Sichuan University - Pittsburgh Institute

ME 1042

Thermal Fluids Lab

Bench-top Heat Exchangers

Revised December
2019

Mechanical Engineering Department

<u>Goal</u>: To explore the heat-transfer characteristics of: 1) Concentric tube heat exchangers and 2) shell-and-tube heat exchangers.

<u>Equipment Needed</u>:
TD 360 Bench Top Service Module
TD 360a Concentric tube Heat Exchanger
TD 360c Shell-and-Tube Heat Exchanger
Versatile Data Acquisition System (VDAS)

1 Introduction and Basic Theory

Heat exchangers are an essential and common piece of equipment used to transfer heat efficiently from one medium to another. Most often, the two mediums are fluids, such as air, water, oil etc. Heat exchangers are used everywhere from the radiator in your automobile to your refrigerator in your kitchen. On an industrial level, hydraulic fluid-heat exchangers and cooling towers are essential to keep important mechanical components from over-heating.
In this lab we will explore convective heat transfer between hot and cold water, through two different heat exchanger designs: 1) Concentric tube heat exchanger, 2) shell and tube heat exchanger. The system is controlled through the Service Module. These systems are outlined in the following sections.

1.1 *Service Module*

The service module, seen in Figure 1 is the main part of the Bench-top Heat Exchangers. It is a compact bench-mounting frame that connects to a suitable electrical supply and a cold water supply and drain. It has two water circuits – hot and cold. Each circuit has a flow sensor to measure and display the flow rate. The cold-water circuit is simply the incoming mains cold water supply, which passes through an incoming flow regulator, through a hand adjusted flow control valve, through the heat exchanger and to the drain. The hot circuit comes from the electrical tank and heater and an adjustable controller sets the tank temperature. A pump in the hot water circuit recirculates hot water from the tank, through a hand adjusted flow control valve, through the heat exchanger and back to the tank. The cold water circuit flow is controlled by the incoming line pressure regulator, and drains out of the back of the machine. This is called open loop cooling, since the cooling fluid is not re-circulated back through the system.

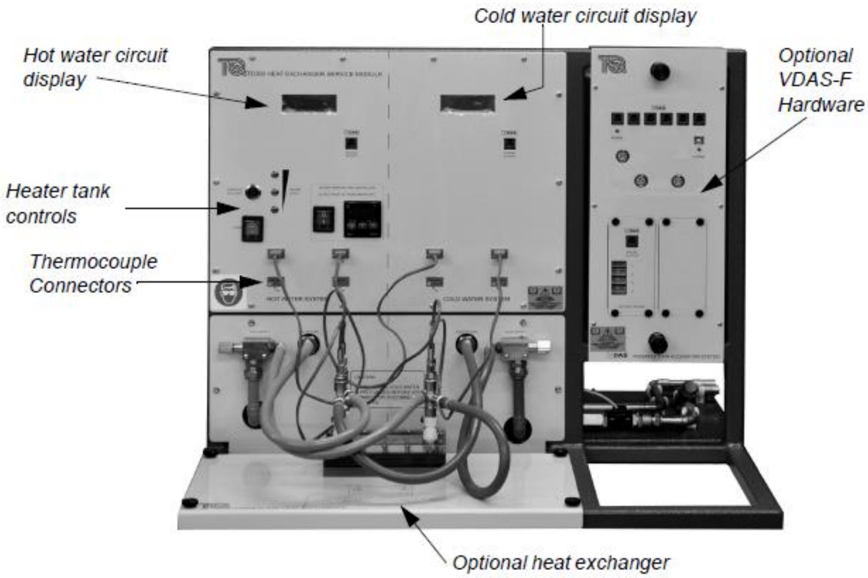

Figure 1: The service module TD 360.

1.2 Thermocouple Connections and Displays

Table 1 below shows the symbols used on the thermocouple connections and the displays and what they mean. The concentric tube heat exchanger (TD360A) has an intermediate thermocouple (T_{C3} and T_{H3}). For the experiments to follow, use this reading as the average temperature. For all other heat exchangers, use the average between input and output.

