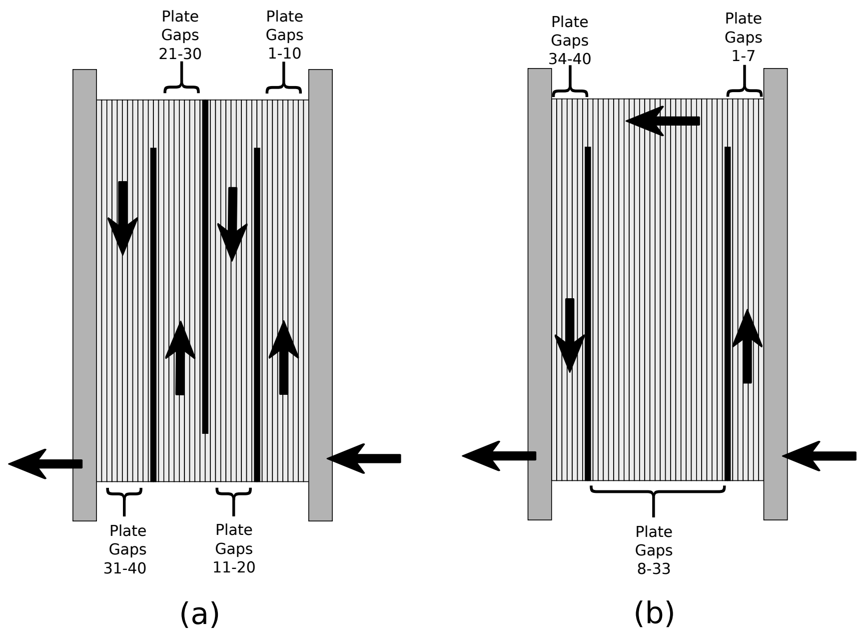

Figure 4: Original four-pass plate arrangement (a) and modified plate arrangement (b)

5.1 Modification of Heat Exchange Plate Arrangement

To address the issues of oversizing and mixed flow configuration, the heat exchanger was disassembled, and the plates were reconfigured as shown in Figure 4b. In the new plate arrangement, a large fraction of the plates are contained within a dead zone in the center of the heat exchanger with no flow, effectively reducing the heat transfer surface area by approximately 70% without changing its physical size or external appearance. The flow direction is also consistent across all plates.

5.2 Results: Overall Heat Transfer Coefficient

Calculation of the overall heat transfer coefficient requires calculation of q and ΔT_{LM} as shown in Equation 4. The area, A, in m^2 was taken from manufacturer specifications as 9.43 square feet. q was calculated separately for the hot and cold streams. The q values calculated for the two streams agreed well (the average difference was approximately 5%), so the average was used in calculating U. In all cases, thermophysical properties were evaluated at the average of the inlet and outlet temperatures of each stream.

Table 3 shows heat transfer rates and overall heat transfer coefficients for the highest and lowest flow rates of HHW.

The experimentally measured values of the overall heat transfer coefficient, U, fell within the expected range for plate heat exchangers. Values for U ranged from 2,390–5,772 $W/(m^2 \cdot^\circ C)$. A wide range of expected values can be found in literature, with values reported from 850-1,700 $W/(m^2 \cdot^\circ C)$ for water-water heat exchangers generally[3,4] to as high as 5,700-7,400 $W/(m^2 \cdot^\circ C)$ for plate heat exchangers in particular[5].

Config	C flow rate	H flow rate	q_C	q_H	ΔT_{LM}	U
	gpm	gpm	kW	kW	C	W / (m^2C)
Co-	1.00	1.00	6.55	6.66	7.81	3,300
Co-	1.00	3.00	10.14	10.52	9.17	4,394
Co-	6.00	1.00	11.98	11.23	10.75	4,209
Co-	6.00	3.00	26.76	26.31	17.93	5,772
Counter-	1.00	1.00	9.12	9.95	15.56	2,390
Counter-	1.00	3.00	12.76	13.63	15.19	3,388
Counter-	6.00	1.00	11.62	13.22	14.22	3,406
Counter-	6.00	3.00	30.51	32.44	22.79	5,386

Table 3: Overall Heat Transfer Coefficients for Highest and Lowest Flow Rates of PCW and HHW

5.3 Wilson Plots

Wilson Plots are useful for visualizing the effect of varying the flow rates of the two streams. Figures 5 and 6 show Wilson Plots for co-current and counter-current configurations, respectively.

The trends shown on the plots agree well with expected results. The positive slope suggests that increasing the hot side flow rate while holding the cold side flow rate constant increases U, and the shift in the intercept suggests that increasing the cold side flow rate while holding the hot side flow rate constant also increases U.

