MEMO TO: Qiuyan Li

FROM: Seth Strayer

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SUBJECT: TF3 – Bench-top Heat Exchangers

On May 29, 2019, Noah Sargent, Aaron Esquino and I conducted an experiment to explore the heat-transfer characteristics of three different heat exchangers: a) concentric tube heat exchanger, b) plate type heat exchanger, and c) shell and tube heat exchanger. Heat exchangers are an essential and common piece of equipment used to transfer heat efficiently from one medium to another. Different types of heat exchangers have different means of transferring heat, and as such, our main objective of the lab is to examine the difference in efficiencies between the three heat exchangers.

The three heat exchangers used in this experiment were the concentric tube type (TD360A), the plate type heat exchanger (TD360B), and the shell and tube type heat exchanger (TD360C). The similarities and differences between these three types of heat exchangers are outlined in Sections 1.3-1.5 of the Thermal Fluids (TF) Lab 3 Handbook. To effectively quantify the differences between the three exchangers, each utilized the same procedure. First, the heat exchanger was first mounted for parallel flow. The hot water was set to a temperature of 60° and a flow rate of 3 [L/min] (*note* that the hot water flow rate remained constant throughout the experiment). Next, the cold-water flow rate was set to an initial value of 3 [L/min], and the inlet and outlet temperatures for both the hot (T_{H1}, T_{H2}) and cold circuits (T_{C1}, T_{C2}) were recorded. *Note* that the concentric tube heat exchanger (TD360A), also provided an average hot and cold temperature (T_{H3}, T_{C3}, respectively). For TD360B and TD360C, the average hot and cold-water temperatures were calculated manually based on the inlet and outlet temperatures. Once all values were recorded, the cold-water flow rate was adjusted to 2, 1, and 0.5 [L/min], and temperature values were recorded at each step. Once all data was collected for parallel flow, the cold-water circuit was turned off and connections were adjusted to provide counterflow. The exact same procedure was then performed for counterflow, with temperature values being recorded at each cold-water flow rate. It was our hypothesis that heat transfer characteristics should change with varying cold-water flow rates and with different types of heat exchangers.

We may calculate several quantities to quantify the effectiveness of each heat exchanger. These quantities include the energy balance coefficient (C_{EB}), the mean temperature efficiency (η), and the heat transfer coefficient (U), given by Equations (2), (3), and (4), respectively. Note that U is a measure of how well the heat exchanger works. A good heat exchanger will have a high coefficient, and therefore this value is especially important to engineers and is the most commonly used specification for heat exchanger performance.

The extended theory used for calculating these quantities is given in Section 1.6 of the TF Lab 3 Handbook. To calculate the heat emitted from the hot water and the heat absorbed from the cold water (Eqn. 1), we need the specific heat capacity at constant pressure (c_p), and the mass flow rate, which is a function of density (ρ). The specific heat and density change as a function of temperature; thus, these parameters must be calculated for different water temperatures. AmesWeb *Specific Heat Capacity of Liquid Water Calculator*[1] was used to calculate specific heat and Kell's formulation[2] was used to calculate density, given the average temperature of the hot/cold water.

Tables 1-3 summarize the data analysis for both parallel and counterflow for the concentric tube, plate, and shell and tube type heat exchangers, respectively (*note* that raw temperature data is not included in these tables, but can be found in the Excel file "TF3 Data.xlxs", sheets "Raw Data" and "Data Analysis"). These tables provide several valuable bits of information, which are summarized below:

1.) Heat emitted/heat absorbed linearly decreases with cold water flow rate
2.) Mean temperature efficiency exponentially increases with decreasing cold-water flow rate (see Figure 1)
3.) Heat transfer coefficient linearly decreases with cold water flow rate.

The fact that heat emitted/heat absorbed linearly decreases with cold water flow rate is trivially explained by Equation (1). I.e., decreasing cold water flow rate linearly decreases the hot water temperature gradient and the heat absorbed by the cold water. We also note that as the hot water temperature gradient linearly decreases, the cold-water temperature gradient increases exponentially. Thus, by Equation (3), the mean temperature efficiency exponentially increases with decreasing cold-water flow rate. Finally, the heat transfer coefficient decreases linearly because of some combination of the linear decrease in heat emitted and exponential increase in logarithmic mean temperature difference. Given the correlation of our experimental results with those predicted by theory, we can say that our experiment was successful and little error was introduced.