Table 1: Symbols used for the experimental measurements.

Symbol	What it means
T_{H1}, T_{H2}, T_{H3}, T_{H4}	Hot circuit temperatures, in and out of the Heat Exchangers
T_{C1}, T_{C2}, T_{C3}, T_{C4}	Cold circuit temperatures, in and out of the Heat Exchangers
F_h	Hot circuit flow
F_c	Cold circuit flow

1.3 Concentric Tube Heat Exchanger

As seen in Figure 3, the concentric tube (CT) heat exchanger consists of two shells and tubes, one inside the other. The inner tube carries the water from the hot circuit of the service module and the other tube carries the water from the cold circuit and heat transfers between the tubes.
The water circuits can be connected to give counter-flow and parallel flow set-ups. This heat exchanger has a mid-point thermo-couple to more clearly understand how temperature varies along the heat exchanger. Figure 4 shows a schematic of the flow for each circuit of the CT heat exchanger.

Figure 2: Concentric tube heat exchanger TD 360a.

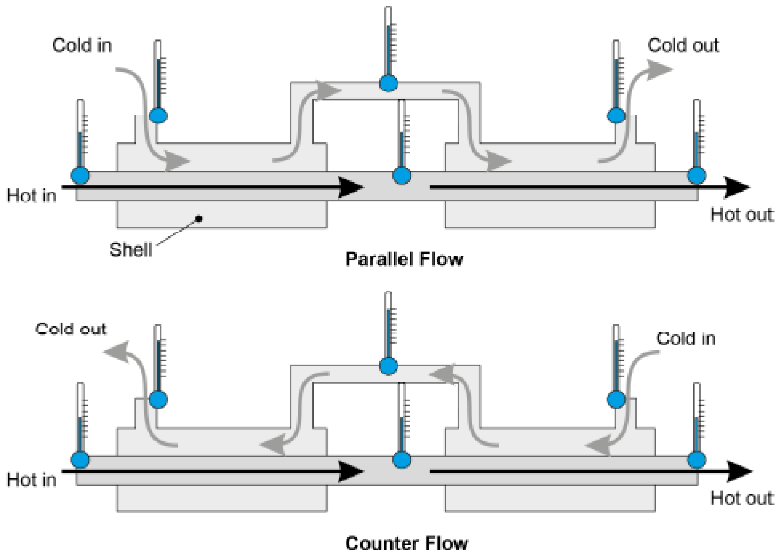

Figure 3: Schematic of the concentric tube heat exchanger operation.

1.4 Shell-and-Tube Heat Exchanger

This is the most common heat exchanger used in industry, particularly oil refineries and chemical plants. It is compact and can work at high pressures. As shown in Figure 4, this type has a large tube (shell) that surrounds several smaller tubes (a bundle). One water circuit passes through the bundles and the other passes through the shell. Heat transfers between them. The bundle has baffles to help create a turbulent flow in the shell with operation in both parallel and counter flow conditions seen in Figure 5.

Figure 4: Shell-and-Tube heat exchanger TD 360c.

