Heat Transfer Project Final Report

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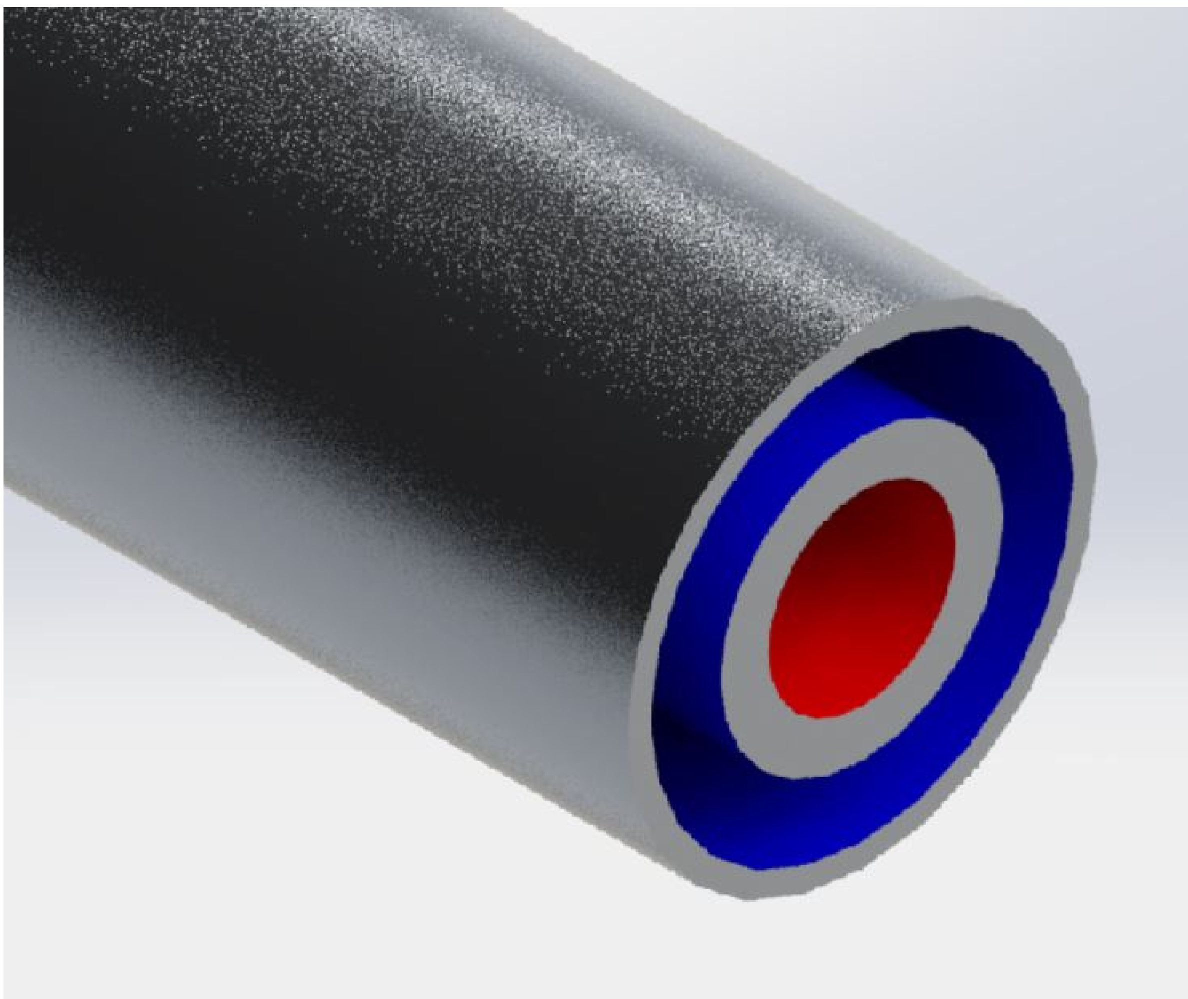
December 9^{th}, 2019



1 Contributions of Each Team Member

The following list summarizes the contributions made by each team member.

