SHELL AND TUBE HEAT EXCHANGER

OBJECTIVE

To determine the overall heat transfer coefficients, $U$, for a shell-and-tube heat exchanger of area $A$ in co-current and counter-current flow.

INTRODUCTION

In many heat transfer processes, heat is transferred from one fluid to another through a solid wall. The exchanger geometry, fluid properties, and flow rates are the parameters that influence the rate of heat transfer. A study of these parameters forms the basis for design of heat exchangers.

The shell-and-tube exchanger [Kessler, Greenkorn, 1999] consists of a bundle of tubes with their axes parallel - much in the manner of soda straws in a carton - but supported at various points by baffles at right angles to the tube axes, which serve to keep the tubes fixed in space in a particular configuration, for example, with the axes spaced on equilateral triangles, or squares, etc. Flow flows through groups of the tubes in parallel.

The tube bundle is encased in a shell, which confines the fluid which flows over the outside of the tubes in the tube bundle. The fluid which flows within the tubes (the tube-side fluid) may make a single pass through the exchanger or multiple passes, where the tubes are divided into groups via baffling at the ends of the exchangers and flow is reversed at the end of the exchanger and sent back and forth through different groups of tubes. Similarly, the fluid flowing external to the tubes (the shell-side fluid) may also make one or more passes across the tube bundle, depending upon the configuration of the baffles.

THEORY

How do we account for the affect of heat loss to the surroundings on the analysis for the overall heat transfer coefficient? The answer is found by setting up and solving the differential energy balance equations for the hot and cold streams to determine the relative heat transfer rate between the hot and cold streams and the heat transfer rate from the cold stream to the surroundings.

The laboratory shell and tube heat exchanger may be operated in either of the two flow
patterns illustrated in Figure 1. In all cases, the hot stream is passed through the tubes. The
differential energy balances around the hot and cold streams assume steady-state operation and
plug flow. The analysis also assumes constant, average, properties. The fluid properties are
evaluated at the average temperature between the feed and effluent. It is assumed that the
thermocouples measure the mixed-cup temperature of each stream.

\[ m_c \overline{c}_p \frac{dT_c}{dx} = \frac{1}{N_t} \sum_{i=1}^{N_t} U_t(T_{c,i} - T_{h,i}) P_t \]

\[ m_h \overline{c}_p \frac{dT_h}{dx} = \frac{1}{N_t} \sum_{i=1}^{N_t} U_t(T_{c,i} - T_{h,i}) P_t + \frac{1}{N_s} \sum_{i=1}^{N_s} U_s(T_c - T_h) P_s \]

where the subscripts \( c \) and \( h \) refer to the cold and hot streams, respectively, \( \dot{m} \) is the mass flow
rate (kg/s), \( \overline{c}_p \) is the average specific heat (J/kg-K), \( T \) is the local temperature (K), \( x \) is the
variable position along the length of the tubes (m), \( U_t \) is the overall heat transfer coefficient
across the tube wall (W/m²•K), \( N_t \) is the number of tubes, \( P_t \) is the tube perimeter (m), \( U_s \) is the
overall heat transfer coefficient across the shell wall (W/m² •K), and \( P_s \) is the shell perimeter
(m).
Counter-Current Energy Balance:

For counter-current flow the sign changes for the cold stream due to the opposite flow direction of the cold stream relative to the hot stream

\[
\dot{m}_h c_{ph} \frac{dT_h}{dx} = U_t (T_c - T_h) N_t P_t
\]

\[
-\dot{m}_c c_{pc} \frac{dT_c}{dx} = U_t (T_h - T_c) N_t P_t + U_s (T_c - T_c) P_s
\]

Analysis

Steady-state experiments give the hot and cold stream temperatures at both ends of the heat exchanger, as shown in Figure 2. The mass flow rates are calculated from the average density, \( \bar{\rho} \) (Kg/m\(^3\)) and volumetric flow rate, \( \dot{V} \) (m\(^3\)/s):

\[
\dot{m} = \dot{V} \bar{\rho}
\]

The dimensions of the tubes and shell are used to calculate the perimeters. The perimeter of the tubes is calculated from the total heat transfer surface area, \( A_t \) (m\(^2\)) and tube length, \( L_t \) (m):

\[
N_t P_t = \frac{A_t}{L_t}
\]

The perimeter of the shell is calculated from the outside shell diameter, \( D_s \) (m):

\[
P_s = \pi D_s
\]

The temperature ranges of the hot and cold streams are relatively small. For these conditions, the specific heats are relatively constant. The specific heats may be taken at the average temperature for each stream.

