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UNDERGRADUATE HEAT EXCHANGER LABORATORY

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ABSTRACT

Heat exchangers are a fundamental part of many industrial and household devices, and a focus in the United States Military Academy at West Point's undergraduate heat transfer course within the school's Department of Civil and Mechanical Engineering. Recently, the department expanded laboratory capabilities to enhance student learning through hands-on experimentation. Prior to this project, a heat exchanger laboratory did not exist for student use, so a new apparatus was designed, developed, built, tested, and will be implemented as a laboratory experience in West Point's heat transfer course. The experimental apparatus includes a fan-cooled heat sink, a high-efficiency water heater, two pumps for water circulation, and numerous valves to change both the direction and route of the flows. This design allows students to test three types of heat exchangers: shell-in-tube, concentric, and flat plate. These devices allow students to evaluate parallel-flow, counter-flow, and cross-flow heat exchangers. The test section is instrumented with flow meters for the hot and cold flows as well as thermocouples at the entrance and exit of each heat exchanger. As part of this laboratory experience, students measure, collect, and analyze data, compare experimental results to theory, and assess error and uncertainty. This heat exchanger laboratory provide realistic, hands-on experience with experimental apparatus, laboratory procedure, instrumentation, and engineering technicians, all of which help students gain physical understanding of the thermal-fluids concepts.

KEY WORDS: Heat Transfer, Heat Exchanger, Undergraduate Laboratory

1. INTRODUCTION

Laboratory experiences represent a significant part of engineering education at the undergraduate level. Laboratories augment classroom instruction by helping students apply theory to real-world scenarios. Students cultivate skills necessary for a career in engineering by developing an understanding of the physical phenomena represented by modeling, understanding assumptions, approximations, and appropriate simplifications. Students subsequently apply simplified models to more realistic situations and complex geometries [1–6]. The Engineering Accreditation Commission of ABET has consistently integrated practical application of engineering principles within its student outcomes that are ideally fulfilled through the use of laboratories and other hands-on activities, including designing and conducting experiments, analyzing and interpreting data, and using techniques, skills, and modern engineering tools [7]. In recent years, virtual and remote laboratory experiences have emerged in response to the cost of developing or maintaining costly laboratory equipment and the development of new technologies, as discussed in many technical and educational articles, including [8–13]. Physical and virtual laboratories play a central role in the engineering curricula at the U.S. Military Academy (USMA) at West Point [14–21].

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Table 1 Summary of Laboratory Experiences, ME480 Heat Transfer.

| LESSON | TOPIC | Technician | Assignment |
|--------|--|------------|----------------------|
| Lab 1 | Problem Solving | None | Homework 1 |
| Lab 2 | Conduction Lab | 2 required | Lab Report |
| Lab 3 | Problem Solving | None | Homework 3 |
| Lab 4 | Structured Programming (Matlab) | 1 required | Project Submission 1 |
| Lab 5 | Problem Solving | None | Project Submission 2 |
| Lab 6 | Convection Lab | 2 required | Lab Report |
| Lab 7 | Simulation Lab | None | Project Simulation |
| Lab 8 | Project Competition | 3 required | No formal report |
| Lab 9 | Heat Exchanger Lab (under development) | 1 required | Summary report |

Heat transfer is a fundamental subject required in most mechanical and other engineering programs. The heat transfer course offered through the Department of Civil and Mechanical Engineering at USMA is a broad one packed with material covering 13 chapters of Bergman [22] in a 17-week semester, requiring a rapid progression through course topics during 40 regular lecture-style lessons (55 minutes each) and nine laboratory periods (120 minutes each). The course introduces or reinforces complex conservation principles and thermo-physical mechanisms, surveying the principal modes of heat transfer – conduction, convection, and radiation – along with special topics on condensation and boiling and applications, such as heat exchangers. Many students struggle to understand the content and topics without appropriate context, application, and visualization. Physical demonstrations delivered during classroom instruction enhance student understanding of many topics. Real world applications, particularly laboratory experiences, also contribute to students’ understanding of physical mechanisms and mathematical modeling of heat transfer phenomena. To improve student learning in an otherwise exceptional course, faculty and technicians recently developed two laboratory experiences. The first is a fin experiment and conduction laboratory based on [4]. The second is an internal flow convection laboratory employing straight and coiled tubes with two different tube materials. Table 1 highlights the course laboratories.