1. CJ and Nick wrote the code
2. Stephanie and Jack completed initial calculations by hand, then verified the results with those obtained with the code
3. Jack, Nick, and Stephanie developed the calculation approach and verified each other's work
4. Stephanie wrote the report and researched heat exchanger materials
5. Jack, Nick, and CJ proofread the report

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2 Problem Statement

Design a counter flow double-pipe heat exchanger with $L = 80$ m for cooling a hot water stream at a mass flow rate of 10.0 $\frac{kg}{s}$ with an inlet hot water temperature of 92^{o}C. The inner and outer diameters of the tube in which hot water flows are 40 mm and 60 mm, respectively. This inner tube is made of aluminum alloy 2024-T6 with a constant thermal conductivity of 237 $\frac{W}{mK}$. The coolant is also water that enters the heat exchanger at a rate of 8.0 $\frac{kg}{s}$ with an inlet cold water temperature of 12^{o}C. The larger outer tube creating the concentric annulus in which cold water flows has an inner diameter of 90 mm and is well-insulated outside. A schematic of the heat exchanger is shown in Fig. **??**.

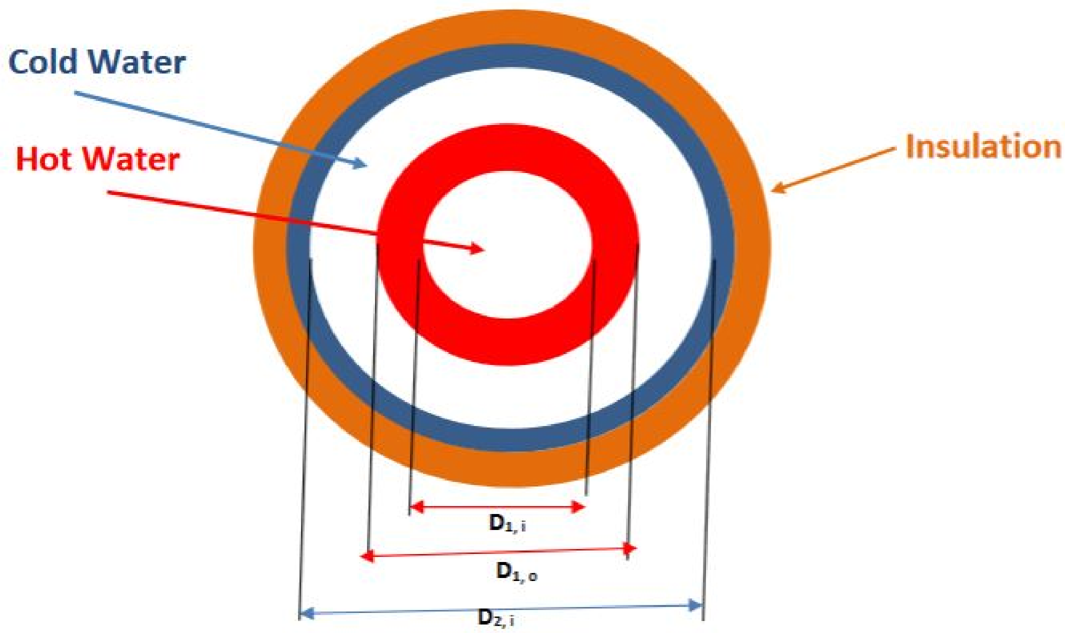


Figure 1: Schematic of Heat Exchanger

a) Curve fit the water properties data for the temperature range of 10 to 100^o C to be able to obtain any property data as necessary.
b) Develop a computational method to calculate the rate of heat transfer and the outlet stream temperatures ($T_{c,o}$ and $T_{h,o}$) for this unit. The mass flow rate and tubes diameters must be variable so that calculations can be repeated for different tube sizes and flow rates.
c) Prepare a results table containing mass flow rate, Re_D, h for both hot and cold streams,

UA, and other relevant information.

d) The existing unit is to be replaced. A vendor is offering a very attractive discount on two identical heat exchangers that are presently stocked in its warehouse, each with $L = 40$ m. The tube diameters in the existing and new units are the same. The vendor is proposing that the two new units could be operated in parallel, such that each unit would process exactly one-half the flow rate of each of the hot and cold streams in a counter flow manner; hence, they together would meet (or exceed) the present plant heat duty (total q). Repeat calculations and give your recommendations, with supporting calculations, on this replacement proposal.

e) Do you have any recommendations with respect to the role of fouling factor, cost, materials, safety, environmental impact, and use of standards for the proposed heat exchanger?

3 Solution Procedure

The following subsections detail the solution procedures utilized to complete each project task.

3.1 Part a

To complete the task presented in part a, Team 1 utilized Microsoft Excel to plot the values in Table A.6 **textbook**. First, the entire table was transcribed into an Excel sheet. Next, the team used Excel's curve fit function to generate equations for each of the fluid properties. However, after assessing the accuracy of the equations, the team found that it is more accurate to perform linear interpolation.