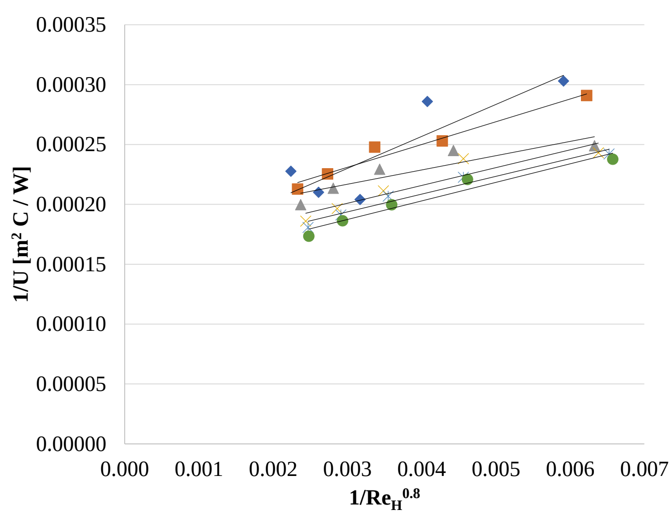

Figure 5: Wilson Plot for co-current configuration

A statistical analysis could be performed for each of the models represented by the trend lines on the Wilson Plots. However, for purposes of statistical analysis, it is preferable to construct a single model to describe the variability in $\frac{1}{U}$ rather than fitting numerous linear trend lines. See Section 5.5 for a discussion of the statistical analysis.

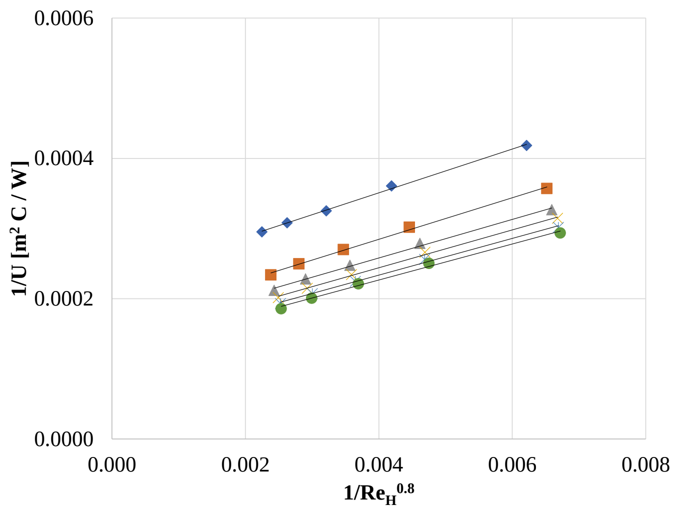

Figure 6: Wilson Plot for counter-current configuration

5.4 NTU-Effectiveness

The NTU-Effectiveness Method is typically used in the design and sizing of heat exchangers, but it also provides another opportunity for students to compare their experimental data with expected results. Figure 7 shows experimental and predicted values of NTU and Effectiveness for co-current configuration with $C_R = 0.5$. In Figure 7, curves show theoretical values while data points show experimentally measured values. ϵ increases with increasing NTU as expected, and the experimental values agree well with theoretical values.

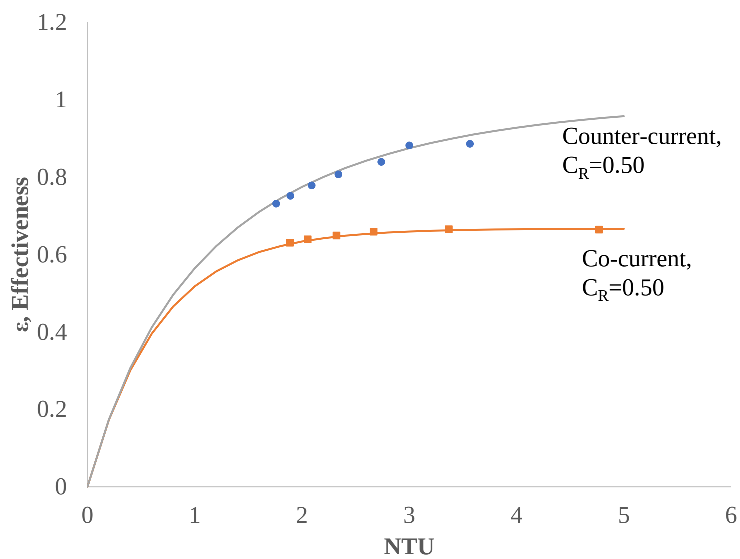

Figure 7: NTU vs Effectiveness for Co-Current and Counter-Current Flow with C_R = 0.5. Curves show theoretical values, points show experimental values