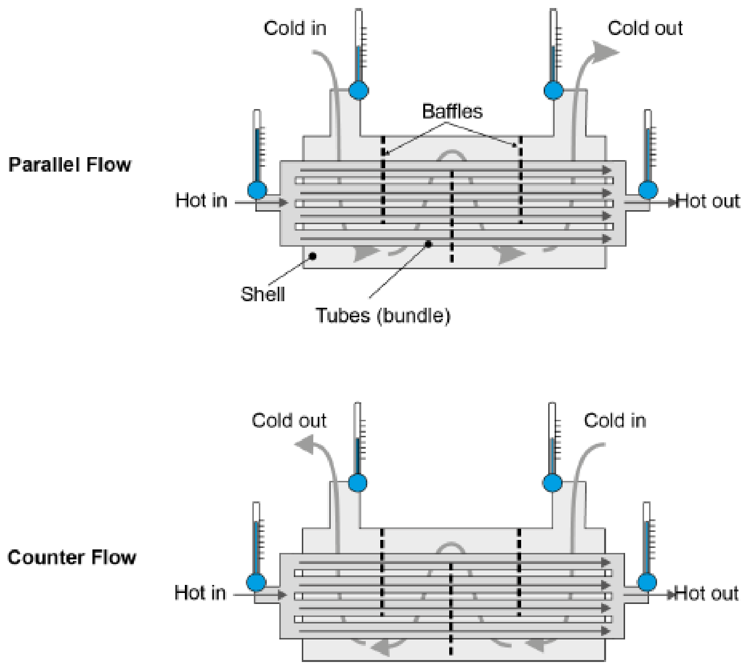

Figure 5: Schematic of the shell-and-tube heat exchanger operation.

1.5 Heat Exchanger Theory

Table 2 outlines useful notation and units used in this experiment and analysis. The first terms to consider are heat capacity and specific heat capacity. Heat capacity is a measure of the heat needed to increase the temperature of a given mass of material by 1 degree (Kelvin or Celsius). It is a product of the mass of the material m and its specific heat capacity, c

$$C = m \times c$$

Table 2: Heat exchanger theory terms and units.

Symbol	Definition	Units
A	Heat Transfer Area	m^2
C	Heat capacity	$J.K^{-1}$
cp	Specific Heat Capacity of Water at Constant Pressure	$J.kg^{-1}K^{-1}$
$LMTD$	Logarithmic Mean Temperature Difference	K or °C where shown
r	Density of water	$kg.L^{-1}$
η_o	Overall Efficiency	%
CEB	Energy Balance Coefficient	-
$\bar{\eta}$	Mean Temperature Efficiency	%
Q	Heat energy transferred for a unit mass	$J.kg^{-1}$
$\dot{Q}$	Heat energy transferred for a unit time (heat transfer rate - or power)	W
$\dot{Q}_a$ and $\dot{Q}_e$	Heat energy (power) absorbed and emitted in a unit time	W
T	Temperature	K or °C where shown
DT	Change in Temperature	K or °C where shown
$\bar{T}$	Mean Temperature	K or °C where shown
U	Heat Transfer Coefficient	$W.m^{-2}K^{-1}$
VH and VC	Volumetric Flow Rate (hot circuit and cold circuit)	$m^3.s^{-1}$ or $L.min^{-1}$ where stated
mH and mC	Mass Flow Rate (hot circuit and cold circuit)	$kg.s^{-1}$

Specific heat capacity is the amount of heat energy needed to raise the temperature of exactly 1 kg of material by 1 degree (Celsius). It is a ratio of the change in heat energy and the change in temperature, given by the following equation:

$$c = \frac{\Delta Q}{\Delta T}$$

Pressure and temperature affects specific heat capacity. Therefore, assuming constant pressure over a known range of temperature, the isobaric (constant pressure) specific heat capacity is defined as:

$$c_p = \frac{Q}{\Delta T}$$

Figure 6 shows specific heat capacity of water vs. temperature. This plot can be used to estimate specific heat capacity of water using mean temperatures recorded during experiment.