3.2 Part b

Because of the team's familiarity, Excel and Microsoft VBA were used to write the program used to complete part b. To calculate the rate of heat transfer and the outlet stream temperatures for the presented unit, the team first obtained the properties of water at both the inlet and outlet temperatures. Because the outlet temperatures are unknown, the inlet temperatures serve as a starting point for iteration. With these initial properties, the next step was to calculate the Reynold's number and determine the flow regime of both the hot and cold flows. Since the mass flow rates are known, the Reynold's number for each stream was computed with the following equation:

$$Re_D = \frac{4\dot{m}}{\pi \mu D} \tag{1}$$

Because the cold stream is in the annulus region, the hydraulic diameter, defined as $D_h = D_{2,i} - D_{1,o}$, was used in the computation of the cold stream Reynold's number, Re_D. For the hot stream, the inner diameter, $D_{1,i}$ was used. This calculation presents three possible flow regimes for each flow: laminar, fully turbulent, and transitional. These regions are defined in Table **??**. In the case of the given parameters, both the hot and cold flows are fully turbulent. However, because the mass flow rates and tube diameters are variable, Team 1's program uses these ranges to check the flow regime for each scenario presented.

Table 1: Reynold's Number Range for Each Flow Regime

Flow Regime	Re_D Range
Laminar	0 - 2,300
Transitional	2,301 - 9,999
Turbulent	10,000 - ∞

The transitional flow regime is characterized by extreme flow instability, and consequently, it is difficult to predict a fluid's behavior at these Reynolds Numbers. In general, the transitional flow regime is avoided in heat exchanger design consequently **transitional**, and because of this, Team 1 has decided to output an error message if this regime is achieved.

The next step in the calculation is to determine whether or not the flow is hydrodynamically and thermally fully developed. However, because the length of the pipe is 80 m, only a very large tube diameter would produce an entry length long enough for entry effects to be significant. Consequently, Team 1 has assumed that the flow will always be fully developed.

The calculation of the average Nusselt Number, $\overline{NU_D}$, is then based off of both the flow regime and entry length. The equations used to calculate the Nusselt Number for fully developed flow are summarized in Table **??**.

Table 2: $\overline{NU_D}$ Information for Fully Developed Flow in Each Flow Regime

Scenario	$\overline{NU_D}$ Equation
Laminar	See Table 8.2 **textbook**
Turbulent (Heating)	$\overline{NU_D} = 0.0243 Re_D^{\frac{4}{5}} Pr^{0.4}$
Turbulent (Cooling)	$\overline{NU_D} = 0.0265 Re_D^{\frac{4}{5}} Pr^{0.3}$

If turbulent, the heating equation corresponds with the cold stream, as it is being heated by the hot stream. The cooling equation is used to calculate the Nusselt Number for the hot stream, since it is experiencing cooling. With the average Nusselt Number, the average heat transfer coefficient, $\overline{h}$, can be calculated for the hot and cold streams. This can be completed using Equation **??**.

$$\overline{h} = \frac{\overline{NU_D} k_f}{D} \tag{2}$$

Again, for the cold water in the annulus region, the hydraulic diameter is used. With the average heat transfer coefficient for each stream, UA can be calculated using Equation **??**.

$$UA = \left[\frac{1}{\overline{h_c} A_c} + \frac{\ln(\frac{D_{1,o}}{D_{1,i}})}{2\pi k_s L} + \frac{1}{\overline{h_h} A_h} \right]^{-1} \tag{3}$$

With these parameters, the $NTU - \epsilon$ method can be used to calculate the total heat transfer and the hot and cold outlet temperatures. The first step in this process is to calculate the heat capacities of the hot and cold streams. These are defined in Equations **??** and **??**.

$$C_h = \dot{m}_h c_{p,h} \tag{4}$$

$$C_c = \dot{m}_c c_{p,c} \tag{5}$$

The next step is to identify C_{max} and C_{min}, which correspond with the high and low heat capacities calculated above. With these identified, the ratio of the heat capacities, C_r, can be calculated with Equation **??**.

$$C_r = \frac{C_{min}}{C_{max}} \tag{6}$$

The number of transfer units, NTU, and the effectiveness, ϵ, can then be computed with Equations **??** and **??** respectively.