5.5 Statistical Analysis

A statistical analysis was performed using the statistical analysis software JMP. The mathematical model tested was based on Equations 6 and 7:

$$\frac{1}{U} = \beta_0 + \beta_1 \frac{1}{Re_H^{0.8}} + \beta_2 \frac{1}{Re_C^{0.8}} \tag{14}$$

where β_0 is the intercept, and β_1 and β_2 are fit parameters for $1/Re^{0.8_H}$ and $1/Re_H^{0.8}$ respectively. The null hypothesis in this analysis was:

$$\beta_0 = \beta_1 = \beta_2 = 0$$

The alternative hypothesis was that at least one $B_i \neq 0$. The critical p-value was 0.05.

For co-current flow, the overall model was found to be significant with a p-value of <0.0001. The factors $\frac{1}{Re_C^{0.8}}$ and $\frac{1}{Re_H^{0.8}}$ were found to have significant effects with p-values <0.0001. The intercept relates to the wall resistance, and the expected value is $L/(KA)$ = 0.000132. The intercept was found to be significant (p <0.0001) with a value of 0.000126, which agrees well with the expected value. The adjusted R-squared was 0.793.

A plot of actual and predicted values of 1/U for counter-current flow (Figure 8) shows that model is a reasonably close fit to the data.

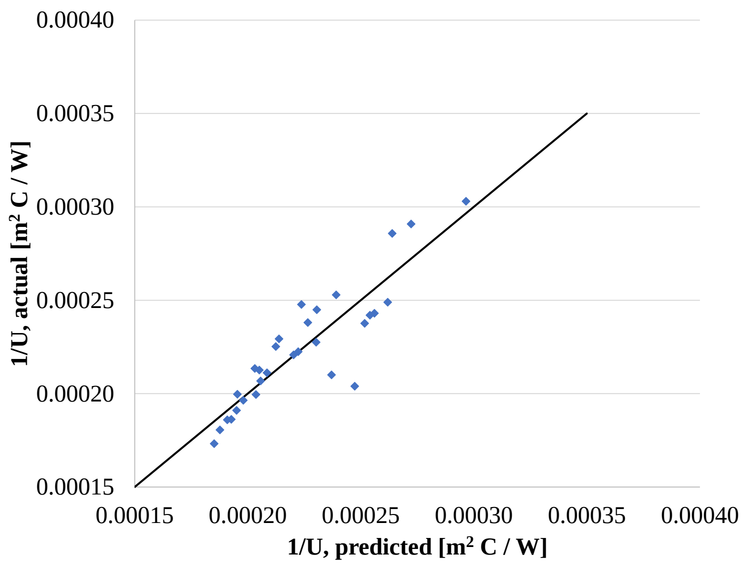

Figure 8: Actual vs predicted values for 1/U, co-current

For counter-current flow, the overall model was found to be significant with a p-value of <0.0001. The factors $\frac{1}{Re_C^{0.8}}$ and $\frac{1}{Re_H^{0.8}}$ were found to have significant effects with p-values <0.0001. The adjusted R-squared was 0.998. The intercept was significant ($p < 0.0001$) with a value of 7.288E-5, which is about half of the expected value.

A plot of actual and predicted values of 1/U for counter-current flow (Figure 9) shows that model is an excellent fit to the data.

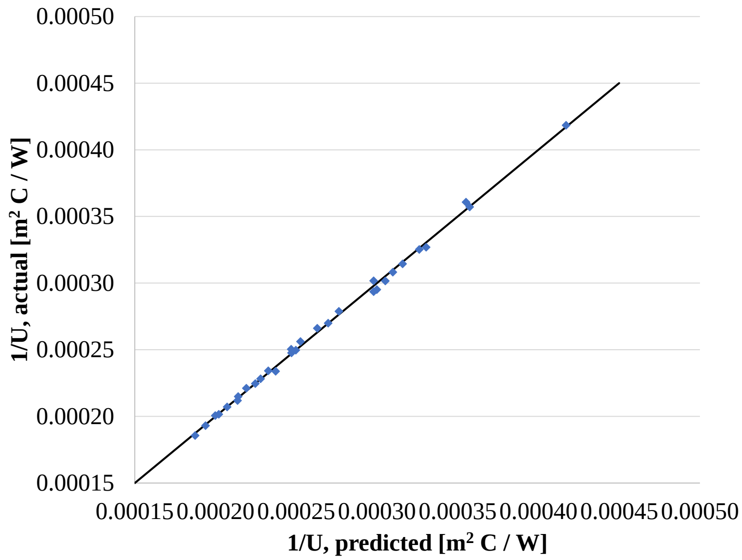

Figure 9: Actual vs predicted values for 1/U, counter-current

6 Conclusions

The newly-constructed Plate Heat Exchanger in the Unit Operations Laboratory at Ohio State has been operated numerous times by students, and no safety or operational issues have been encountered. The total cost of the main flow components was approximately $3,900, and a list of components is included in Table 1.