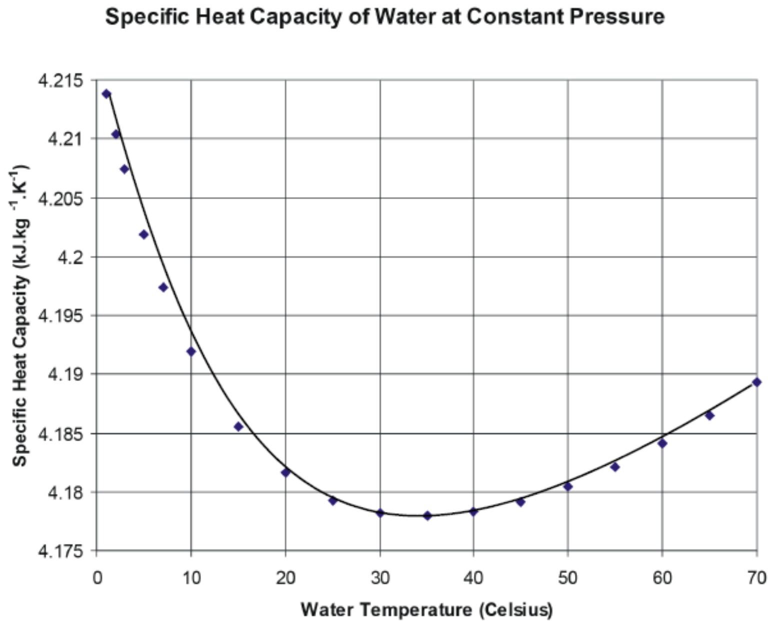

Figure 6: Specific heat capacity of water at constant pressure with respect to temperature.

The next important concept is density, which as water temperature changes its density changes slightly. Its maximum density is at approximately 4 degrees and decreases as temperature increases or decreases from this value, as seen in Figure 7. This affects all calculations. Figure 7 can be used to estimate density of water vs. the mean temperature in the heat exchanger.

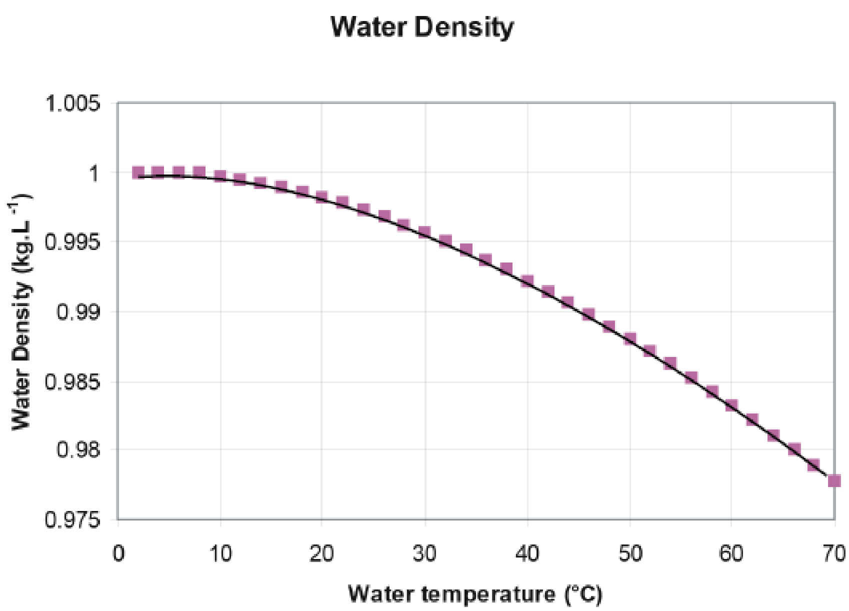

Figure 7: Density of water with respect to temperature.

In heat exchangers, heat transfers or "flows" from the hot water circuit to the cold water circuit. The heat transfer rate is a function of the fluid mass flow rate, the temperature change and the specific heat capacity of the fluid (at mean temperature), given by the following relation:

$$\dot{Q} = \dot{m} c_p \Delta T$$

In an ideal heat exchanger, that does not lose or absorb heat from its surroundings, the cool fluid absorbs all the heat from the hot fluid. So the heat transfer rate is:

$$\dot{Q} = \dot{Q}_e = \dot{Q}_a = \dot{m}_H c_{p_H} \Delta T_H = \dot{m}_C c_{p_C} \Delta T_C$$

Where $\dot{Q}_e$ is heat emitted and $\dot{Q}_a$ is heat absorbed and mass flow rate is defined by the following equation:

$$\dot{m} = \dot{V}\rho$$

To better understand heat transfer in a heat exchanger, assume it is a 'system' with the hot and cold water flows as its inputs and outputs, as seen in Figure 8.