$$NTU = \frac{UA}{C_{min}} \tag{7}$$

$$\epsilon = \frac{1 - exp(-NTU(1 - C_r))}{1 - C_r exp(-NTU(1 - C_r))} \tag{8}$$

Finally, the total heat transfer rate, q, and the hot and cold outlet temperatures can be calculated.

$$q = \epsilon C_{min}(T_{h,i} - T_{c,i}) \tag{9}$$

$$T_{c,o} = \frac{q}{C_c} + T_{c,i} \tag{10}$$

$$T_{h,o} = \frac{-q}{C_h} + T_{h,i} \tag{11}$$

The final step is to compare the new outlet temperature to the temperature used to obtain the average temperature in the beginning. If the error is not within an acceptable range, click the "Iterate" button until an acceptable accuracy is achieved. In Team 1's analysis, an acceptable error was less than 0.1%.

3.3 Part d

The solution procedure used in part b was also used in part d. The only differences between the calculations were the length of the heat exchanger and the hot and cold mass flow rates, which were all halved. Once the total heat transfer rate, q, was found for one heat exchanger, the value was doubled to determine the total heat transfer rate of two units.

4 Results

The following section details the results obtained by Team 1's analysis.

4.1 Part a

Fig. **??** shows the results of the curve fit for viscosity.

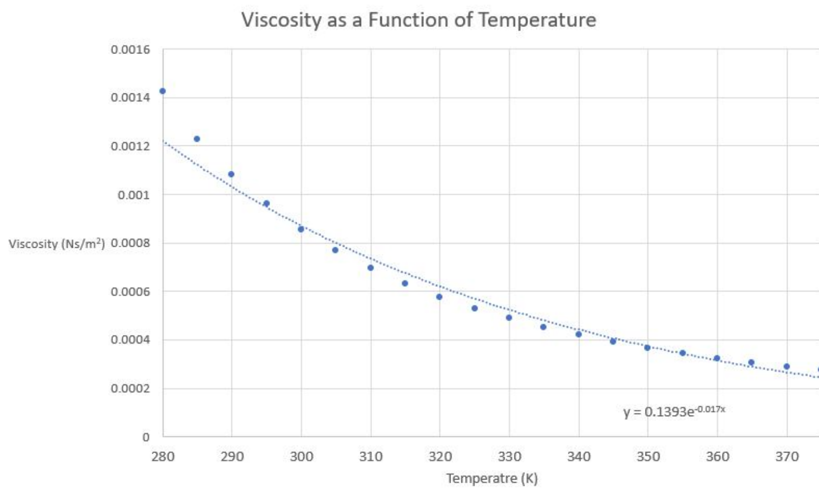


Figure 2: Viscosity Curve Fit Results

The equation obtained from the curve fit is as follows:

$$y = 0.1393e^{-0.017x} \tag{12}$$

As is apparent in Fig. **??**, the best curve fit only matches up with the data from Table A.6 **textbook** at a few points. Otherwise, it is fairly inaccurate. After calculating the viscosity at 280K with the Equation **??** and comparing it to the table results, the team calculated a maximum error of 16.1%. The minimum error occurs at approximately 355K, and it was found to be 2.8%. The spacing between data points in the table is only 5K, at at this small of a deviation, linear interpolation is very accurate. Because of the inaccuracies in Equation **??**, Team 1 decided to perform linear interpolation in Excel for all calculations.

4.2 Part c

The results calculated in part b are summarized in Table ??.

Table 3: Results of Part b

$\dot{m}_h$ ($\frac{kg}{s}$)	$\dot{m}_c$ ($\frac{kg}{s}$)	$L(m)$	$Re_{D,h}$	$Re_{D,c}$	h_h ($\frac{W}{m^2K}$)	h_c ($\frac{W}{m^2K}$)	UA ($\frac{W}{K}$)	$T_{h,o}$ (^oC)	$T_{c,o}$ (^oC)	q (kW)
10.0	8.0	80.0	739162.8	570558.8	29225.7	35875.1	115531.6	38.8	78.7	2228.63

4.3 Part d

The results of part d are summarized in Table ??.