It is proven by Result (3) that all heat exchangers perform less favorably at lower cold-water flow rates, at least with respect to the heat transfer coefficient. However, the data also shows that the heat exchangers themselves perform differently. For parallel flow, the shell and tube type heat exchanger performed most favorably with a heat transfer coefficient $U = 1.465$ (Table 3). For counterflow, the concentric tube type heat exchanger performed most favorably with a heat transfer coefficient of $U = 1.449$ (Table 1). The plate type heat exchanger performed least favorably for either case, with a maximum heat transfer coefficient of $U = 0.781$ (Table 2).

The differences in performance metrics for the concentric tube and shell and tube type heat exchangers seem quite arbitrary. I.e., the shell and tube type had a higher heat transfer coefficient but a lower mean temperature efficiency than the concentric tube type for parallel flow. Thus, we may conclude that these two types perform remarkably similar and the differences in results may be explained by slight measurement error. Inaccurate readings from the thermocouples (system not yet at steady state, inconsistencies in measurement readings, etc.) would be a primary cause of said measurement error. Nonetheless, this experiment was successful in determining the heat transfer characteristics of the three types of heat exchangers and proved that, in any applicable setting, concentric tube and shell and tube type heat exchangers should be used over plate type heat exchangers when thermal efficiency is of the essence. Plate type heat exchangers may only suffice in situations where limited space is available, and efficiency is not at the forefront of design criteria.

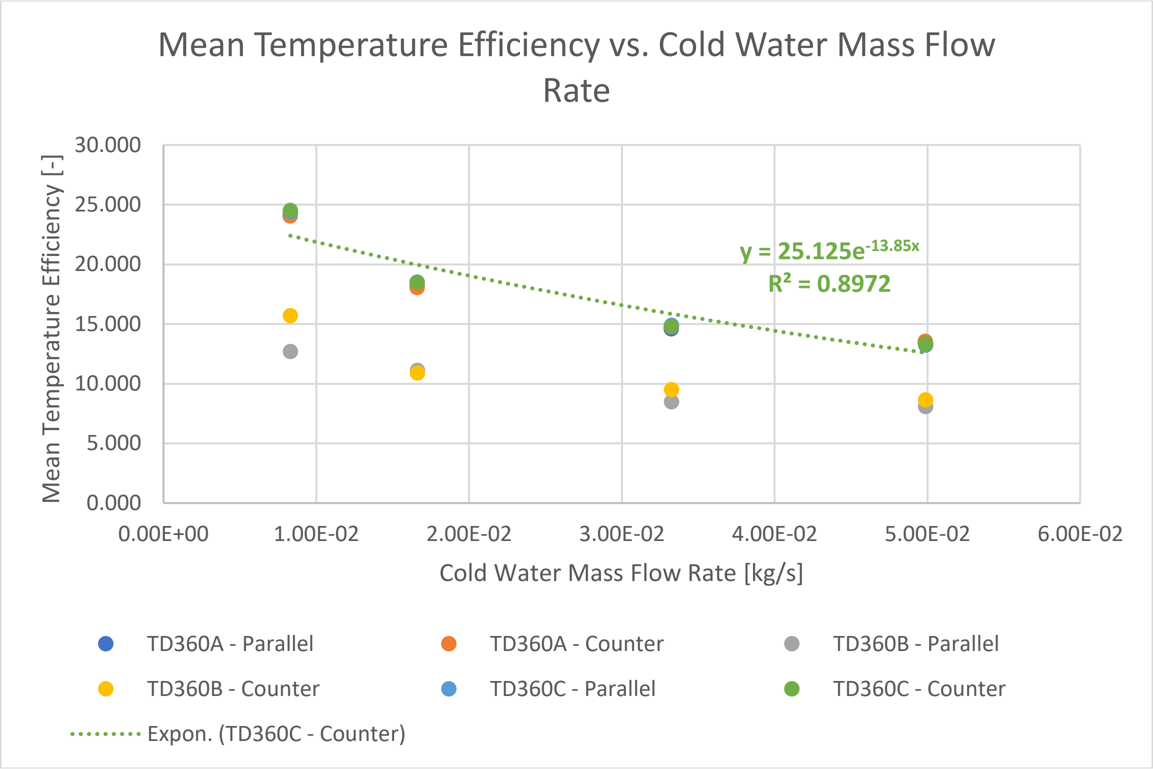

Figure 1: Mean Temperature Efficiency vs. Cold Water Mass Flow Rate

Reference Equations

The heat transfer rate is given by:

$$\dot{Q} = \dot{Q}_e = \dot{Q}_a = \dot{m}_h c_{ph} \Delta T_h = \dot{m}_c c_{pc} \Delta T_c \tag{1}$$

Where $\dot{Q}_e$ is heat emitted and $\dot{Q}_a$ is heat absorbed, $\dot{m}$ is mass flow rate, c_p is specific heat of water at constant pressure, and ΔT is the change in temperature. Given heat emitted and heat absorbed, the energy balance coefficient is given by:

$$C_{EB} = \frac{\dot{Q}_a}{\dot{Q}_e} \tag{2}$$

The mean temperature efficiency is the average of the hot and cold temperature efficiency:

$$\bar{\eta} = \frac{\eta_h + \eta_c}{2} \tag{3}$$

Where the hot and cold temperature efficiencies are given by Equations (8) and (9) of the TF Lab 3 Handbook. Finally, the heat transfer coefficient is given by:

$$U = \frac{\dot{Q}_e}{A \cdot LMTD} \tag{4}$$

Where $A = 0.02$ [m^2] is the heat transfer area of each heat exchanger and $LMTD$ is the logarithmic mean temperature difference, given by Equation (11) of the TF Lab 3 Handbook.

Table 1: Data Analysis for Concentric Tube Type Heat Exchanger (TD360A)

Flow	Flow Rate [m^3/s]	ΔT_h [C]	T_{aveh} [C]	c_{ph} [kJ/kg-K]	ρ_h [kg/m^3]	$\dot{m}_h$ [kg/s]	ΔT_c [C]	T_{avec} [C]	c_{pc} [kJ/kg-K]	ρ_c [kg/m^3]	$\dot{m}_c$ [kg/s]	$\dot{Q}_e$	$\dot{Q}_a$	CEB	$\bar{\eta}$	U
P	5.00E-05	4.8	57.1	4.184	984.150	4.92E-02	5.8	22.9	4.181	997.266	4.99E-02	0.988	1.209	1.224	13.418	1.457
P	3.33E-05	4.1	57.6	4.184	983.899	4.92E-02	7.5	23.9	4.180	997.016	3.32E-02	0.844	1.042	1.235	14.610	1.257
P	1.67E-05	3.1	58.8	4.185	983.289	4.92E-02	11.6	26.3	4.179	996.377	1.66E-02	0.638	0.805	1.262	18.193	0.981
P	8.33E-06	2.3	59.2	4.185	983.084	4.92E-02	17.1	30.5	4.178	995.135	8.29E-03	0.473	0.592	1.252	24.069	0.801
C	5.00E-05	4.9	58.1	4.185	983.646	4.92E-02	6.1	22.6	4.181	997.339	4.99E-02	1.009	1.272	1.261	13.547	1.449
C	3.33E-05	4.2	58.4	4.185	983.494	4.92E-02	7.7	23.5	4.180	997.117	3.32E-02	0.864	1.070	1.238	14.764	1.271
C	1.67E-05	3	59.5	4.185	982.930	4.91E-02	11.7	26.1	4.179	996.432	1.66E-02	0.617	0.812	1.316	18.059	0.941
C	8.33E-06	2.4	59.4	4.185	982.982	4.91E-02	17	29.6	4.178	995.414	8.30E-03	0.494	0.589	1.193	24.069	0.835

Table 2: Data Analysis for Plate Type Heat Exchanger (TD360B)