The heat exchanger's original plate arrangement was problematic. The four-pass design resulted in a mix of co-current and counter-current flows. This combined with the oversized surface area and low approach temperatures resulted in undefined values for log-mean temperature difference. Rearranging the plates in the heat exchanger to reduce the effective area resolved these issues and produced results consistent with expectations.

- Overall heat transfer coefficients were 2,390–5,772 $\frac{W}{m^2 \cdot {}^\circ C}$
- Wilson Plots showed the expected trends: U increased with increasing $Re_H^{0.8}$ and increased with increasing cold water flow rate.
- Effectiveness values agreed well with theoretical values and followed the expected trends.
- A statistical analysis based on the sum of resistances model showed that the flow rates of both streams had significant effects on the overall heat transfer coefficient, and the sum of resistances model used with the expected relationship $h \propto Re^{0.8}$ was an excellent fit to the data.

Overall, the new plate heat exchanger experiment in the Unit Ops Lab at OSU has been a success. At a relatively low cost, an off-the-shelf, pilot-scale heat exchanger was adapted to operate at lab-scale flow rates. The experiment has proven to be safe and reliable, and students are able to measure statistically significant effects that follow trends predicted by heat exchanger theory. It is the hope of the authors that other Unit Ops Labs will use the information presented here to "steal this experiment!"

Acknowledgement

The authors would like to acknowledge graduate teaching associates Ross Chongson and Wenhan Jia, and high school interns Jordan Weiler, Fatmata Daramy, and Nahom Tadesse who constructed the PHX apparatus.

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Appendix A: Images

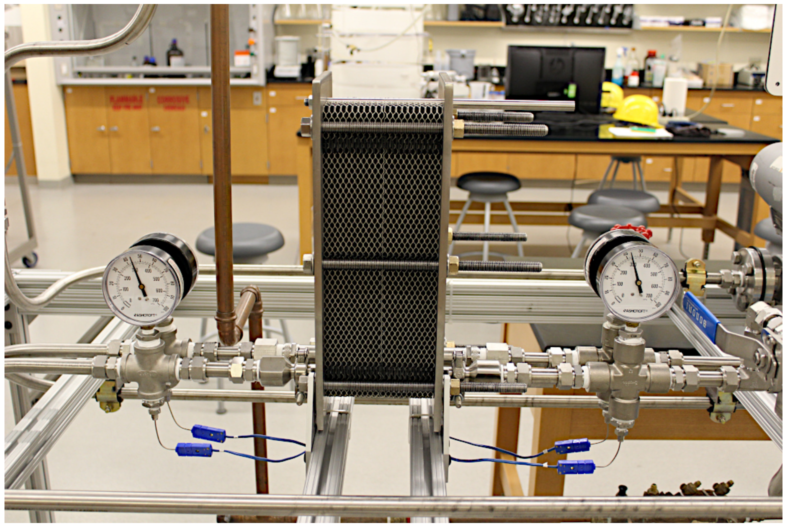

Figure 10: View of plate heat exchanger. PCW thermocouples (near side) and HHW thermocouples (far side) are visible

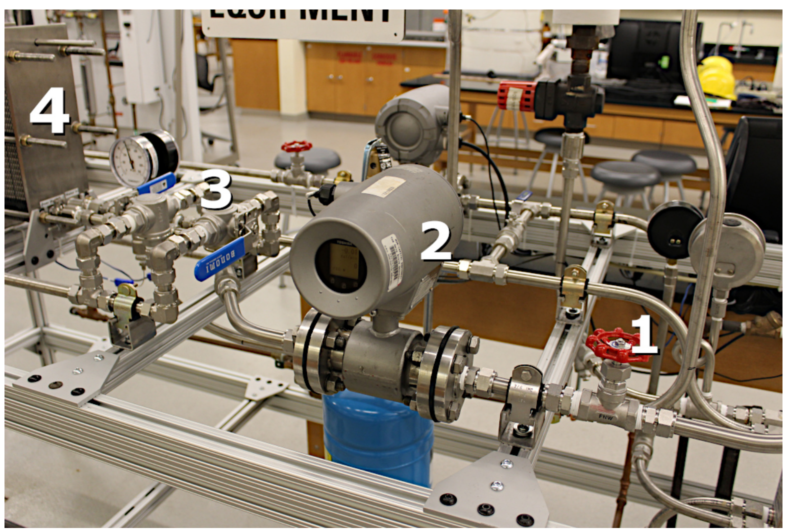

Figure 11: View Showing (1) PCW flow rate adjustment valve, (2) PCW flowmeter, (3) three-way valves for controlling PCW flow direction, and (4) plate heat exchanger