This paper details a new heat exchanger laboratory experience motivated by other, comparable laboratories including [1, 2, 4, 5, 20, 21, 23] among many others. The experimental apparatus includes a fan-cooled heat sink, a high-efficiency water heater, two pumps for water circulation, and numerous valves to change both the direction and route of the flows. This design allows students to test three types of heat exchangers: shell-in-tube, concentric, and flat plate. These devices allow students to quantitatively evaluate thermal performance of parallel-flow, counter-flow, and cross-flow heat exchangers individually and as part of a larger system. The test section is instrumented with flow meters for the hot and cold flows; thermocouples are placed at the entrance and exit of each heat exchanger. As part of this laboratory experience, students measure, collect, and analyze data, compare experimental results to theory, and assess measurement error and uncertainty.

2. EXPERIMENTAL APPARATUS

The heat exchanger laboratory apparatus was constructed from a basic steel frame and mounted on a sheet of three-quarter inch plywood. It is composed of two water tanks, a water heater, two water pumps, two flow meters, twelve thermocouples, a fan-cooled heat sink, a concentric heat exchanger, a flat plate heat exchanger, a shell-and-tube heat exchanger, polyvinyl chloride (PVC) valves, and PVC piping to connect these items. Additionally, the apparatus itself is held evenly off of the board by 3D printed pipe clips. This apparatus gives students the opportunity to test parallel-flow, counter-flow, and cross-flow pattern heat exchangers. The system is depicted in Figure 1.

The system has two separate flows, with a hot loop and a cold loop originating from storage tanks that feed into two separate sections of plumbing, both of which can be routed through any of the heat exchangers by

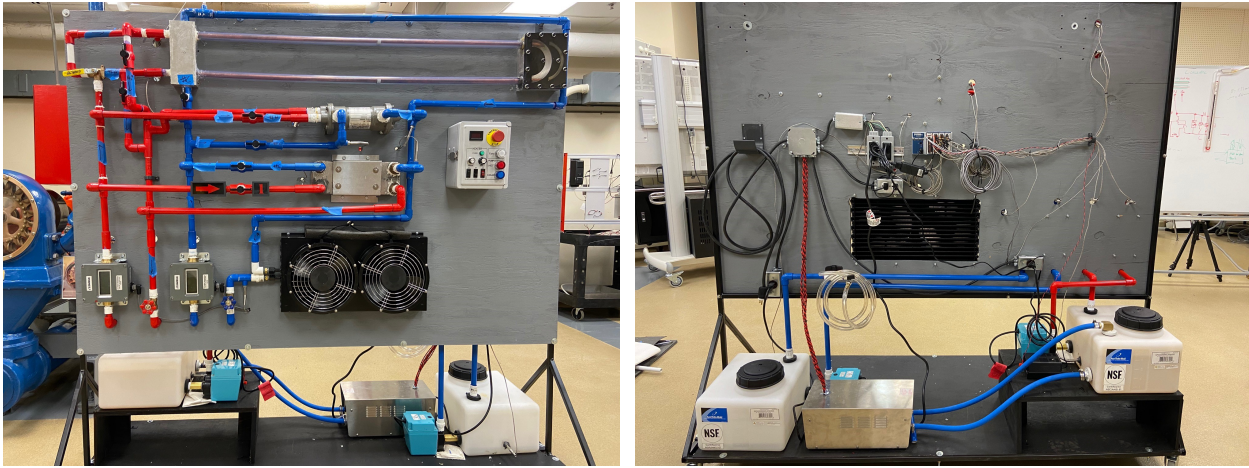


Fig. 1 Front (left) and back (right) of heat exchanger laboratory.

modifying which valves are open or closed. The cold water is cooled through a fan-cooled heat sink before being returned to the cold storage tank, while the hot water is circulated through a portable water heater connected to the hot storage tank.