The system of differential equations is solved simultaneously over the length of the tubes by Euler’s method. The equations are integrated from the hot stream inlet end. For example, Euler’s method applied to counter current flow gives the following difference equations that approximate the solution over the range of nodes, \( j \).
\[ T_{h,j+1} = T_{h,j} + \Delta x \left[ \frac{U_t \left( T_{c,j} - T_{h,j} \right) A_t}{\dot{V}_h \rho_h c_{ph} L_t} \right] \] (8)

\[ T_{c,j+1} = T_{c,j} - \Delta X \left[ \frac{U_t \left( T_{h,j} - T_{c,j} \right) \left( A_t / L_t \right) + U_s \left( T_\infty - T_{c,j} \right) \pi D_s}{\dot{V}_c \rho_c c_{pc}} \right] \] (9)

\[ j = 0 \ldots n \] (10)

\[ \Delta X = \frac{L_t}{n} \] (11)

where \( j \) is the step index and \( n \) (~ 50) is the number of integration steps. The system of ODE’s is subject to the initial conditions:

\[
\begin{align*}
T_{h,0} &= T_{hi} \\
T_{c,0} &= T_{ci}
\end{align*}
\] (12)

Euler’s method is implemented in Excel. The Solver tool in Excel is used to automatically find the unknown heat transfer coefficients, \( U_t \) and \( dU_s \), that minimize the following objective function for the calculated temperatures at \( x = L \) relative to the experimental values.

\[ \text{ObjFunc} = \left( T_{ho} - T_{h,n} \right)^2 + \left( T_{ci} - T_{c,n} \right)^2 \] (13)

An energy balance around the heat exchanger is used to calculate the total heat transfer rate between the heat exchanger and the surroundings, \( q_s \) (W). The energy balance may be simplified using average properties as described above:

\[ q_s = \dot{m}_h c_{ph} \left( T_{ho} - T_{hi} \right) + \dot{m}_c c_{pc} \left( T_{co} - T_{ci} \right) \] (14)

The model equations are solved for the overall heat transfer coefficients for a range of flow rates and configurations. The resulting values may be correlated for Reynold’s number in the tubes.

Other experimental objective options include considering the effects of insulation, pressure drop, and hot feed to the shell side.
REFERENCE


EQUIPMENT

1. Shell and tube heat exchanger
2. Stopwatch
3. 2-1 gallon plastic bottles
4. Top loading balance

CHEMICALS/MATERIALS

1. Hot water
2. Cold water

PROCEDURE

A schematic of the shell and tube heat exchanger apparatus is shown in Figure 2. The set-up is designed to control the flow rates of hot and cold water and measure the inlet and outlet stream temperatures and static pressures. Thermocouples are used to measure the stream temperatures. The temperature data are collected with a computer based data acquisition system. The dimensions of the heat exchanger are provided by the manufacturer and are shown in Table 1. These include the length and area of heat transfer.

Collect flow and temperature data in both the co-current and counter-current flow modes using hot water flowing through the inner tubes and cold water flowing through the shell. Keep either the hot or cold water flow constant and vary the other flow from low to high flow rates.

Figure 2. when viewed on your computer monitor does not show the valve, thermocouple, and flow control valve numbers (they are small), but they will show when printed out. Follow the instructions below to set up the heat exchanger system so you can collect the experimental data.

1. Ensure that all valves in the system are closed. These include V101, V102, V103, V104, FCV1 and FCV2.
2. Open the two green handled water main shut off valves located to the right of the red flow
control valves above the cup sink drains (V101 and V102).

3. Open Valves V103 and V104

4. Open the cold and hot water control valves (Red Valves in front of the heat exchanger [FCV1 and FVC2]) until you see flow on the flow meters attached to the wall to the right of the emergency shower. These valves are opened with an open end wrench. Pull up on the black knob on top of the valve, slip the wrench on the nut underneath and move the wrench to the left to open the valve. There is a catch mechanism so that you will have to use some

Figure 2. Schematic diagram of Shell and Tube heat exchanger
5. If available a loop calibrator can be connected to the leads from the control valve so the valve can be opened by feeding a 4-20 mA signal to the valve. A button on the loop calibrator labeled 25% will open the valve 25% each time it is pressed. The up and down arrow buttons will increase or decrease the output by 0.010 mA each time they are pressed. The valve will not move each time an increase of 0.010 mA is made. It may take a change of 0.1 to 0.2 mA before the valve will move. You will have to experiment with the change in mA and the amount of valve change. Note that when the valve is about 50% open (12 mA) there will no longer be a change in flow.

6. Allow the heat exchanger to reach steady state. **(Note:** This may take up to 10 minutes on initial start up due to the long lag time in the building hot and cold water piping, especially when water is not being used frequently. After initial start up, steady state should be reached within a minute or two. Monitor temperatures to determine when steady state is reached.)

7. The flow of both hot and cold water can be monitored using the variable area flow meters attached to the wall to the right of the emergency showers. The left meter is for cold water and the right meter is for hot water.