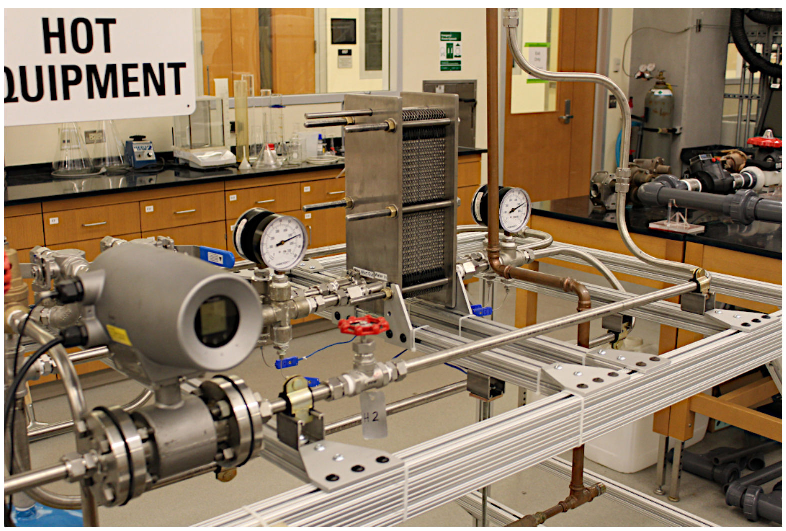

Figure 12: View Showing HHW flow rate adjustment valve and flowmeter.

Appendix B: Data Acquisition Components

Table 4: Data Acquisition Components

Description	Qty	Price	Cost	Model #	Supplier
Thermocouple and Voltage DAQ and Data Logger System	2	349	698	DI-2008	DATAQ
T-Type Thermocouple Extension Wire	1	49.58	49.58	EXPP-T-20-10	Omega
T-Type, Miniature Thermocouple Connectors	4	3.51	14.04	SMP-T-F	Omega
6 in, 1/16 diameter, grounded T-type Quick Disconnect Thermocouples with Miniature Connectors	4	32.79	131.16	TMQ316SS-062G-6	Omega

Appendix C: Structural Components

Table 5: Structural Components

Description	Qty	Price	Cost	Model #	Supplier
T-Slotted Framing Silver Tee Surface Bracket for 1.5” High Single Rail	12	9.9	118.8	47065T279	McMaster
T-Slotted Framing Silver Mounting Foot for 1.5” High Single Rail	8	15.77	126.16	47065T843	McMaster
T-Slotted Framing (8 ft) Double Six Slot Rail, Silver, 3” High x 1-1/2” Wide, Solid	4	96.19	384.76	47065T109	McMaster
Silver Corner Bracket 3” Long for 1-1/2” High Rail T-Slotted Framing	8	6.77	54.16	47065T241	McMaster
T-Slotted Framing (3 ft) Single Four Slot Rail, Silver, 1.5” High x 1.5” Wide, Solid Length, Ft. 3	10	25.92	259.2	47065T103	McMaster
T-Slotted Framing (4 ft) Single Four Slot Rail, Silver, 1.5” High x 1.5” Wide, Solid Length, ft. 4	4	32.06	128.24	47065T103	McMaster
T-Slotted Framing Silver Corner Surface Bracket for 1.5” High Rail	6	9.48	56.88	47065T271	McMaster
Strut-Mount Vibration-Damping Routing Clamp with TPE Rubber Cushion, Zinc-Plated Steel, 3/4” ID	50	1.82	91	32625T54	McMaster
Single Four Slot Rail, Silver, 1.5” High x 1.5”Wide, Solid	4	25.92	103.68	47065T103	McMaster
Drop-in Nut with Spring Loaded Ball, 5/16” -18 Thread Size	50	1.31	65.5	47065T327	McMaster
Silver Tee Surface Bracket for 1.5” High Single Rail	14	9.9	138.6	47065T279	McMaster