

Design and Construction of a Heat Exchanger Analyzer for an Undergraduate Thermal–Fluids Laboratory*

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A team of undergraduate mechanical engineering technology students designed and built a heat exchanger learning module. Hot and cold fluid delivery systems provide fluids to a heat exchanger that is used to teach fundamental concepts of heat transfer in a thermal science laboratory. Design provisions enable analysis of heat exchangers in either parallel or counter flow configurations. The module uses a data acquisition system to record temperatures along the heat exchanger loops. The effect of flow configuration and mass flow rate on heat transfer characteristics of the heat exchangers is evaluated. Overall heat transfer coefficient (U) of 500 ($W/m^2 \text{ } ^\circ C$) for a heat exchanger with parallel flow configuration was determined. Assessment results for this module obtained through a survey by students who used it in their thermal science laboratory course during the Spring 2005 semester is presented, and indicates that this home-made instrument is user friendly pedagogically sound and safe to operate.

Keywords: heat exchanger; ASHRAE; thermal science laboratory

INTRODUCTION

The Mechanical Engineering Technology (MEET) program of University of North Texas was awarded a grant from the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) through their Undergraduate Senior Project Grant Program [1]. ASHRAE's program provides funds for materials and supplies needed for successful completion of senior projects. A second similar project with the aim of designing and building a thermal conductivity measuring system for evaluating solid materials is currently underway. Although great learning modules are available commercially [2], these instruments are generally expensive and, in this case, the cost of a heat exchanger with the desired specifications was beyond the MEET program budget. Another aspect that makes building a homemade heat exchanger more favorable, as opposed to purchasing a commercial one, is the great deal of engineering practice that goes into the design and building of the system, which serves as an opportunity for senior undergraduate students to fabricate an apparatus, apply theoretical constructs, see their errors and experience working on a real open-ended problem for which many correct answers exist. Completion of such projects could be one way that ABET can gage the technical depth of a given program [3].

Researchers and educators have developed many useful tools in teaching heat transfer topics

including design and applications of heat exchangers [4–7]. Ozar and his group complemented the traditional lecture format in engineering education by developing web-based learning modules for Thermal–Fluid Engineering and other Mechanical Engineering courses [4]. J. Ball and K. Patrick [5] constructed computer animations using mathematical models of unsteady state heat transfer in conduction and in heat exchangers and steady state in forced convections. K. C. Leong and K. C. Toh [6] wrote software for the thermal and hydraulic design of shell and tube heat exchangers with flow induced vibration checks. C. Borkowski *et al.* [7] developed a self-contained computer environment to assist in the teaching and learning process through experimentation with a focus on thermal sciences. All these tools are valuable, but are no substitute for the practical hands-on aspect essential in engineering programs and particularly for engineering technology students.

K. Sherwin and M. Mavromihales [8] designed and fabricated a cross-flow heat exchanger that simulated a car radiator and required students to design exchanger height and width, tube pitch, and the number of rows in a staggered configuration to optimize their heat exchanger performance. Hosni I. Abu-Mulaweh [9] used tube-within-a-tube heat exchangers and modified them by an insert displacement device, a swirl flow device, extended surfaces, and obstruction devices to assist undergraduate students in the understanding of basic heat transfer processes. D. L. Dekker [10] involved three groups of students (3 to 5 students per group) to design, build, and evaluate/redesign.

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The first group designed the heat exchanger and passed it to the second group to build, while the third group evaluated/redesigned it. The focus in this strategy is on leadership skills and encouraging inter-group communications. Most recently, in his senior design course with an ASHRAE grant, C. Forsberg [11] designed and constructed a thermal science demonstration unit. It included three types of heat exchangers: a double pipe heat exchanger with parallel and counterflow configurations, a shell-and-tube heat exchanger, and a cross-flow heat exchanger. Their system did not, however, include the application of software for data logging.

In our project, a learning unit was designed and built to demonstrate the fundamentals of heat exchangers as covered in Chapter 13 of Cengel's textbook on heat transfer [12]. This module was required to have the capability of testing differently configured heat exchangers. Specifically, this system was designed to test tube-in-tube heat exchangers with either parallel or counterflow configurations. Since undergraduate students were to be the main users of this system, it was required that the operation of the heat exchanger learning module be without safety concerns. Data collection and analysis was streamlined through the application of a data acquisition system.

This paper provides details of the heat exchanger design as well as two suggested experiments.

The first experiment will compare tube-in-tube heat exchanger performance in which hot and cold flow directions are parallel to the case where hot and cold flow are in opposite directions. The second experiment facilitates analysis of fluid mass flow rates on the performance of heat exchangers with different flow configurations. The following sections provide detail and components of the system, followed by the students' assessment of the apparatus and the conclusions section. Finally, the Appendix contains theory and procedures for the two experiments with sample data.

