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CBE 140A: Heat Exchanger

1 Introduction

The temperature manipulation of industrial process streams can be observed as necessary for many reasons: to name a few, a certain reaction might proceed at economically viable rates only above a threshold temperature; a distillation column must have heat supplied and removed at its reboiler and condenser, respectively, to properly operate; a plant might be more economical if heat is recovered in exiting process streams. In this project, the behavior of a concentric-tube heat exchanger will be characterized.

2 Objective

The heat exchanger apparatus, with flow streams on inner and outer tubes, allows for the transfer of heat from a hot and cold water either in the co-current or counter-current direction. For both flow patterns, the heat exchanger's performance can be explored as a function of the cold and hot stream volumetric flow rates, as well as the hot stream inlet temperature.

3 Theory

The following derivation for analysis of heat transfer in a double-pipe exchanger, concluding in the log-mean temperature difference (LMTD) model, is adapted from Section 13.2 of [1].

See Figure 1 for an illustration of a double-pipe heat exchanger—one pipe is fixed in the center of a larger diameter pipe, which one fluid flows inside the smaller pipe while the other fluid flows in the annular region between the two pipes. This derivation assumes the hot and cold fluids flow in the inner pipe and in the annular region, respectively. Insert A shows a side cut-away view, while insert B illustrates a cross-sectional view of the two pipes.

Assuming steady state behavior and a well-insulated heat exchanger (preventing interaction with the surroundings), we can conclude the heat gained by the cold fluid is equal, but of opposite sign, to the heat lost by the hot fluid. This can also be described differentially, considering the amount of heat transferred over some minute length of the exchanger:

$$|dQ_H| = dQ_C = |(\dot{m}C_P dT)_H| = (\dot{m}C_P dT)_C \tag{1}$$

where Q = heat power in units of energy per time,
$\dot{m}$ = mass flow rate,
C_P = heat capacity,
T = temperature,

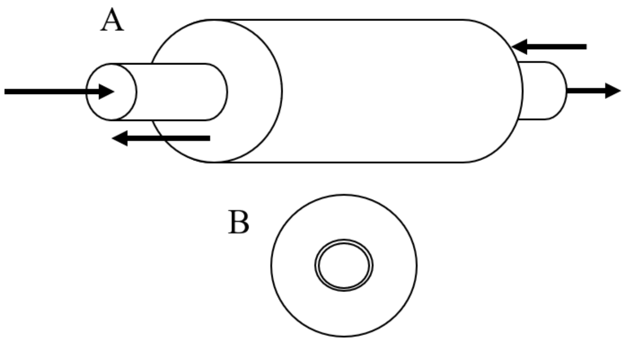

Figure 1: Concentric tube heat exchanger from two perspectives.

and subscripts H and C denoting the hot and cold streams, respectively. Since the hot side is losing heat, absolute values are included to have sign agreement. Redefining the product of $\dot{m}C_P$ as C for shorthand, the equations can be rewritten:

$$dT_C = \frac{d|Q_H|}{C_C} \quad \text{and} \quad dT_H = -\frac{d|Q_H|}{C_H} \tag{2}$$

Defining the difference of the hot and cold temperatures as $\Delta T = T_H - T_C$ and subtracting the equations in (2) from one another yields:

$$dT_H - dT_C = d(\Delta T) = d|Q_H|\left(-\frac{1}{C_H} - \frac{1}{C_C}\right) \tag{3}$$

Considering the overall energy balances for both streams, assuming negligible temperature dependence for the heat capacity, we can write the following where 1 and 2 represent the extreme temperatures for each stream on the left and right-hand side of the exchanger, respectively.