Table 4: Results for Part d

$\dot{m}_h$ ($\frac{kg}{s}$)	$\dot{m}_c$ ($\frac{kg}{s}$)	$L(m)$	$Re_{D,h}$	$Re_{D,c}$	h_h ($\frac{W}{m^2K}$)	h_c ($\frac{W}{m^2K}$)	UA ($\frac{W}{K}$)	$T_{h,o}$ (^oC)	$T_{c,o}$ (^oC)	q (kW)
5.0	4.0	40.0	384093.2	269884.7	17152.9	20077.5	39982.0	43.8	72.4	2018.1

When compared to the results of part b, the total heat transfer rate of the halved heat exchangers is comparable to that of the original design, but it does not meet this value. From that standpoint alone, the exchangers offered by the vendor should not be purchased as a replacement for the old heat exchanger, especially if the discount being offered is a one-time deal. However, if the vendor is willing to sell the heat exchangers at a discount every time they need to be replaced, it may be worthwhile to investigate the impact the lower heat duty has on operations. Depending on the application, this heat duty may suffice, or it may be possible to modify other aspects of operations to account for this loss. If that is the case, it could result in significant savings over time.

4.4 Part e

In heat exchangers, the proper selection of material is just as crucial to its functionality as the design itself. As is true for most designs, this selection of material typically involves compromises driven entirely by design intent. This considers a wide variety of factors and material characteristics, such as cost, ease of manufacture, structural integrity, material conductivity, material fouling, codes, standards, and environmental impact. The perfect material for heat exchangers would be one with a high thermal conductivity, high corrosion and erosion resistance, high structural integrity, and low cost. However, it is often difficult to find a material with all of the listed characteristics, and consequently, compromise may be necessary.

In the case of the heat exchanger with the dimensions and flow characteristics presented in part b, it is important that the team select a material that has high corrosion and erosion resistance. This is due to the fact that the flow regime is fully turbulent, as turbulent flow can induce localized erosion, known as impingement, resulting in a reduction of corrosion resistance **aluminumbronzecorrosion**. Along with this, it would be advantageous to select a highly conductive material for use in the inner pipe in order to facilitate a high rate of heat exchange between the hot and cold flows. A material with a low thermal conductivity and high corrosion resistance would reinforce the insulation on the outside of the heat exchanger and should consequently be considered for the outer tube.

Along with the heat exchange rate and erosion-corrosion resistance, the structural integrity of the materials should be considered. This is an area of potential compromise, as some design applications may not expose the heat exchanger to external, potentially damaging forces. This, along with the factors discussed above, contribute to cost and environmental impact of the heat exchanger. In regard to cost, while it may be advantageous to select inexpensive materials with low corrosion resistance and structural integrity in the short term, this would result in high maintenance costs when considering long-term operation, as the unit would likely need to be replaced frequently due to damage or corrosion. This would also result in a higher environmental impact, as each damaged exchanger would likely be disposed and a new heat exchanger would be fabricated. This would ultimately generate more waste due to fabrication and require much more material over time. Heat exchanger failure may also be hazardous, and choosing proper materials to increase heat exchanger life can mitigate this risk.

Aluminum alloy 2024-T6 is an extremely strong and lightweight material that is typically utilized in the aerospace field. However, despite its benefits, 2024-T6 has poor corrosion and impingement resistance, and if used in a heat exchanger, it would likely degrade very quickly **asm**. In this application, resistance to impingement attack is crucial, as this can significantly degrade the corrosion resistance of an otherwise noncorrosive material. While it is simple to find a material with a low thermal conductivity that resists impingement attack, finding one with a high thermal conductivity has proven to be impossible.

In regard to thermal conductivity and general corrosion resistance, Team 1 believes that a copper tube is the best choice. However, copper does not resist impingement corrosion well. In fact, for water applications exceeding 140^{o}F (approximately 60^{o}C), the maximum recommended fluid velocity should not exceed 2.0 to 3.0 $\frac{ft}{s}$ (0.6 to 0.9 $\frac{m}{s}$) **maxvelocity**. Using the hot stream inlet temperature to obtain fluid properties, the average velocity of the water in the hot tube is 2.06 $\frac{m}{s}$, greatly exceeding these recommendations. Conversely, aluminum bronze alloys have a very high resistance to erosion-corrosion and high strength. However, these alloys can only achieve very low thermal conductivities **aluminumbronze**. Using these alloys would significantly increase the life of the heat exchanger at the expense of overall heat transfer. This predicament leads to a necessary compromise in the material properties of the inner tube. If the goal of the heat exchanger is to reduce lifetime cost, achieve a lower environmental impact, and reduce fouling and corrosion, Team 1 has two possible material recommendations for the inner tube.