Product design

The heat exchanger module consists of five main components including:

- Cabinet
- Fluid systems
- Heat exchangers
- Electrical system
- Data acquisition

The cabinet is 99-inches wide, 32-inches deep and 69.75-inches tall, constructed with 16 gage one-inch 304 stainless steel square tubing. The same grade stainless steel was used for cabinet side panels. The tubing material was selected to minimize deflection. Panels are made of the same material and are corrosion resistance to the atmosphere. ASTM A-595 grade C structural 2 inch



Fig. 1. Heat exchanger analyzer module.

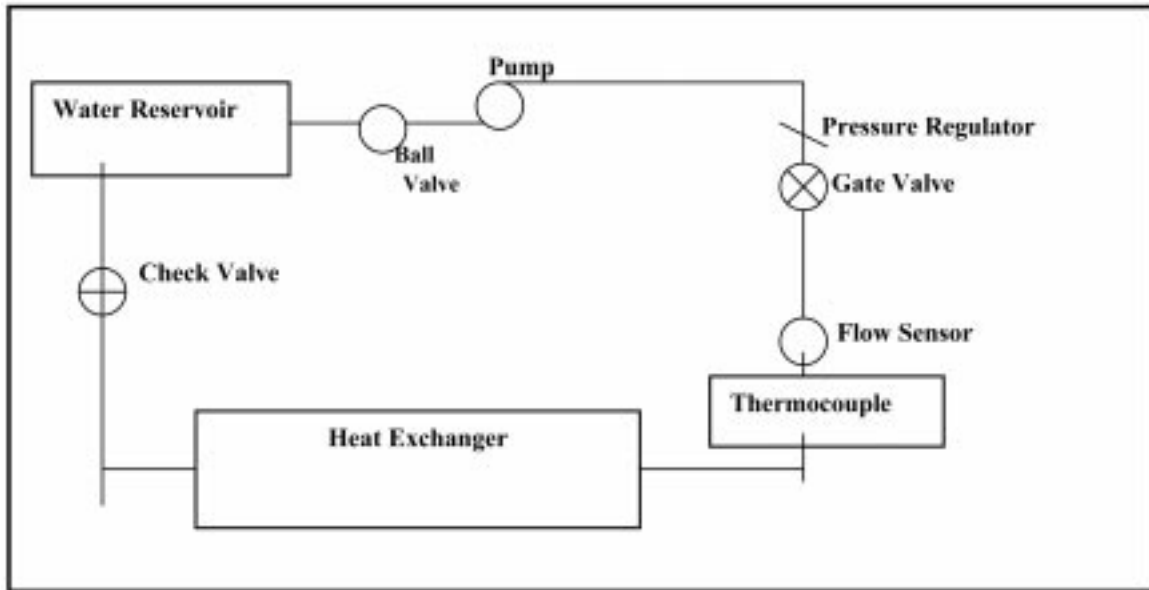


Fig 2. Schematic diagram of cold fluid system. Hot fluid system uses the same configuration with an added heating element in the water storage tank.

square, 1/4-inch wall steel tubing was used for the base frame. Figure 1 shows a picture of the heat exchanger analyzer module.

Two independent closed-loop pumping systems are used to transport the hot and cold fluids to and from the heat exchanger. Each loop contains a 10-gallon storage tank, 1/2-hp pump, relief valve, test

fittings, and shut-off valves. A maximum volume flow rate of 10 G. P. M. is achievable and controlled with a brass gate valve. A full range flow rate is necessary for creating optimal heat transfer conditions. Figure 2 shows schematics of the hot and cold fluid systems.