$$|Q_H| = C_C(T_{C1} - T_{C2}) = C_H(T_{H1} - T_{H2}) \tag{4}$$

By substituting equations from (4) into (3) and rearranging, one arrives at:

$$d(\Delta T) = \frac{d|Q_H|}{|Q_H|}(\Delta T_2 - \Delta T_1) \tag{5}$$

Where $\Delta T_1 = T_{H1} - T_{C1}$ and $\Delta T_2 = T_{H2} - T_{C2}$. Note these difference are between hot and cold stream temperatures evaluated on each end of the exchanger. Writing another differential energy balance for a small region of the heat exchanger, now in terms of the total temperature difference, introduces an overall heat transfer coefficient, U:

$$d|Q_H| = UdA(T_H - T_C) \tag{6}$$

Where dA is a differential section of exchanger area at which heat transfer takes place—this choice of either inner or outer surface of the inner tube impacts the definition of U, which will be expanded upon later. Rephrasing Equation (5) in terms of (6), we arrive at:

$$d(\Delta T) = \frac{UdA\Delta T}{|Q_H|}(\Delta T_2 - \Delta T_1) \tag{7}$$

or, equivalently,

$$\frac{d(\Delta T)}{\Delta T} = \frac{U}{|Q_H|}(\Delta T_2 - \Delta T_1)dA \tag{8}$$

So long as U is constant across the area of the heat exchanger, this equation can be integrated and solved for Q, resulting in:

$$|Q_H| = UA\frac{\Delta T_2 - \Delta T_1}{ln\frac{\Delta T_2}{\Delta T_1}} = UA\Delta T_{LM} \tag{9}$$

Where ΔT_{LM} denotes the log-mean temperature difference, given in the previous form of the equation. This final form allows a separate method of characterizing the performance of a heat exchanger—through the overall heat transfer coefficient, U.

How can the overall heat transfer coefficient be predicted? As introduced in Equation 6, U is the proportionality between a temperature difference driving force and the heat flux from the hot to cold fluid bulk streams. An analysis of the potential resistances to heat transfer in this process concludes there is, in series, 1) convective heat transfer from the hot fluid bulk to the inner pipe wall, 2) conductive heat transfer across the wall, and 3) convective heat transfer from the inner pipe to the cold fluid bulk. Considering this system is most easily described in radial coordinates, the result is:

$$U_iA_i = U_oA_o = \left[\frac{1}{h_oA_o} + \frac{ln\frac{r_o}{r_i}}{k} + \frac{1}{h_iA_i}\right]^{-1} \tag{10}$$

Where subscripts i and o denote the inner and outer sides of the smaller pipe, respectively. The thermal conductivity of the inner wall is represented by k and the fluid convective heat transfer coefficients are denoted by h. Here, we can observe the choice of inner or outer pipe surface area will vary the value of U correspondingly. If substantial exchanger fouling occurs, as a result of corrosion, bio-film build-up, or other reasons, additional heat transfer resistance is encountered. This can be accounted for with an additional term R_{fouling} within the brackets on the right-hand side of equation 10.

To predict the behavior of a heat exchanger, Equation 10 can be used so long as the pipe material, as well as hot and cold flow physical properties, are known. Empirical studies have been able to predict convective heat transfer coefficients with reasonable accuracy using dimensionless analysis. Many correlations exist, depending on the geometry, flow type, surface conditions, etc., and are well documented in the corresponding textbooks. For example, fully-developed laminar flow over a constant-temperature plate yields the following (derived in [2, 352]), relating the Nusselt number (which, once known, allows determination of the convective heat transfer coefficient, h) to a function of the Prandtl and Reynolds numbers:

$$Nu = 0.664Pr^{\frac{1}{3}}\sqrt{Re} \tag{11}$$

From these types of correlations, the convective heat transfer coefficients for the hot and cold fluids, and the overall heat transfer coefficient in turn, can be estimated. Combining the predicted value of U with the overall energy balances, outlet temperatures can be predicted for any trial's operating conditions.