Efficient pipe routing in the laboratory design minimizes potential sources of error by reducing pipe lengths, connections, and fittings as much as possible across the cycle. The hot and cold inlets are instrumented with independent flow meters to measure their respective mass flow rates. Thermocouples are located at the inlet and outlet of every heat exchanger, sensor, and the fan-cooled heat sink. This robust instrumentation configuration will give the most accurate data to analyze the heat exchangers and calculate the heat lost throughout the system.

All electrical components of the laboratory are controlled in one central electrical box, with a switched circuit for each pump, the radiator fans, and the heater. A safety relay is inline to cut power with an emergency stop button along with a 20 amp circuit breaker for additional protection. An ammeter is used to monitor the total power through the circuit. The control switches were removed from the water heater and extended up to the control panel for ease of access.

The shell-and-tube and flat plate heat exchangers were both purchased from McMaster-Carr. The shell-and-tube heat exchanger contains four passes in one-fourth inch copper tubes with minimum and maximum temperatures of -20°C and 300°F , respectively, and a heating and cooling capacity of 130,000 BTU/hr. The flat plate heat exchanger includes a brazed plate of 3 ft^2 with a heating and cooling capacity of 80,000 BTU/hr. Students and interns assembled the concentric heat exchanger using two clear PVC pipes, two copper tubes, and several parts fabricated in-house using both subtractive and additive manufacturing techniques. Custom fabricated parts (the 180° turn, as well as the inlet and outlet block) were machined out of aluminum with two separate channels for the two incoming flows. Additionally, there are two 3D printed spacers that maintain the spacing between the copper tubing and PVC pipes while minimally restricting the flow of the water. Hot water travels through the copper tubing and cold water travels through the clear PVC pipe. The hot water direction can be reversed, allowing for both parallel-flow and counter-flow configurations.

3. HEAT EXCHANGER THEORY

Students are expected to use the collected flow rate and temperature data to compare actual to theoretical performance of the various heat exchanger configurations discussed in § 2. There are two primary methods to analyze heat exchangers: the Log Mean Temperature Difference (LMTD) method and Effectiveness-NTU method, where NTU stands for Number of Transfer Units. If the inlet and outlet temperatures are either known

or easily solved for using an energy balance, the LMTD method is simple to implement. If the inlet or outlet temperatures are not known or not easily found, the Effectiveness-NTU method becomes preferred [22].

The LMTD method uses an energy balance focusing on either the hot or cold stream to determine the rate of heat transfer between the streams, as

$$q = \dot{m}_h c_{p,h}(T_{h,i} - T_{h,o}) = \dot{m}_c c_{p,c}(T_{c,o} - T_{c,i}) \quad (1)$$

where \dot{m} is the mass flow rate, c_p the specific heat, and T the temperature. Subscripts c and h represent cold or hot sides of the heat exchanger, respectively, and i and o the inlet or outlet. The heat transfer rate can also be written in terms of an overall heat transfer coefficient, U , and log-mean temperature difference as,

$$q = UA\Delta T_{lm} \quad (2)$$

with T_{lm} defined as

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)} \quad (3)$$

The variable A represents an appropriate surface area through which energy transfer occurs. Two canonical configurations include *parallel-flow* and *counter-flow*. For a parallel-flow exchanger, temperature differences can be derived as,

$$\begin{bmatrix} \Delta T_1 = T_{h,1} - T_{c,1} = T_{h,i} - T_{c,i} \\ \Delta T_2 = T_{h,2} - T_{c,2} = T_{h,o} - T_{c,o} \end{bmatrix}$$

and similarly for a counterflow exchanger,

$$\begin{bmatrix} \Delta T_1 = T_{h,1} - T_{c,1} = T_{h,i} - T_{c,o} \\ \Delta T_2 = T_{h,2} - T_{c,2} = T_{h,o} - T_{c,i} \end{bmatrix}$$