This system uses a 240 V-40 A-power supply. A

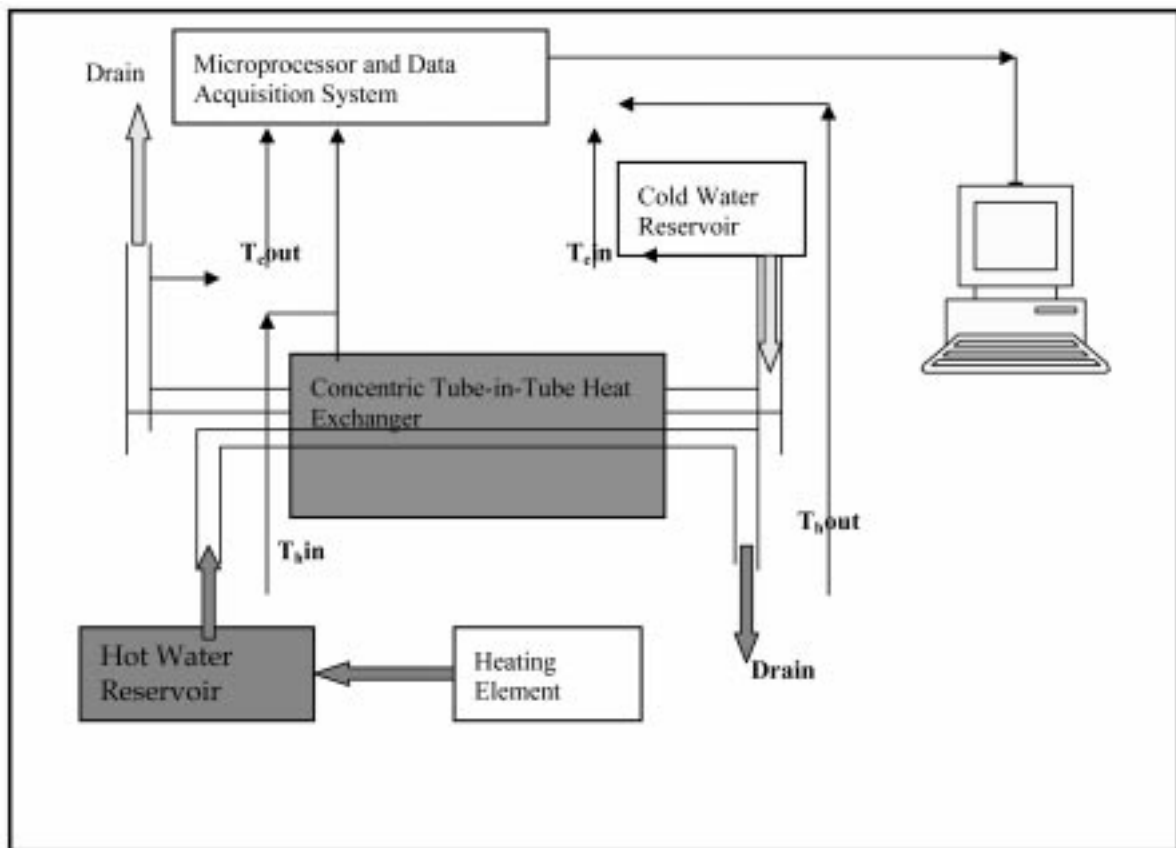


Fig 3. Schematic diagram showing data acquisition based on Log Mean Temperature Difference method of heat exchanger analysis.

4500-W heating element provides the hot water supply. All other components are 110 V. Electrical components consist of two 1/2-hp pumps, a 4500-W heating element, a process control device, an electric fan, and a power strip to run a standard PC with monitor. An emergency off SPST-NC switch, which can shut off all the power, is used to provide a safe runoff in an emergency. The use of bus bars for power and grounds allows easier wiring connection and troubleshooting of components.

Four type T thermocouples are placed on the intake and outlet of both hot and cold sides of the heat exchanger. Flowmeters are located on both hot and cold intake sides. All sensors are wired to a microprocessor board. The flowmeter readings are displayed on two digital readouts. Seven inputs for thermocouples and seven channels are recorded into a PC. The I/O board comes with software that is compatible with most C++ programming languages and Lab View. The software is ready to use and allows for signal verification, data logging, and provides a graphical view of real time data using a variety of input instrumentation. The data acquisition system design is based on the Log Mean Temperature Difference Method for determining heat exchanger performance. Four temperature readings and a mass flow rate reading are needed for this method (Fig. 3). However, the I/O board will allow an additional three thermocouples inputs for additional readings. An additional J-type thermocouple is located in the hot water tank and is wired to the electrical process control device for temperature regulation. All

sensors are commercially available and can be upgraded while remaining compatible with the rest of the system.

ASSESSMENT OF HEAT EXCHANGER ANALYZER MODULE

Graduating seniors registered for the thermal science laboratory course during the Spring 2005 semester who used this apparatus were given a questionnaire (Appendix A) related to the characteristics of this module. Results of this student evaluation are shown in Fig. 4. Figure 4 indicates that the majority of students believed this module was user-friendly and all students thought the module was safe to operate. About 81% of the students either 'strongly agreed' or 'agreed' that this apparatus enhanced their understanding of heat transfer. In addition, students unanimously felt that the design and construction of this module demonstrated the competence of graduating seniors of the MEET program. Finally, 72% of students either 'strongly agreed' or 'agreed' that the two heat exchanger experiments performed using this module were the best of the twelve experiments that they completed during the semester.

DISCUSSION

The senior capstone project at UNT provides an opportunity for students to practice teamwork as