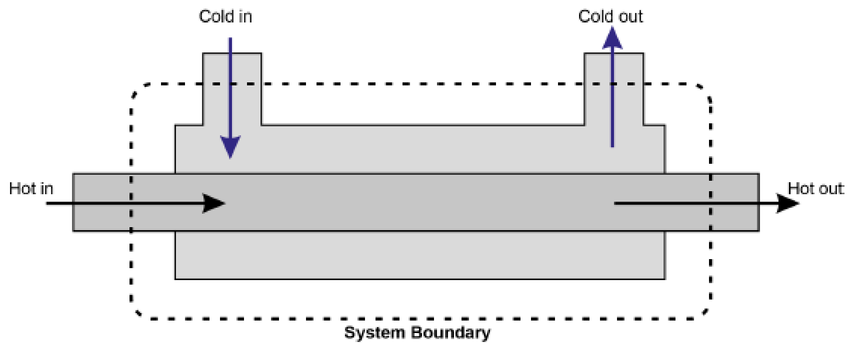

Figure 8: System boundary definition for a common heat exchanger.

In an ideal heat exchanger, there is no heat transfer across the 'system boundary'. In reality the hot and cold fluids are usually at different temperatures to the surroundings, so some heat transfers across the system boundary. For example, heat from a warm room would transfer to a cold fluid. The energy balance coefficient (C_{EB}) gives the relationship between energy absorbed and emitted, as seen below:

$$C_{EB} = \frac{\dot{Q}_a}{\dot{Q}_e}$$

but, as discussed, because of the possible heat flow into or out of the system, the energy balance coefficient can give answers of greater than 1 if the heat exchanger absorbs energy from its surroundings, so it is only an idealized condition. The mean temperature efficiency, $\bar{\eta}$, and heat transfer coefficient give more useful results for comparison between heat exchangers.

The **temperature efficiency** of the **hot** circuit is the ratio of the temperature change in the hot circuit, divided by the difference between the maximum and minimum temperatures of the hot and cold circuits, given by the relation:

$$\eta_H = \frac{T_{H_1} - T_{H_2}}{T_{H_1} - T_{C_1}} \times 100\%$$

The **temperature efficiency** of the **cold** circuit is the ratio of the temperature change in the cold circuit, divided by the difference between the maximum and minimum temperatures of the hot and cold circuit:

$$\eta_C = \frac{T_{C_2} - T_{C_1}}{T_{H_1} - T_{C_1}} \times 100\%$$

The **mean temperature efficiency** of the two circuits is the average of the hot and cold temperature efficiency, given by:

$$\bar{\eta} = \frac{\eta_H + \eta_C}{2}$$

The ***Logarithmic Mean Temperature Difference*** is a measure of the heat driving force that creates the heat transfer. It is a logarithmic average of the temperature difference between the hot and cold circuits at each end of the heat exchanger, given by:

$$LMTD = \frac{\left(\left(T_{H_2} - T_{C_2}\right) - \left(T_{H_1} - T_{C_1}\right)\right)}{\ln \frac{\left(T_{H_2} - T_{C_2}\right)}{\left(T_{H_1} - T_{C_1}\right)}}$$

The ***Heat Transfer Coefficient*** is the overall heat transfer coefficient for the wall and boundary layers. It is a measure of how well the heat exchanger works. A good heat exchanger will give a high coefficient, therefore this value is very important to engineers and is the most commonly used specification for heat exchanger performance. It is given by the following equation:

$$U = \frac{\dot{Q}_e}{A \times LMTD}$$

where A is the heat transfer area of the heat exchanger. **All heat exchangers in this lab have the same heat transfer area of 0.02 m^2 to allow for direct comparison.**

2 Experimental Procedure

The objective of the lab is to examine the efficacy of different types of heat exchangers.
This lab is split into two parts: 1) Effect of varying flow rate in parallel and counter flow for a concentric tube heat exchanger and 2) Effect of varying flow rate in parallel and counter flow for a shell-and-tube heat exchanger.

Each section requires adjustments to either the flow rate or incoming water temperature. Data will only be collected once steady state conditions are met. When a parameter is adjusted, wait at least 3 minutes for steady state before recording any data.