Alternative analysis of heat exchanger effectiveness can be conducted using the Effectiveness-NTU Method. To use this method, the maximum possible rate of heat transfer must be found by using,

$$q_{max} = C_{min}(T_{h,i} - T_{c,i}) \quad (4)$$

where C_{min} is the minimum heat capacity rate and equal to the smaller of C_c or C_h . The maximum rate of heat transfer helps define the heat exchanger effectiveness by comparing it to the actual rate of heat transfer by the following relationship where ε is the heat exchanger effectiveness,

$$\varepsilon = \frac{q}{q_{max}} \quad (5)$$

The heat exchanger effectiveness is related to NTU through a series of relationships easily found in many heat transfer textbooks such as [22]. NTU is a dimensionless quantity representing the number of transfer units, which can be related back to the thermal resistances in the heat exchanger through the following equation,

$$NTU = \frac{UA}{C_{min}} \quad (6)$$

4. LABORATORY OBJECTIVES AND EXPERIMENTAL PROCEDURE

During this laboratory, students explore how convective and conductive heat transfer principles combine by collecting data and analyzing heat exchangers to find trends for different cases. The objectives of this laboratory include:

- Explain the differences between different heat exchangers and understand how they function.
- Collect and analyze temperature data for different heat exchanger cases and choose the correct method for analysis.
- Determine the effectiveness (ϵ), Log Mean Temperature Difference (ΔT_{lm}), Number of Transfer Units (NTU), and heat transfer rate (q).
- Create plots showing how effectiveness relates to NTU and any other relevant relationships.

There are five authorized configurations for this laboratory experiment, one prohibited configuration, and one drain configuration which can be seen in Table 2. For future use, an open valve is one that is in-line with the flow, and a closed valve is one that is perpendicular to the flow of the system. The prohibited configuration is when all valves are in the closed position. If the system is run in this configuration, it will cause damage to the pumps or the seals on the pipes, and render the laboratory inoperable. The most common configuration is the “drain” configuration, where the user opens all valves for the water to return to the storage tanks. The “drain” configuration is employed any time that the system is not in use. The remaining four configurations are for experimentation with the separate heat exchangers. Students and instructors must ensure both pumps are off prior to switching between configurations to avoid system damage.

To begin the laboratory, students turn on the LabView™ system and view the thermocouple temperature readings. The data acquisition system allows students to select thermocouples that match the configuration to be tested. Students fill the cold-water tank with ice and add tap water in the two tanks. The device can then be powered on. The hot water tank must reach a temperature between 65 – 70°C before initiating a run. Students maintain the cold water tank between 0 – 5°C by adding ice and draining off excess water as necessary. Once the storage tanks reach an appropriate temperature, students set valves into an appropriate configuration to conduct the case under investigation, turn on the fan, initiate both hot and cold water pumps, and collect the data.

Table 2 Heat Exchanger Authorized Configurations.

| Configuration | Open Valves | Closed Valves | Notes |
|----------------------------|---------------------|---------------------|----------------------------------|
| Concentric (Parallel-Flow) | 3, 4 | 2, 5, 6, 7, 8 | Valve 1 handle must point left |
| Concentric (Counter-Flow) | 2, 4 | 3, 5, 6, 7, 8 | Valve 1 handle must point down |
| Shell-and-Tube | 5, 6 | 2, 3, 4, 7, 8 | Valve 1 position inconsequential |
| Flat Plate | 7, 8 | 2, 3, 4, 5, 6 | Valve 1 position inconsequential |
| Drain | 2, 3, 4, 5, 6, 7, 8 | None | Valve 1 position inconsequential |
| PROHIBITED | None | 2, 3, 4, 5, 6, 7, 8 | System damage will occur |

5. RESULTS

To validate the new laboratory configuration, each approved configuration of the apparatus was run until completion and the tanks were reheated and cooled between trials. The data collected by the thermocouples was used to obtain each heat exchanger’s effectiveness and NTU. The rate of heat transfer between the hot and cold flow lines differed because the heat exchangers are not perfectly insulated. Portions of the heat lost from the hot flow were released into the atmosphere; therefore, the cold flow values were used for calculations.