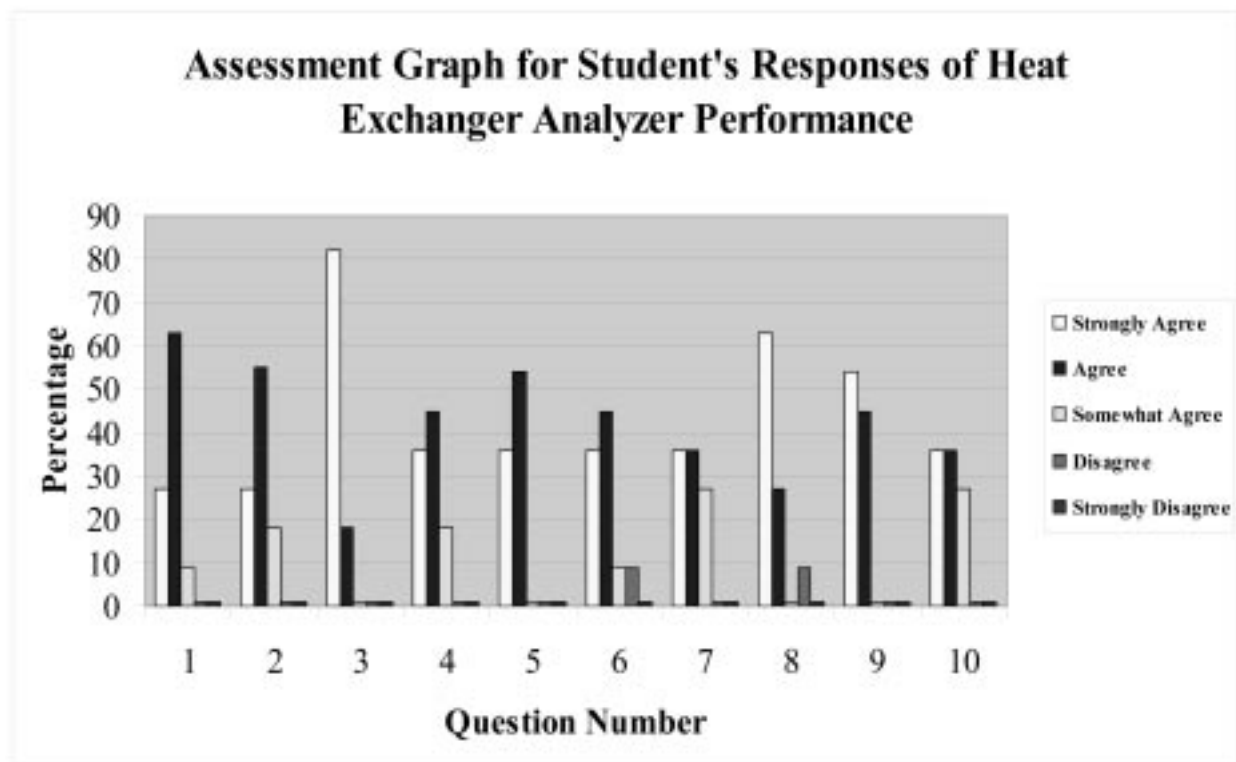


Fig. 4. Students' response to questions listed in Table 1 for assessment of the heat exchanger module.

well as leadership skills. To achieve this, the course is structured such that a group of 4–5 students with mechanical and electronic engineering technology backgrounds form a team that models a company; the course instructor serves as the Chief Executive Officer of the company. An engineer, usually from a different faculty from the course instructor, or an industrial representative, supervises each team. It is well established that project-driven classes provide students with the opportunity to experience team design work from idea conception to completion [13–16]. Students in the MEET program are required to employ their technical knowledge to design and develop a marketable product. Products are required to have brochures, Web sites, and other marketing characteristics to facilitate the introduction into a virtual market. In addition, students who complete this course gain a great deal of management and specifically project life management skills.

In this particular design, students employed their knowledge of solid mechanics, thermal sciences, and instrumentation. Interfacing hardware and software was a requirement in this project. This design included complete integration of hardware and software such that temperatures measured around the heat exchanger loops were stored in memory for future analysis. Similar systems designed by other researchers did not include this feature.

Cost effectiveness is another feature that makes these types of projects favorable. The total cost of this project was about \$5000.00. A similar commercial apparatus with the same capabilities is significantly more costly. A second system designed and built to analyze thermal conductivity of solid materials has already been completed and

addition of several such homemade apparatuses to a newly develop laboratory like UNTs' thermal science laboratory can equip the laboratory with minimal cost.

CONCLUSIONS

A team of senior undergraduate mechanical engineering technology students designed and constructed a heat exchanger analyzer module, sponsored by ASHRAE. Two experiments to demonstrate the principles of heat transfer in heat exchangers were developed to use this heat exchanger analyzer in either parallel or counter-flow configurations at the thermal science laboratory of UNT. The overall heat transfer coefficient (U) of a typical heat exchanger was determined as $500 \text{ W/m}^2 \text{ }^\circ\text{C}$. The design process proved to be effective in providing students with an opportunity to experience teamwork, project management, product marketing, and communication. Assessment results obtained through a student survey showed students' overall satisfaction of this module with 72% of students ranking the heat exchanger experiment as the best of the twelve experiments that they performed during the Spring 2005 semester.

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APPENDIX A

Table 1 Questionnaire used in acquiring students' opinion about the heat exchanger module

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1. Heat exchanger module is a user friendly system
 2. Heat exchanger module facilitated two new and useful experiments
 3. Heat exchanger module is a safe instrument to operate
 4. Heat exchanger module is a home made instrument that is comparable with a commercially available one
 5. Software used in heat exchanger module successfully controls hardware
 6. My understanding of heat exchangers was enhanced by using heat exchanger module
 7. Results obtained using heat exchanger module was expected and followed theory
 8. Heat exchanger module is flexible in testing differently configured heat exchangers
 9. Heat exchanger module design and construction demonstrates capability of my fellow students who were educated in my program here at UNT-MEET program
 10. Heat exchanger experiments performed using heat exchanger module was the best of 12 experiments I did in MEET 4360 class
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APPENDIX B

*Experiment #1**Parallel and counter flow heat exchangers**Objective*

The objective of this experiment is to study the working principles of a concentric tube heat exchanger operating under parallel and counter flow.