8. There are also two Krohne magnetic flow meters attached to the wall to the right of the heat exchanger that can be used to monitor the water flow. One measures cold water flow and the other the hot water flow. On/off switches for these meters are on the wall above the meters.

9. Calibration of these meters will have to be done by using a stop watch and a one gallon plastic container or a 4 L graduated cylinder. Weigh a one gallon plastic container on the top loading balance. Collect water from the discharge plastic hose into the container for a known period of time. Weigh the container and water to determine the mass of water collected. Record this weight, the temperature of the water, collection time and the flow meter reading. If you use the 4 L graduated cylinder you can record the volume collected, the temperature of the water, collection time and flow meter reading.

10. Determine which flow mode you are going to use, co-current or counter-current flow. The hot water stream flow is in only one direction. If you want the cold water flow to be in the co-current flow mode, the arrow on valve V105 should be pointing to the right, valve V106 should be closed and valve V107 should be open. If you want the cold water flow to be in the counter flow mode, the arrow on valve V105 should be pointing to the left, valve V106 should be open and Valve V107 should be closed.

11. Open the flow control valves so the flow meters are showing the flows that you want to run the experiment at.

12. Start the collection of temperature data into the Excel spreadsheet. See Appendix A for instructions on how to do this. Four type K thermocouples provide the temperature data for the data acquisition system. The data acquisition system collects data from each of the four thermocouples every second for 10 minutes (600 temperature data points).

13. Record the hot and cold water flows on paper and enter the data into the spreadsheet after the run so the data acquisition system does not lock up. Check the flow meters periodically to ensure that the flows have not changed.
14. Adjust the flow rates to the next desired flow rate. The heat exchanger should reach steady state within a minute or two. Monitor temperatures to determine when steady state is reached and then start data collection. Repeat steps 11-13.

15. Shut off the flow to the heat exchanger and change the valve positions when switching from co-current to counter current flow or vice-versa. Set the flow controllers to provide the desired flow rate for the next experiment. The heat exchanger should reach steady state within a minute or two. Monitor temperatures to determine when steady state is reached and then start data collection.

16. Continue adjusting flow rates and repeat steps 10-13 until temperature data is collected for all the modes and flow rates you have determined that should be run for this experiment.

17. Upon completion of this experiment, close the flow control valves, FCV1 and FCV2 and valves V101, V102, V103, V104. Allow the water to drain out of the system.

SAFETY NOTES

1. Safety glasses with side shields shall be worn at all times during the experiment. Hot and cold water is used in this experiment under building main pressure reduced to approximately 30 psi. There is a chance of a tube bursting or a valve leaking water and start to spray the area around the area of the heat exchanger.

2. Prior to operation of the system, familiarize yourself with the equipment. Trace all process lines, test all valves, and ensure that all valves are closed.

3. Cold water should be admitted first and then the hot water in order to avoid damage due to thermal expansion.

4. While admitting hot water to the system, open the valves cautiously and check all connections for possible leaks.

5. At the end of the experiment, the hot water supply should be shut off first. Allow the cold water to circulate for a couple of minutes before shutting off the cold water supply.

6. Be aware of unlagged hot water lines, they heat up rapidly.

7. If a valve appears tight or doesn't yield to hand force, do not attempt to turn it with a wrench. Turn off the steam or hot water, permit the system to drain and cool down, then loosen the packing bonnet slightly and try again.

8. Keep the laboratory working space clean and uncluttered. Be aware of potential hazards such as wet spots or debris on floors that could cause slips or falls.

WASTE DISPOSAL PROCEDURES

1. There is no waste associated with this experiment. Only hot and cold water are used in this experiment and they can be sent to the drain.
# Table I. Heat Exchanger Data

## OPERATING LIMITATIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>US</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Operating Pressure – Shell side</td>
<td>500 psi</td>
<td>3,400 kPa</td>
</tr>
<tr>
<td>Non-Shock Service</td>
<td>750 psi</td>
<td>5200 kPa</td>
</tr>
<tr>
<td>Maximum Pressure for Steam Service</td>
<td>125 psi</td>
<td>860 kPa</td>
</tr>
<tr>
<td>Maximum Operating Temperature</td>
<td>800 °F</td>
<td>425 °C</td>
</tr>
<tr>
<td>Maximum Average Temperature Difference</td>
<td>125 °F</td>
<td>70 °C</td>
</tr>
</tbody>
</table>