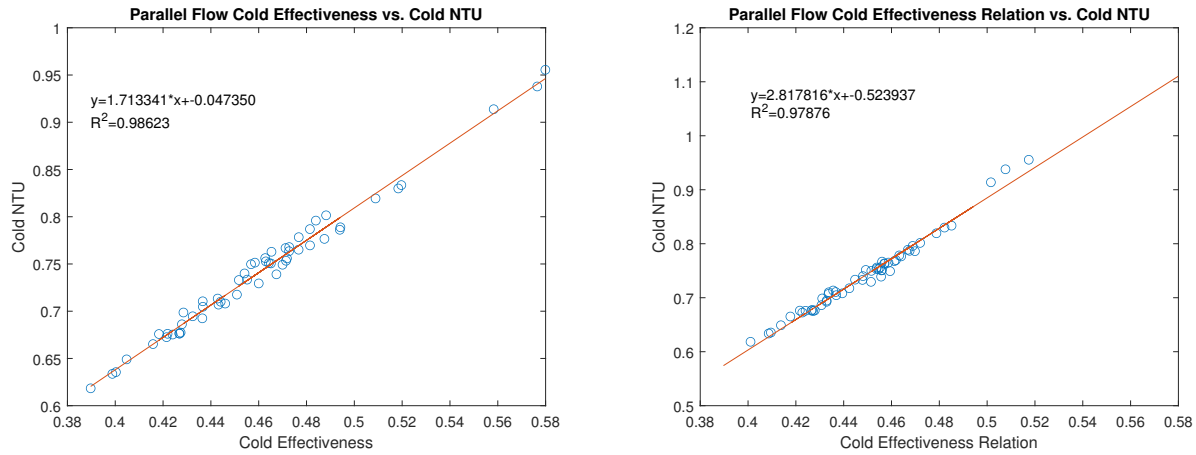


Fig. 2 Parallel Flow NTU vs Effectiveness - LMTD Method (left) and Effectiveness-NTU Method (right).

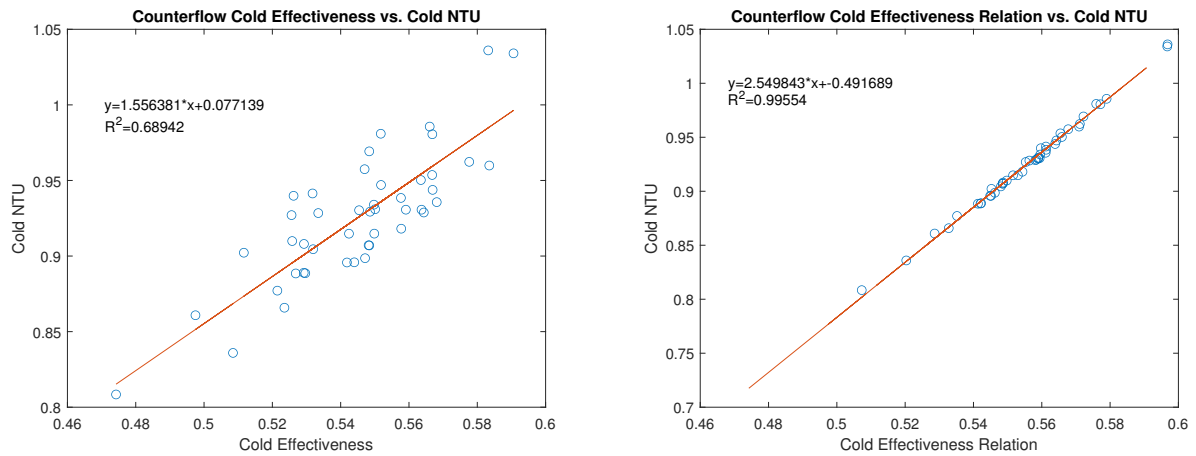


Fig. 3 Counter Flow NTU vs Effectiveness - LMTD Method (left) and Effectiveness-NTU Method (right).