Theory

The overall heat transfer coefficient, although very important in heat exchanger analysis, can also be difficult to obtain experimentally. This coefficient depends primarily on fluid convection and wall conduction resistances as well as resistances caused by deposits and chemical reactions, known as fouling, which take place on the inside surfaces of the heat exchanger during normal operation. To find the overall heat transfer coefficient for this experiment we will use the equation:

$$q = UA\Delta T_{lm} \quad (1)$$

where ΔT_{lm} is the log-mean temperature difference. Because the temperatures at the inlet and exit for the hot and cold fluids are normally readily available, we must find an expression for ΔT_{lm} in terms of these inlet and exit temperatures.

If you follow the derivation in the reference using the log-mean temperature difference analysis, you will find that:

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)} \quad (2)$$

For the parallel flow exchanger we will have:

$$\Delta T_1 = T_{h,i} - T_{c,i} \quad (3a)$$

$$\Delta T_2 = T_{h,e} - T_{c,e} \quad (3b)$$

and for the counter flow heat exchanger we will have:

$$\Delta T_1 = T_{h,i} - T_{c,e} \quad (4a)$$

$$\Delta T_2 = T_{h,e} - T_{c,i} \quad (4b)$$

Solving for the overall heat transfer coefficient in Equation (1) and substituting in for ΔT_m , ΔT_{lm} , we now obtain:

$$U = \frac{q_{abs}}{A\Delta T_{lm}} \quad (5)$$

where q_{abs} is the heat that is absorbed.

If it is assumed that potential and kinetic energies are negligible and specific heats are constant we can write an energy balance for the system involving the cold fluid as:

$$\bar{q}_{absorbed} = (\bar{V}\rho c_p)_c (T_{c,e} - T_{c,i}) \quad (6)$$

Similarly, for the system involving the hot liquid we have:

$$\bar{q}_{emitted} = (\bar{V}\rho c_p)_h(T_{h,i} - T_{h,e}) \quad (7)$$

and for the whole heat exchanger, not assuming that the exchanger is adiabatic, we have:

$$q_{loss} = q_{emitted} - q_{absorbed} \quad (8)$$

Finally, we can find the efficiency of the heat exchanger by:

$$\eta = \frac{q}{q_{max}} = \frac{q_{absorbed}}{q_{emitted}} \times 100\% \quad (9)$$

Apparatus

The apparatus for this experiment is the Thermal Lab Systems heat exchanger test bench, and one of the various concentric tube heat exchangers as assigned by the instructor. The test bench has two fluid tanks, one with a resistance heater inside to heat water to a constant temperature of 50°C. Once the water is heated to the desired temperature it is transferred to the heat exchanger by a water pump in the lower section of the cabinet. The cold water is kept at room temperature, and likewise delivered by a pump. On the outlet side of the pump there is a flow control valve that varies the volume of water delivered to the heat exchanger.

The actual heat transfer takes place from the hot fluid flowing inside the metal center tube, through the tube wall, to the cold water flowing through the PVC pipe. Part A of the experiment focuses on the parallel flow set up, while Part B is for counter flow. These flow arrangements are detailed in their respective sections. The flow rates can be adjusted for both cold and hot water by turning the flow control valve knobs located in the lower section of the cabinet. Thermocouples are located at the inlet and exit of the insulated heat exchanger tubing for both hot and cold water.

Note: It is important to note that the lab set up has an EMO, or Emergency Off, button, located in the upper right corner of the cabinet. If at any time a large leak, component failure, or other unsafe condition occurs, simply depress the EMO and the entire system will shut down. Immediately notify the lab teaching assistant and/or the class instructor.

PART A: PARALLEL FLOW PROCEDURE

1. Open the front doors of the cabinet and verify that the water level is within 1 inch below the full mark for both hot and cold tanks. Add water as necessary, but do not overflow.
2. Turn on the heater controller power switch. The temperature in the hot water tank will increase, and stabilize at around 50°C. This should take 10 to 15 minutes, so move on to Step 3.
3. Place the heat exchanger on the cabinet work surface and carefully connect the red hose marked 'HOT SUPPLY' and thermocouple 'CH 1' to the heat exchanger inlet as shown in Fig. 5. Connect the hose marked 'HOT RETURN' and thermocouple 'CH 3' to the heat exchanger outlet as shown. In the same manner, connect the cold water supply and return hoses, and thermocouples. Care should be taken in handling the hoses and connections to prevent damage to the sealing surfaces and the thermocouples located in the connectors. This configures the heat exchanger for parallel flow operation.