Flow	Flow Rate [m^3/s]	ΔT_h [C]	T_{aveh} [C]	c_{ph} [kJ/kg-K]	ρ_h [kg/m^3]	$\dot{m}_h$ [kg/s]	ΔT_c [C]	T_{avec} [C]	c_{pc} [kJ/kg-K]	ρ_c [kg/m^3]	$\dot{m}_c$ [kg/s]	$\dot{Q}_e$	$\dot{Q}_a$	CEB	$\bar{\eta}$	U
P	5.00E-05	2.8	58.6	4.185	983.392	4.92E-02	3.8	21.1	4.181	997.691	4.99E-02	0.576	0.793	1.376	8.088	0.770
P	3.33E-05	2.1	58.75	4.185	983.315	4.92E-02	4.8	21.6	4.181	997.576	3.33E-02	0.432	0.667	1.544	8.498	0.583
P	1.67E-05	1.8	59.3	4.185	983.033	4.92E-02	7.3	22.95	4.181	997.253	1.66E-02	0.370	0.507	1.370	11.125	0.512
P	8.33E-06	0.8	59.6	4.185	982.878	4.91E-02	9.5	24.15	4.180	996.952	8.31E-03	0.165	0.330	2.005	12.685	0.234
C	5.00E-05	2.8	58.3	4.185	983.544	4.92E-02	4.2	21.3	4.181	997.646	4.99E-02	0.576	0.876	1.520	8.642	0.781
C	3.33E-05	2.4	58.5	4.185	983.443	4.92E-02	5.3	21.85	4.181	997.518	3.33E-02	0.494	0.737	1.492	9.506	0.676
C	1.67E-05	1.5	58.95	4.185	983.213	4.92E-02	7.3	22.95	4.181	997.253	1.66E-02	0.309	0.507	1.644	10.891	0.431
C	8.33E-06	1.4	59.9	4.185	982.723	4.91E-02	11.5	25.25	4.180	996.663	8.31E-03	0.288	0.399	1.387	15.693	0.420

Table 3: Data Analysis for Shell and Tube Type Heat Exchanger (TD360C)

Flow	Flow Rate [m^3/s]	ΔT_h [C]	T_{aveh} [C]	c_{ph} [kJ/kg-K]	ρ_h [kg/m^3]	$\dot{m}_h$ [kg/s]	ΔT_c [C]	T_{avec} [C]	c_{pc} [kJ/kg-K]	ρ_c [kg/m^3]	$\dot{m}_c$ [kg/s]	$\dot{Q}_e$	$\dot{Q}_a$	CEB	$\bar{\eta}$	U
P	5.00E-05	5	57.5	4.184	983.949	4.92E-02	5.8	22.1	4.181	997.459	4.99E-02	1.029	1.209	1.175	13.235	1.465
P	3.33E-05	4.5	57.25	4.184	984.075	4.92E-02	7.5	22.95	4.181	997.253	3.32E-02	0.926	1.042	1.125	14.888	1.364
P	1.67E-05	3.1	58.25	4.185	983.570	4.92E-02	11.9	25.25	4.180	996.663	1.66E-02	0.638	0.826	1.295	18.519	0.984
P	8.33E-06	2.5	58.85	4.185	983.264	4.92E-02	17.3	28.15	4.179	995.849	8.30E-03	0.514	0.600	1.166	24.384	0.869
C	5.00E-05	4.8	56.8	4.184	984.300	4.92E-02	5.9	22.05	4.181	997.471	4.99E-02	0.988	1.230	1.245	13.342	1.434
C	3.33E-05	4.2	57.6	4.184	983.899	4.92E-02	7.8	23	4.181	997.241	3.32E-02	0.864	1.084	1.254	14.778	1.262
C	1.67E-05	3.2	58.2	4.185	983.595	4.92E-02	11.8	25.1	4.180	996.703	1.66E-02	0.659	0.819	1.244	18.473	1.012
C	8.33E-06	2.4	59	4.185	983.187	4.92E-02	17.6	28.2	4.179	995.834	8.30E-03	0.494	0.610	1.236	24.510	0.832

References

[1] "SPECIFIC HEAT CAPACITY OF WATER." Specific Heat Capacity of Water, AmesWeb, www.amesweb.info/Materials/Specific-Heat-Capacity-of-Water.aspx.

[2] Jones, Frank E., and Georgia L. Harris. "ITS-90 Density of Water Formulation for Volumetric Standards Calibration." Journal of Research of the National Institute of Standards and Technology, vol. 97, no. 3, 1992, pp. 335–340., doi:10.6028/jres.097.013.