The effectiveness of each heat exchanger was calculated using two different methods. Both began by finding the rate of heat transfer into the cold flow. The first method calculated effectiveness by taking the ratio of the actual rate of heat transfer and the maximum rate of heat transfer that could be achieved, as in Equation 5. The second method used the log mean temperature difference to find the overall heat transfer coefficient, UA , in Equation 2, then used to compute NTU as in Equation 6. The effectiveness could then be calculated from using known heat exchanger effectiveness relationships [22]. The two forms of analysis were plotted and compared for each case.

The concentric heat exchanger was tested in both a parallel flow configuration and a counterflow configuration and results plotted in Figure 2 and Figure 3, respectively. The Effectiveness-NTU method used the following relationship for parallel flow:

$$NTU = -\frac{\ln[1 - \varepsilon(1 + C_r)]}{1 + C_r} \quad (7)$$

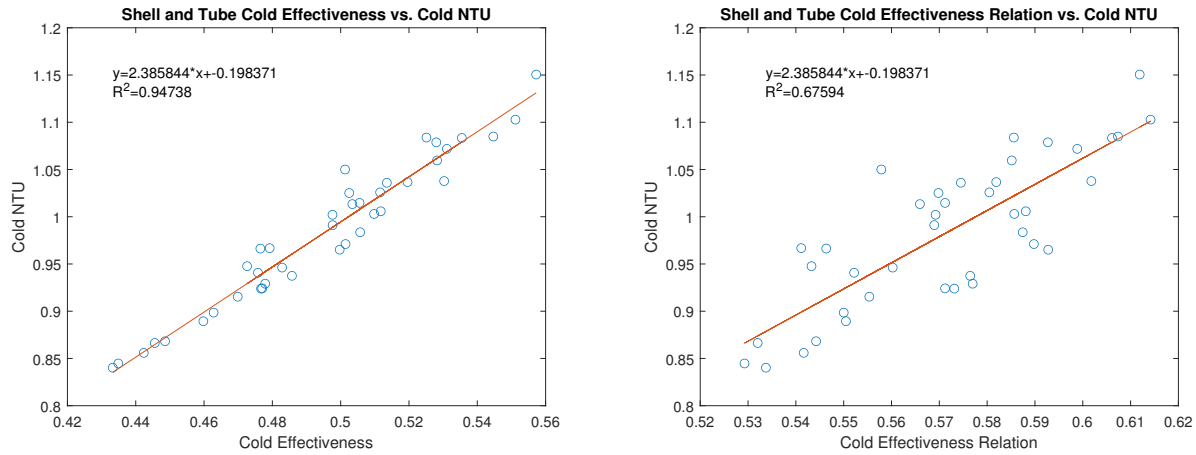


Fig. 4 Shell and Tube NTU vs Effectiveness - LMTD Method (left) and Effectiveness-NTU Method (right).