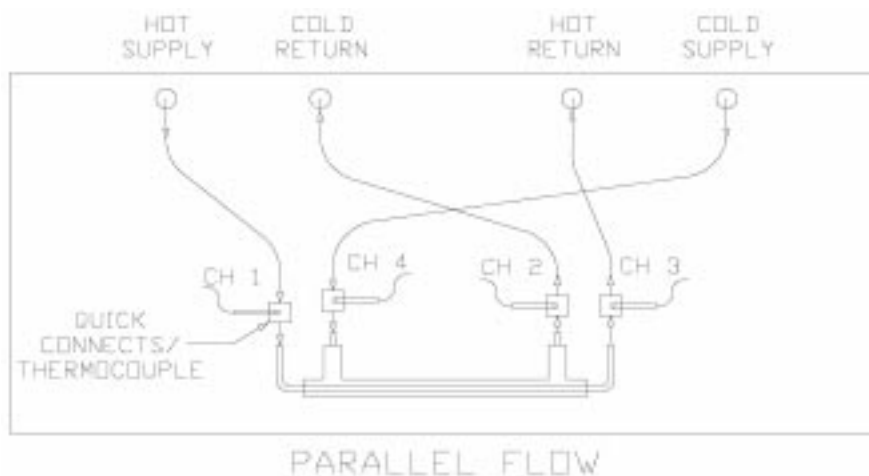


Fig. 5. Parallel flow connection diagram.

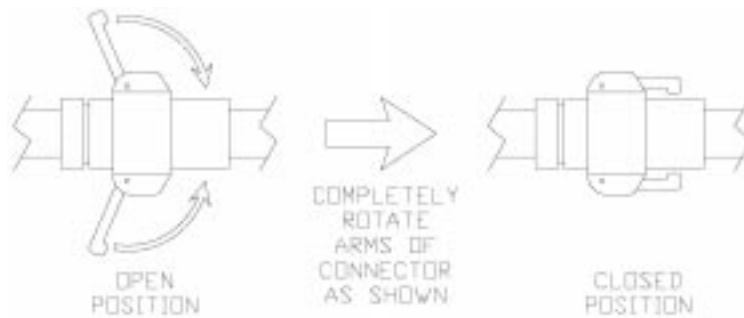


Fig. 6. Quick connect latch diagram.

Note: It is very important to connect the hoses securely to the heat exchanger to prevent the operator of the lab equipment from getting soaked! To verify that the hoses are secure, make sure that the latches on the connectors are completely engaged and rotated around to the body of the hose connector, as shown in Fig. 6.

4. Turn on the computer and monitor, and wait for computer to boot up.
5. Start the DaqView data acquisition software. This will also automatically start Excel.
6. You will see a popup screen—click on ‘Enable Macros’.
7. Another popup ‘DaqView is not currently running —Start now?’—Click on ‘Yes’, and wait for the DaqView software to initialize.
8. On the Excel screen, create a new page.
9. Maximize the DaqView software screen.
10. On the DaqView screen, click on the ‘Hide INACTIVE Channels’ button (toward the upper left—looks like an accordion).
11. On the DaqView screen, click on the start button (upper middle —looks like the start arrow on a VCR). You should now see values in the ‘Readings’ column, updated in real-time. The only value you are concerned with at this time is the tank temperature.
12. Inside the lower section of the cabinet, locate the hot and cold flow control valves. These are identified as shown in Fig. 7. Make sure both the hot and cold water control valves are wide open by turning them fully counter-clockwise.
13. Monitor the tank temperature—once it reaches 50°C, move on to Step 14.
14. Verify that the heat exchanger connections and flow control valves are set, and turn on the hot and cold water pumps, and rate meters with the switches at the instrument panel.
15. While observing the flow meter readouts, turn the control valves clockwise, and set the flow rate for both hot and cold water to 7.5 +/- .2 LPM. These are the mass flow rates of the system, and are kept equal to simplify calculations. Record these values.
16. Wait approximately 2–3 minutes for the heat exchanger temperatures to stabilize.

Note: The pumps are equipped with thermal overload sensors. If they are operated for more than 10–15



Fig. 7. Flow control valves.

minutes with the flow throttled down severely, as described in Step 15 above, the thermal protection will likely trip. In the event this occurs, simply turn the power switch off for both pumps, let them cool down for approximately 10 minutes, and restart the lab exercise at Step 12.