2.1 Concentric Tube Heat Exchanger

The aim of this section to show how different cold water flow rates affect the performance of the heat exchanger in both parallel flow and counter flow. The hot water temperature and flow rate are fixed.

1. Connect and set-up the concentric tube heat exchanger (TD360A) for parallel flow using the diagram on the bedplate of the heat exchanger and the quick connections of the hot and cold circuits.
2. Create a blank results table similar to Table 3 in your lab notebook for parallel flow.
3. Start the heater and circulation pump on the TD360. Be sure the heater tank is full indicated by the indicator lights.
4. Adjust the hot water controller to 60 degrees.
5. Adjust the hot water circuit flow rate to 3 L/min. This will be constant throughout the experiment. Be sure the hot water temperature is reading 60 °C.
6. Turn on the cold circuit flow valve and adjust until the flow rate reaches 3 L/min.
7. Wait at least 3 minutes for the temperature to reach steady state and record the thermocouple values.
8. Adjust the flow control valve on the cold water circuit to read 2 L/min, wait at least 3 minutes and record the thermocouple readings.
9. Repeat for 1 L/min and 0.5 L/min flow rates.
10. After all data is collected for parallel flow, turn OFF the cold water circuit and your TA will adjust the quick connections on the hot and cold water circuits for counter flow. Use the diagram on the heat exchanger bed plate as a guide.
11. Make a new results table similar to Table 3, noting COUNTER flow.
12. Repeat steps 6-10 for counter flow.

Table 3: Data table to be used for experimental data recording

RATE (L/min)	T_{H1} (° C)	T_{H2} (° C)	T_{H3} (° C)	T_{C1} (° C)	T_{C2} (° C)	T_{C3} (° C)
3						
2						
1						
0.5						

2.2 Shell-and-Tube Heat Exchanger

13. Connect hot and cold water circuits for parallel flow on the shell and tube heat exchanger. Consult the Lab Engineer for assistance.
14. Make a new results table similar to Table 3 and note the shell and tube for parallel flow.
15. Repeat steps 6-10 and record the data in your table. **NOTE**: Shell and tube (TD360c) does NOT have a mid-point thermo-couple. Use the average of T_1 and T_2 for an estimate of mid-point for both the hot and cold circuits.
16. Once data is collected for all flow rates, adjust the hot and cold circuits for counter flow as shown on the bed plate of the heat exchanger.
17. Make a new results table and note counter flow.
18. Repeat steps 6-10 for shell and tube counter flow and record all data.

3 For the Report

The report should compare parallel and counter flow for the two different bench-top heat exchangers as carried out in Section 2. Organize your report to include the following data for both heat exchangers.

1. Find the change in temperature for each circuit (parallel and counter) and the average temperature for each circuit. **NOTE**: for the concentric tube heat exchanger (TD360a), use the mid-points T_{H3} and T_{C3} as the average temperatures.
2. Use the charts or equations in the theory section to calculate the water density for the hot and cold water circuits (ρ_H and ρ_C) and the specific heat capacity (C_p). You must convert your flow rates from L/min to m^3/sec and be sure to use the average temperature when calculating specific heat capacity.
3. Calculate the heat emitted, heat absorbed, mean temperature efficiencies and energy balance coefficients for all flow rates for each circuit (parallel and counter flow). You can combine these values into one table for each heat exchanger. Properly label your tables.
4. Plot mean temperature efficiency (y axis) against cold water flow rate (x-axis) for parallel and counter flow on the same axes. Comment on the difference in mean temperature efficiency between parallel and counter flow. Is there a difference? Limitations?
5. Calculate the heat transfer coefficient for each flow rate for both parallel and counter flow. Comment on how heat transfer coefficient depends on flow rate and/or flow direction.
6. Perform an uncertainty analysis on your calculated values from your experimental data.
7. Comment on the performance of each heat exchanger. Which heat exchanger had the highest heat transfer coefficient? What are some of the limitations of each heat exchanger?

The form of the report should be an extended memo. This will include a few paragraphs of theory and a description of the experiments, followed by results and discussion. Be sure to format your figures properly step the reader through your conclusions.