1. Utilize copper and reduce the mass flow rates in both flows of the heat exchanger so that erosion-corrosion does not occur

2. Maintain the current mass flow rates and use an aluminum bronze alloy in both the inner and outer tubes

The first option should be selected if a high amount of heat exchange must be maintained, and the second option should be utilized if the current mass flow rates must remain the same. Team 1 recommends using an aluminum bronze alloy for the outer tube in both scenarios, since its low thermal conductivity will reinforce the insulation in the heat exchanger regardless of the mass flow rates used.

5 Summary and Conclusions

In summation, the group was tasked with creating a code to evaluate the outlet temperatures of a crossflow heat exchanger based upon varying flow rates and tube diameters. Values were found for the initial situation and for a situation wherein the flow was divided into two equivalent heat exchangers. The two designs were compared in Tables **??** and **??**. This yielded the result that one heat exchanger would be slightly more efficient than two shorter ones, as the single tube had a q value of 2228.63 kW, while the two tubes had a q value of 2018.1 kW. Tables for the necessary coefficients and equations for the proper situations were compiled into a working code in VBA and iterated to a 0.1% convergence. The code was compared to hand calculations by the group and found to be accurate. Later, materials were investigated which could potentially create a better heat exchanger. The materials recommended are aluminum bronze for the outer tube and either copper if the flow rate could be reduced or aluminum bronze if longevity is more valued than conductivity for the inner tube.

6 Appendix

6.1 List of Equations Used

$$Re_D = \frac{4\dot{m}}{\pi \mu D}$$

$$\overline{NU_D} = 0.0243 Re_D^{\frac{4}{5}} Pr^{0.4}$$

$$\overline{NU_D} = 0.0265 Re_D^{\frac{4}{5}} Pr^{0.3}$$

$$\overline{h} = \frac{\overline{NU_D} k_f}{D}$$

$$UA = \left[\frac{1}{\overline{h_c} A_c} + \frac{\ln(\frac{D_{1,o}}{D_{1,i}})}{2\pi k_s L} + \frac{1}{\overline{h_h} A_h} \right]^{-1}$$

$$C_h = \dot{m}_h c_{p,h}$$

$$C_c = \dot{m}_c c_{p,c}$$

$$C_r = \frac{C_{min}}{C_{max}}$$

$$NTU = \frac{UA}{C_{min}}$$

$$\epsilon = \frac{1 - exp(-NTU(1 - C_r))}{1 - C_r exp(-NTU(1 - C_r))}$$

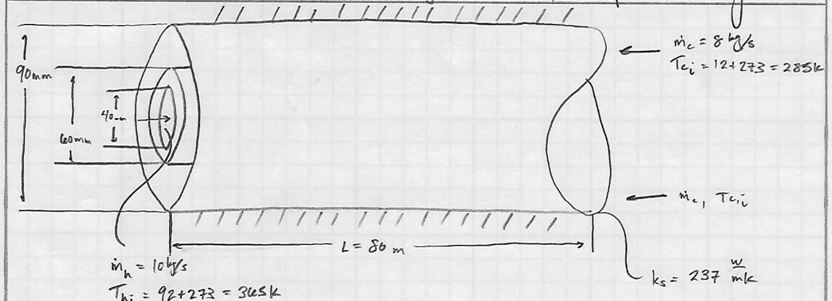
$$q = \epsilon C_{min}(T_{h,i} - T_{c,i})$$

$$T_{c,o} = \frac{q}{C_c} + T_{c,i}$$

$$T_{h,o} = \frac{-q}{C_h} + T_{h,i}$$

6.2 Hand Calculations: Part b

Part b ME 573 Project Stephanie Farney



Hot

$\rho_h = 963.39\,kg/m^3$, $c_{p_h} = 4209 \frac{J}{kgK}$, $\mu_h = 306 \times 10^{-6} \frac{Ns}{m}$
$k_{f_h} = 0.677 \frac{W}{mK}$, $Pr = 1.91$

$Re_{D_h} = \frac{4\dot m}{\pi \mu D_h} = \frac{4(10\frac{kg}{s})}{\pi(306\times10^{-6}\frac{Ns}{m})(0.04m)} = 1,040,228.386$

$\overline{Nu}_{D_h} = 0.0265\, Re_{D_h}^{4/5} Pr^{0.3} = 0.0265(1,040,228.386)^{4/5} * (1.91)^{0.3} = 2095.361$

$\bar h_h = \frac{\overline{Nu}_{D_h} k_{f_h}}{D_h} = \frac{(2095.361)(0.677\frac{W}{mK})}{0.04m} = 35463.98 \frac{W}{m^2K}$