17. On the DaqView screen, click on the square stop button.
18. On the Excel spreadsheet, click the A1 cell (DaqView will automatically minimize).
19. In the Excel toolbar at the top of the screen, click on 'Tools', 'DaqViewXL', 'Set Data Destination Cell' (this tells DaqView XL where to send data).
20. Again in Excel toolbar, click on 'Tools', 'DaqViewXL', 'Go!'.
21. You will see a popup screen—click on 'Manual Trigger' button. DaqView will start collecting data and send these data points to the Excel spreadsheet. Column A is a system reference temperature, and is not to be used in the heat exchanger calculations. Column B is temperatures for Channel 1 (Hot supply); column C—Ch.2 (Cold supply); column D—Ch.3 (Hot return); column E—Ch.4 (Cold return). Column F is the hot water tank temperature, and is not used in the calculations.
22. Save this data to a disk and clear all values from the Excel file.
23. Turn off both of the water pumps.
24. Slowly open **ONLY ONE** of the latches on the cold supply connector until you notice a gurgling sound. Carefully lift the heat exchanger (with hoses attached) and slowly tilt it from side to side to allow the remaining water to drain back through the hoses. Be careful not to touch the high temperature plumbing (copper tubing), as it will still be hot.
25. Place the heat exchanger back on the work surface. Watch for any water spills and clean up with towels as supplied.

This concludes data collection for Part A.

PART B: COUNTER FLOW

Procedure

26. Carefully disconnect only the cold water hoses at the heat exchanger. Watch for any remaining water in the hoses—clean up any spills with towels as provided.
27. Reverse the flow direction by connecting the hose marked 'cold return' to the inlet side of the heat exchanger from the previous lab exercise, and connect the hose marked 'cold supply' to the previous outlet end. Again, care should be taken in the handling of the hoses, connections, and thermocouples. This configures the heat exchanger for counter flow operation as shown in Fig. 8.

Note: It is very important to connect the hoses to the heat exchanger securely to prevent the operator of the lab equipment from getting soaked! To verify that the hoses are secure, make sure that the latches on the connectors are completely engaged and rotated around to the body of the hose connector, as shown in Part A, Fig. 2.

28. Once the hose connections are verified turn on only the cold water pump and check for leaks.
29. Maximize the DaqView software screen and click on the start button.
30. Turn on the hot water pump.
31. Verify that the flow rates for both hot and cold water match the values in Part A. Adjust as necessary.
32. Wait approximately 2 minutes until the temperatures stabilize.
33. On the DaqView screen, click on the square stop button.
34. On the Excel spreadsheet, click the A1 cell (DaqView will automatically minimize).

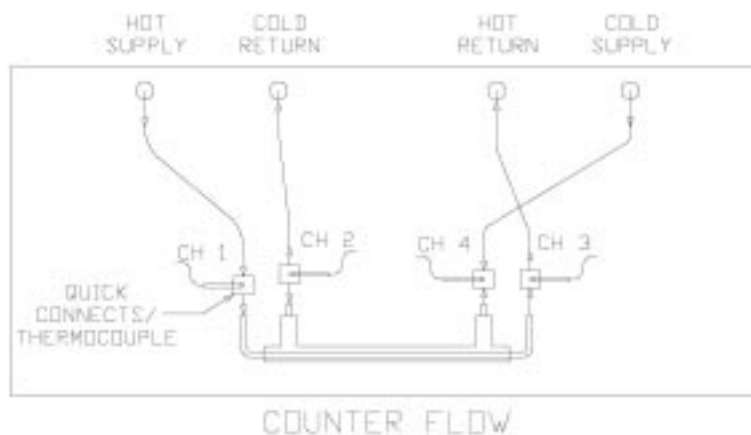


Fig 8. Counterflow connection diagram.

35. In the Excel toolbar at the top of the screen, click on 'Tools', 'DaqViewXL', 'Set Data Destination Cell'.
36. Again in Excel toolbar, click on 'Tools', 'DaqViewXL', 'Go!'.
37. You will see a popup screen—click on 'Manual Trigger' button. DaqView will start collecting data and send these data points to the Excel spreadsheet. Column A is a system reference temperature, and is not to be used in the heat exchanger calculations. Column B is temperatures for Channel 1 (Hot supply); column C—Ch.2 (Cold supply); column D—Ch.3 (Hot return); column E—Ch.4 (Cold return). Column F is the hot water tank temperature, and is not used in the calculations.
38. Save this data to a disk and close the Excel file.
39. Turn off both of the water pumps, the heater, and rate meters.
40. Open the hot and cold flow control valves by turning them fully counter-clockwise.
41. Slowly open ONLY ONE of the latches on both the hot supply connector and the cold supply connector until you notice a gurgling sound. Carefully lift the heat exchanger (with hoses attached) and slowly tilt it from side to side to allow the remaining water to drain back through the hoses. Be careful not to touch the high temperature plumbing (copper tubing), as it will still be hot.
42. Place the heat exchanger back on the work surface and carefully disconnect the cold water hoses. Watch for any remaining water in the hoses—clean up any spills with towels as provided by the instructor.
43. Wait another 3–5 minutes before disconnecting the hot water hoses. This will allow the connectors to cool so they can be handled. Again, watch for any remaining water in the hoses, and clean up any spills with towels as provided by the instructor. This concludes data collection for Part B.