## Shell and Tube Heat Exchanger Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>US</th>
<th>Metric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Length</td>
<td>23.00 in</td>
<td>584 mm</td>
</tr>
<tr>
<td>Transfer Area</td>
<td>6.73 ft²</td>
<td>0.63 m²</td>
</tr>
<tr>
<td>Tube Length</td>
<td>20.00 in</td>
<td>508 mm</td>
</tr>
<tr>
<td>Tube OD</td>
<td>0.125 in</td>
<td>3.2 mm</td>
</tr>
<tr>
<td>Tube Wall</td>
<td>0.0125 in</td>
<td>0.32 mm</td>
</tr>
<tr>
<td>Tube Count</td>
<td>127</td>
<td></td>
</tr>
<tr>
<td>Baffle Count</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Shell Volume</td>
<td>38.4 in³</td>
<td>629 cc</td>
</tr>
<tr>
<td>Tube Volume</td>
<td>25.5 in³</td>
<td>418 cc</td>
</tr>
</tbody>
</table>

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APPENDIX A

Shell & Tube Heat Exchanger
Computer Data Acquisition Instructions

The temperature data is collected with a DATAQ DI-1000TC Instrumentation module for temperature measurement. The software program WinDaq/Lite will be used for data acquisition.

1. Connect the thermocouple (TC) wires to the DI-1000TC box.
2. Connect the USB cable from the DI-1000TC box to the USB port on the portable computer.
3. Turn on the computer and select the student account in Windows XP. Enter student as the password. Wait for Windows XP to finish loading.
4. Double click on the WinDaq 1000TC shortcut icon on the desktop to load the data acquisition software.
5. A window opens (DI-1000 Acquisition 0) showing an oscilloscope tracing of the temperatures for 4 thermocouples. The data as it is displayed moves from left to right. When the cursor reaches the right side of the window it starts again at the left side of the graph. The mode of data display can be changed but this is probably the best way to view the data on the monitor.
6. The software has been configured to collect 1 data point/sec/TC (4 samples/sec). Over a 10 minute period 600 temperature data points are collected for each thermocouple. The number of data points/sec/TC and the length of the sample time can be changed but for this experiment, this is the best configuration. If it is not set up right, see the Lab Services Coordinator.
7. Set up the heat exchanger in the proper configuration so it is operating to your satisfaction.
8. During the 10 minute period you collect temperature data you will also record 3 to 4 sets of pressure data. Also check the flow meters during the 10 minute period to ensure that the flow has not changed. Record the flows.
10. A small dialogue box appears on the spreadsheet. This dialogue box is named WinDaq-XL. Click on the circle in this box to open up another dialogue box.
   a. Under “Select the WinDaq Device” click on DI-194 Serial Device (xx)
   b. In the “Starting Cell” entry field, enter the cell designator for the upper left corner where you want to begin putting the data. A1 is the default. If you want to begin in another row or column enter that cell designator.
   c. In the “Rows to Fill” entry field enter 600. 600 data points will be collected over the 10 minute period (10 min x 60 sec/min x 1 data point/sec) for each thermocouple. When 600 data points have been collected the program will stop importing the data into the spreadsheet.
   d. Click on “start” to begin data acquisition.
11. The program automatically puts °C in each of the columns in the first row of the designated starting cell.
12. The thermocouple names for each column is listed below. They are the same as channels 1, 2, 3, 4 shown on the oscilloscope chart in the data acquisition program.

<table>
<thead>
<tr>
<th>Column</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column 1</td>
<td>Hot Water in</td>
</tr>
<tr>
<td>Column 2</td>
<td>Hot Water out</td>
</tr>
<tr>
<td>Column 3</td>
<td>Cold Water in/out (dependent on whether co-current/counter-current flow)</td>
</tr>
<tr>
<td>Column 4</td>
<td>Cold Water in/out (dependent on whether co-current/counter-current flow)</td>
</tr>
</tbody>
</table>

13. Do not enter data into the spreadsheet while it is collecting data from Windaq. If you press **Enter** or click on another cell to enter data into a cell at the same time that data is being entered into a cell by the data acquisition system, the data acquisition system will lock up and you may lose your data. You will have to restart the run. (There are times when the computer will have to be rebooted.)

14. The spreadsheet should be saved after each run.

15. Data from additional experimental runs can be put to the right of the previous run. Data can not be collected in columns beyond column HZ. Data from each experimental run can also be put into a new sheet.
**Department of Chemical Engineering**  
Stockroom Checkout slip  

Shell and Tube Heat Exchanger  

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Out</th>
<th>In</th>
<th>Equipment</th>
<th>Out</th>
<th>In</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stopwatch</td>
<td></td>
<td></td>
<td>4 L PE Graduated Cylinder</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Name: ____________________________  
(print name)  

Date: ____________________________  

Lab No.: Lab 1 Tuesday 12:00 - 4:50 PM  
Lab No.: Lab 2 Thursday 12:00 - 4:50 PM  
Lab No.: Lab 3 Tuesday and Thursday morning (9:30 - 11:50 AM)  
(circle one)  

Name: ____________________________  
(Signature)