4 Experimental Apparatus

An illustration of the apparatus is given in Figure 2, with a front and back view given in inserts A and B. Its parts of interest are numbered: A covered (7) water reservoir (1) contains a heating element (2) which provides a steady supply of hot water through a pump (6) which, when plugged in, provides hot water flow to the insulated (13) heat exchanger, a flow meter (23) and a control valve (20). The heating element can be turned on from a switch (8) and its set point temperature manipulated using the switch (9). Cold water, supplied from the building plumbing to (21), can be directed to flow co-currently or counter-currently depending on the positions of the valves (16). (The appropriate valve positions for each flow pattern is provided on the front board of the apparatus.) The cold water flows through a control valve (18), flow meter (19), and out to a drain through (22). Note that this heat exchange feeds hot water through the inner tube and cold water flows in the annular outer region. Bleed valves (11) can be opened to remove air trapped in the heat exchanger. Several Bluetooth-enabled Vernier temperature probes are installed through the apparatus to observe the hot and cold stream temperatures at their inlets, midpoints, and outlets (10, 12, 14, 15, 17).

Dimensions of the heat exchanger are as follows, confirmed on the apparatus board front: The inner tube has an outer diameter of 15 mm and a wall thickness of 0.7 mm. The outer tube has an outer diameter of 22 mm and wall thickness of 0.9 mm. The insulation thickness is 20 mm. The total length of the heat exchanger is 1.5 m.

5 Safety

The major hazards associated with this experiment are the following: The pump, powered from an electrical outlet, introduces the risk of injury from electric shock. Avoid by ensuring the pump power cord does not become submerged and is not touched when in operation. The heating element and hot water produced by this apparatus introduces the risk of scalds and burns. Mitigate by maintaining containment of the hot water stream and not handling exposed hot-water pipes. Through accumulation of biological contaminants in the water, there is a risk of infection. Contact the instructional staff if you believe the piping needs cleaned or replaced. If water splashes out of the apparatus, there are risks to clothing damage, slips, and falls. Avoid this by carefully considering the impact of opening or closing of valves prior to acting, and clean spills immediately if they do occur. This list is only a starting point and not intended to be fully comprehensive—please keep the safety of yourself and others in mind throughout the laboratory sessions.

6 Experimental Procedure

In studying the steady-state behavior of this heat exchanger, substantial time will be required to permit the system to reach steady state. Teams are recommended to contact the instructional staff to preheat the water to a desired temperature prior to the laboratory session.

For the first trial, the hot water temperature set point should be 60 °C, with the valves (16) positioned such that the resulting flow pattern is co-current. Check to ensure the cold water return tubing is securely placed in a sink. Subsequently, turn on the hot water pump and open the cold water supply valve. Set the hot and cold volumetric flow rates to 2 and 1 $\mathrm{L \cdot min^{-1}}$, respectively. Periodically collect temperature readings from all six thermometers until steady state is reached, at which point the trial is complete.

Repeat the trial for identical conditions except for a counter-current flow pattern.

Conduct a series of trials exploring the effect of hot water set-point temperature, hot water flow rate, and cold water flow rate for both co and counter-current flow patterns. In all cases, collect both dynamic and steady state data from all thermometers. For faster data collection, it is often more efficient to collect data for different trials starting at a higher temperature and cooling the system, compared to heating up the exchanger across trials.