Required calculations

Calculate q emitted, q absorbed, q lost, log-mean temperature differences, overall heat transfer coefficients, and the efficiencies for both parallel flow and counter flow. The tubing sizes for the heat exchanger are 1 inch schedule 40 for the outer shell and 3/4-inch type K copper for the inner tube. Provide all calculations, raw data, and present the final calculated values in tabular format. Note: For each of the temperatures required (T_{hin} , T_{hout} , T_{cin} , T_{cout}), use excel to average the data points in each of the columns B–D. Use these averaged values in your calculations.

Compare and comment on the two types of flow. Discuss the effect of parallel flow vs. counter flow on the calculated data above. Discuss any error from this experiment that may skew your results.

Plot the temperature distributions similar to Fig. 9.

Results

The following are typical results obtained for a parallel flow configuration.

Heat exchanger length (m) = 0.6
 1 inch Sch 40 PVC ID (m) = 0.02624
 Flow area inside (m²) = 0.000540776
 3/4-inch copper ID (m) = 0.01892
 3/4-inch copper OD (m) = 0.02223
 Flow area (inside) (m²) = 0.000281146
 Flow area (outside) (m²) = 0.000388122
 Heat exchange area = (Length) × (3/4-inch OD circumference) = 0.041902527
 Flow area between PVE and copper area (m²) = 0.000152654
 Q = Flow rate (LPM) = 7.57
 Q = converted to (m³/s) = 0.000126167
 $V_{hot} = Q/A$ (inside copper) (m/s) = 0.448758668
 $V_{cold} = Q/A$ (between PVC and copper) (m/s) = 0.826490226
 ΔT_1 (°C) = $T_{hin} - T_{cin} = 19.3725$
 ΔT_2 (°C) = $T_{hout} - T_{cout} = 13.667$
 $\Delta T_{lm} = (T_1 - \Delta T_2) / \ln(\Delta T_1 / \Delta T_2)$ (°C) = 16.35421218

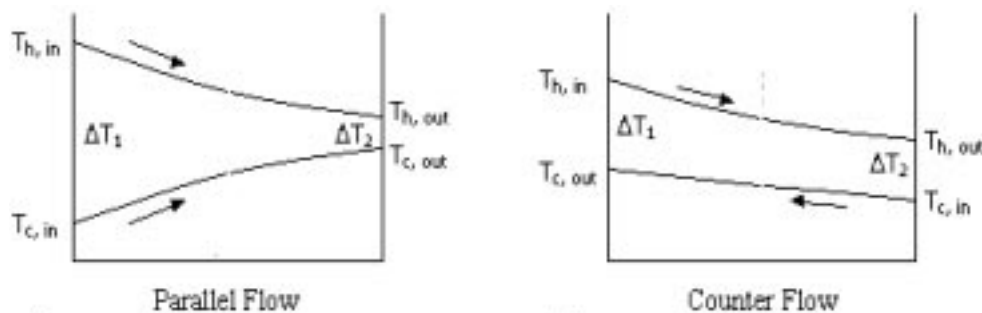


Fig 9. Schematic of temperature distributions for concentric heat exchanger.

$$\text{H}_2\text{O } C_p @ 15^\circ \text{C (kJ/kg}^\circ \text{C)} = 4.187$$

$$\text{H}_2\text{O } @ 15^\circ \text{C (kg/m}^3\text{)} = 999.2$$

$$q_{emit} = (V_{hot} * \rho * C_p) * (T_{hin} - T_{hout}) \text{ (W/m}^2\text{)} = 0.673662632$$

$$q_{abs} = (V_{cold} * \rho * C_p) * (T_{c,out} - T_{c,in}) \text{ (W/m}^2\text{)} = 12.48335979$$

$$q_{lost} = q_{abs} - q_{emit} \text{ (W/m}^2\text{)} = 0.574673347$$

$$\Delta T_{lm} = (\Delta T1 - \Delta T2) / \ln(\Delta T1 / \Delta T2) \text{ (}^\circ \text{C)} = 16.35421218$$

$$\text{Heat transfer coefficient (U)} = q_{abs} / (A * \Delta T_{lm}) \text{ (W/m}^2\text{ }^\circ \text{C)} = 500.028724$$

T_{hin} (° C)	$T_{c,in}$ (° C)	T_{hout} (° C)	$T_{c,out}$ (° C)
50.94	30.03	48.08	32.9
50.83	30.14	47.98	33
50.71	30.26	47.87	33.11
50.5	30.29	47.67	33.13
50.42	30.34	47.6	33.19
50.34	30.4	47.53	33.26
50.21	30.43	47.41	33.3
50.17	30.5	47.28	33.38
50.11	30.58	47.23	33.45
49.98	30.66	47.11	33.52
49.93	30.72	47.07	33.57
49.87	30.82	47.02	33.66
49.8	30.87	46.96	33.76
49.76	30.95	46.93	33.81
49.71	31.08	46.89	33.95
49.68	31.12	46.87	34
49.66	31.2	46.86	34.05
49.64	31.21	46.75	34.06
49.63	31.23	46.76	34.09
49.63	31.24	46.77	34.11
Av.= 50.07	Av.= 0.7	Avg.= 47.2	Av.= 33.5

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