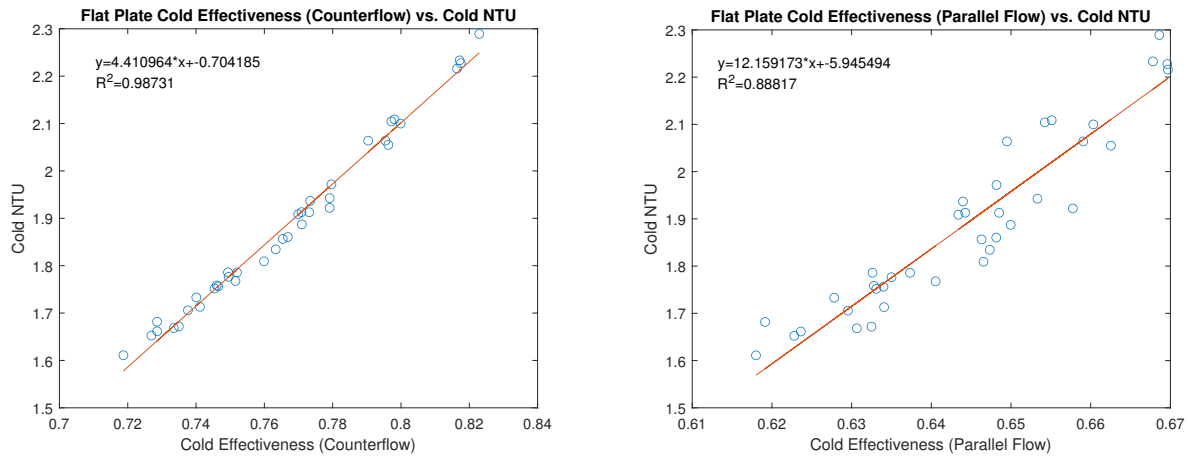


Fig. 5 Flat Plate NTU vs Effectiveness - Effectiveness-NTU Method (left and right).

And the following equations for counterflow:

$$NTU = \frac{1}{C_r - 1} \ln \left(\frac{\varepsilon - 1}{\varepsilon C_r - 1} \right) \quad (C_r < 1) \quad (8)$$

$$NTU = \frac{\varepsilon}{1 - \varepsilon} \quad (C_r = 1) \quad (9)$$

where C_r is the ratio of heat capacities. Both methods show a relatively linear relationship between effectiveness and NTU over the range of temperatures, with the Effectiveness-NTU Method being more precise. The counterflow plot shows more variation than the parallel flow when using the LMTD Method.

The shell-in-tube heat exchanger was also analyzed using both methods. The relationship between effectiveness and NTU for the shell-in-tube heat exchanger is much more complex:

$$NTU = -(1 + C_r^2)^{-1/2} \ln \left(\frac{E - 1}{E + 1} \right) \quad (10)$$

$$E = \frac{2/\varepsilon - (1 + C_r)}{(1 + C_r^2)^{1/2}} \quad (11)$$

The results are much more varied for this more complex heat exchanger which can be seen in Figure 4. The LMTD method gave more accurate results in this configuration.

The final configuration is the flat plate heat exchanger. No definitive correlation could be found for this type of heat exchanger in the literature, so it was analyzed as both counterflow and parallel flow, since there are instances of both types within the device. The Effectiveness-NTU Method was used with both types of flows and the results show that the flat plate correlates much more closely to the counterflow relationship than parallel flow, as seen in Figure 5.

6. CONCLUSION

A heat exchanger laboratory experience was recently developed and implemented within the Heat Transfer course at West Point. The laboratory enhances student learning through hands-on experimentation. Prior to this project, a hands-on heat exchanger experience did not exist in ME480. The experimental apparatus includes a fan-cooled heat sink, a high-efficiency water heater, two pumps for water circulation, and numerous valves to change both the direction and route of the flows. This design allows students to test four types of heat exchangers: shell-in-tube, concentric, cross-flow, and flat plate. These devices allow students to evaluate parallel flow, counter flow, and cross flow heat exchangers. The test section is instrumented with flow meters for the hot and cold flows as well as thermocouples at the entrance and exit of each heat exchanger. As part of the laboratory experience, students measure, collect, and analyze data; compare experimental results to theory; and quantitatively and qualitatively assess error and uncertainty. The heat exchanger laboratory provides realistic, hands-on experience with experimental apparatus, laboratory procedure, instrumentation, and engineering technicians, all of which will help students gain physical understanding of relevant thermal-fluids concepts.

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