Cold

$\rho_c = 1000\,kg/m^3$, $c_{p_c} = 4189 \frac{J}{kgK}$, $\mu_c = 1225 \times 10^{-6} \frac{Ns}{m}$, $k_{f_c} = 0.59 \frac{W}{mK}$
$Pr = 8.81$

$D_{c_h} = D_o - D_i = 0.09 - 0.06m = 0.03m$

$Re_{D_c} = \frac{4(\dot m)}{\pi \mu D_h} = \frac{4(8\,kg/s)}{\pi(1225\times10^{-6}\frac{Ns}{m})(0.03m)} = 277,167.792$

$\overline{Nu}_{D_c} = 0.0243\, Re_{D_c}^{4/5} Pr^{0.4} = 0.0243(277,167.792)^{4/5}(8.81)^{0.4} = 1311.568$

$\bar h_c = \frac{\overline{Nu}_{D_h} k_{f_c}}{D_{c_h}} = \frac{(1311.568)(0.59\frac{W}{mK})}{0.03m} = 25,794.173 \frac{W}{m^2K}$

$UA = \left[\frac{1}{h_c A_c} + \frac{\ln(D_o/D_i)}{2\pi k_s L} + \frac{1}{h_h A_h}\right]^{-1} = \left[\frac{1}{(35,463.98\frac{W}{m^2K})(\pi)(0.06m)(80m)} + \frac{\ln\left(\frac{0.06}{0.04}\right)}{2\pi(237\frac{W}{mK})(80m)} + \frac{1}{(25,794.173\frac{W}{m^2K})(\pi)(0.04m)(80m)}\right]^{-1}$

$UA = 109,530.75 \frac{W}{m^2K}$

Hot

$C_h = \dot m_h c_{p_h} = (10\,kg/s)(4209\frac{J}{kgK}) = 42090 \frac{W}{K}$

Cold

$C_c = \dot m_c c_{p_c} = (8\frac{kg}{s})(4189\frac{J}{kgK}) = 33512 \frac{W}{K} \leftarrow C_{min}$

$C_r = C_{min}/C_{max} = 33512\frac{W}{K} / 42090\frac{W}{K} = 0.7962$

$NTU = \frac{UA}{C_{min}} = \frac{109,530.75\frac{W}{m^2K}}{33512\frac{W}{K}} = 3.268$

$\varepsilon = \frac{1-\exp[-NTU(1-C_r)]}{1-C_r\exp[-NTU(1-C_r)]} = \frac{1-\exp[-3.268(1-0.7962)]}{1-3.268\,C_{exp}[-3.268(1-0.7962)]} = 0.83$

$q = \varepsilon C_{min}(T_{h_i} - T_{c_i}) = 0.83(33512\frac{W}{K})(92-12\,K) = 2225196.8\,W$

$T_{c_o} = \frac{q}{C_c} + T_{c_i} = \frac{2225196.8W}{33512\,W/K} + 12°C = \boxed{78.4°C}$

$T_{h_o} = -\frac{q}{C_h} + T_{h_i} = \frac{-2225196.8W}{42090\frac{W}{K}} + 92°C = \boxed{39.1°C}$