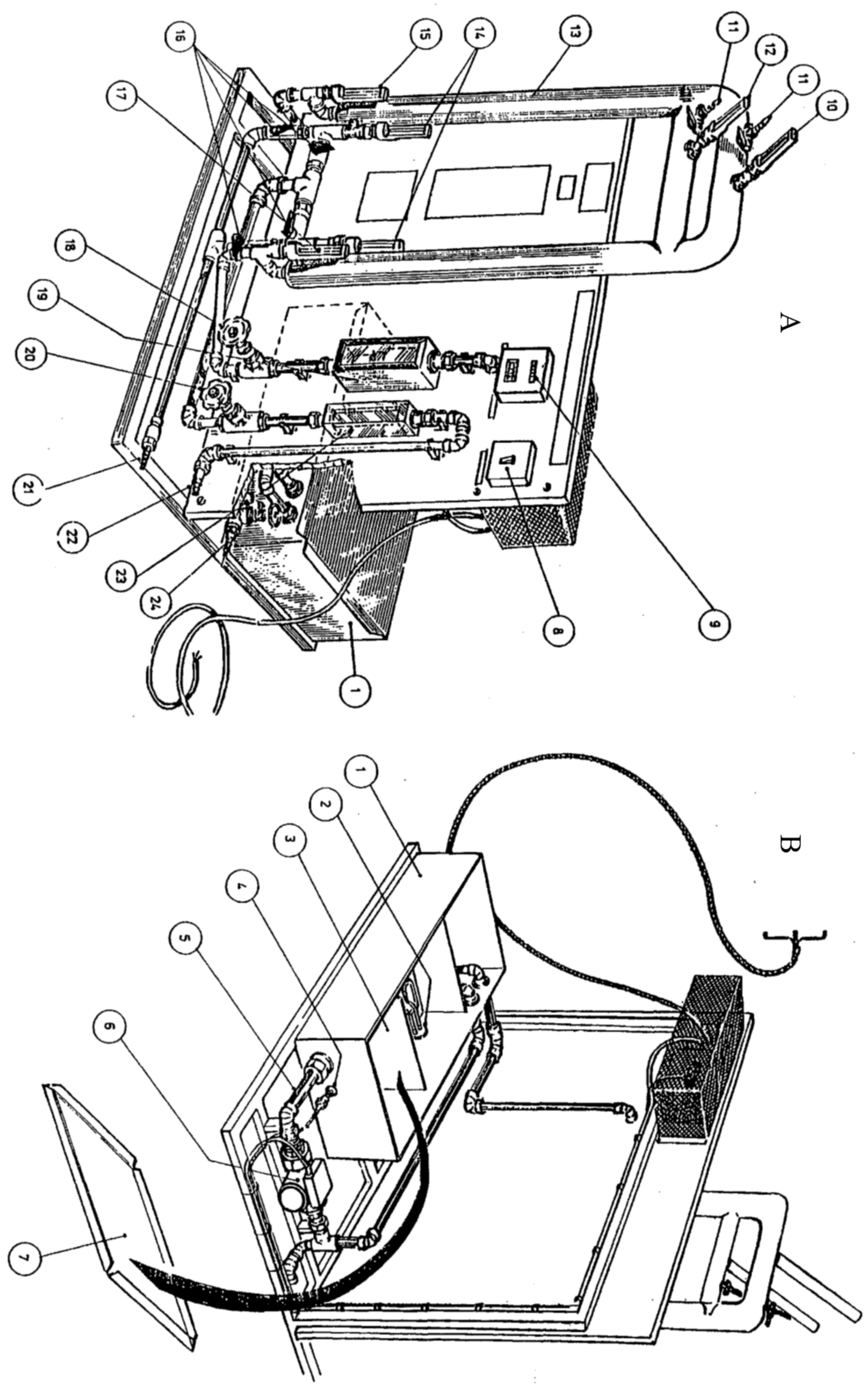

Figure 2: Experiment 4: heat exchanger apparatus.

7 Data Analysis

Create plots illustrating the temperature profiles of the hot and cold streams through the heat exchanger's length for both parallel and counter-current flow using results from the first two trials. Comment on their similarities, differences, and comparisons to expectations. If different, hypothesize why this is the case.

For all trials, characterize the performance of the heat exchanger: Calculate the heat power absorbed by the cold stream and emitted by the hot stream, and calculate their ratio, which can be thought of as one less the proportion of heat lost to the surroundings. Determine the experimental value of the overall heat transfer coefficient, U, using Equation 9. If appropriate, estimate the heat transfer resistance due to fouling. How do all these calculated values compare to their expected magnitude? What reasons could explain their difference, and is there evidence for it? Do any of these values vary when studying the entire exchanger or only the left or right-hand side (e.g., between the left-side thermometers and the midpoint)?

How do the variables quantifying exchanger performance, as just described, vary with hot water set-point temperature, hot water flow rate, cold water flow rate, and flow pattern? Do these trends agree with your predictions? Provide supporting evidence for the source of possible discrepancies.

References

[1] Stanley Middleman. *An introduction to mass and heat transfer*. John Wiley and Sons, Inc., 09 1998.

[2] Julian Smith, Warren McCabe, and Peter Harriott. *Unit operations of chemical engineering*. McGraw-Hill, seventh edition, October 2005.