Figure 3: Part b Hand Calculations

6.3 Hand Calculations: Part d

Part D

Cold Water

$\dot{m}_c = 4.0\,kg/s$

$T_{c,i} = 12^\circ C = 285\,K$

$A_c = 7.54\,m^2$

320 K:

$\rho_c = 989.12\,kg/m^3$

$c_{p_c} = 4180\,J/kg\,K$

$\mu_c = 577\times10^{-6}\,Ns/m^2$

$k_c = 640\times10^{-3}\,W/m\,K$

$Pr_c = 3.77$

$D_c = 0.09m - 0.06m = 0.03m$

$Re_{D,c} = \frac{4\dot{m}}{\mu\pi D}$

$= \frac{4\cdot 4.0\,kg/s}{577\times10^{-6}\,Ns/m^2\cdot\pi\cdot 0.03m}$

$= 294221 \Leftarrow$ Turbulent

Pipe

$k_p = 237\,W/m\,K$

$D_i = 0.04m$

$D_o = 0.06m$

$L = 40m$

Hot Water

$\dot{m}_h = 5.0\,kg/s$

$T_{h,i} = 92^\circ C = 365\,K$

$A_H = 5.03\,m^2$

335 K:

$\rho_h = 982.32\,kg/m^3$

$c_{p_h} = 4186\,J/kg\,K$

$\mu_h = 453\times10^{-6}\,Ns/m^2$

$k_h = 656\times10^{-3}\,W/m\,K$

$Pr_h = 2.88$

$D_H = 0.04m$

$Re_{D,c} = \frac{4\dot{m}}{\mu\pi D}$

$= \frac{4\cdot 5.0\,kg/s}{453\times10^{-6}\,Ns/m^2\cdot\pi\cdot 0.04m}$

$= 351335 \Leftarrow$ Turbulent

Turbulent, Fully Developed, $0.6 \le Pr \le 160$, $Re_D \ge 10000$, $\frac{L}{D} \ge 10$; for both

$Nu_{D,c} = 0.023\,Re_D^{4/5}\,Pr^{0.4}$

$= 0.023\,(294221)^{4/5}\,(3.77)^{0.4}$

$= 927.26$

$h_c = \frac{Nu_{D,c}\cdot k_c}{D_c} = \frac{927.26\cdot 640\times10^{-3}\,W/m\,K}{0.03\,m}$

$= 19781.6\,W/m^2K$

$C_c = \dot{m}_c c_{p_c} = 4.0\,kg/s\cdot 4180\,J/kg\,K$

$= 16720\,W/K \Leftarrow C_{min}$

$Nu_{D,H} = 0.023\,Re_D^{4/5}\,Pr^{0.3}$

$= 0.023\,(351335)^{4/5}\,(2.88)^{0.3}$

$= 863.22$

$h_h = \frac{Nu_{D,h}\cdot k_h}{D_h} = \frac{863.22\cdot 656\times10^{-3}\,W/m\,K}{0.04m}$

$= 14156.8\,W/m^2K$

$C_h = \dot{m}_h c_{p_h} = 5.0\,kg/s\cdot 4186\,J/kg\,K$

$= 20930\,W/K \Leftarrow C_{max}$

$$R_T = \frac{1}{h_c A_c} + \frac{\ln\left(\frac{D_o}{D_i}\right)}{2\pi k_p L} + \frac{1}{h_h A_h}$$

$$= \frac{1}{19781.6\,W/m^2k\cdot 7.54m^2} + \frac{\ln\left(\frac{0.06m}{0.04m}\right)}{2\pi(237\,W/mk)(40m)} + \frac{1}{14156.8\,W/m^2k\cdot 5.03m^2} = 8.743\times10^{-5}\,K/W$$

Figure 4: Part d Hand Calculations (pg. 1)

Part D

$$UA = \frac{1}{R_T} = \frac{1}{8.793\times10^{-5}\ \text{K/W}} = 11372.5\ \text{W/K}$$

$$NTU = \frac{UA}{C_{min}} = \frac{11372.5\ \text{W/K}}{16720\ \text{W/K}} = 0.680$$

$$C_r = \frac{C_{min}}{C_{max}} = \frac{16720\ \text{W/K}}{20930\ \text{W/K}} = 0.799$$

Counterflow

$$\varepsilon = \frac{1-e^{-NTU(1-C_r)}}{1-C_r\cdot e^{-NTU(1-C_r)}} = \frac{1-e^{-0.680(1-0.799)}}{1-0.799\,e^{-0.680(1-0.799)}} = 0.422$$

$$q_{max} = C_{min}(T_{h,i}-T_{c,i}) = 16720\ \text{W/K}\,(92°C-12°C) = 1337600\ \text{W}$$

$$q = \varepsilon\, q_{max} = 0.422\cdot 1337600\ \text{W} = 5.639\times10^{5}\ \text{W}$$

$$T_{c,o} = \frac{q}{C_c} + T_{c,i} = \frac{5.639\times10^{5}\ \text{W}}{16720\ \text{W/K}} + 12°C = 45.7\ °C$$

$$T_{H,o} = T_{h,i} - \frac{q}{C_h} = 92°C - \frac{5.639\times10^{5}\ \text{W}}{20930\ \text{W/K}} = 65.1\ °C$$

$$\boxed{T_{c,o} = 45.7\ °C \qquad T_{H,o} = 65.1\ °C}$$

↑ 318.7 K (320 K vs. 301.9 K AVG)

↑ 338.1 K (335 K vs. 351.6 K AVG)

Figure 5: Part d Hand Calculations (pg. 2)

6.4 VBA Code

```
Attribute VB_Name = "Module1"
Option Explicit
Sub iterate()
Dim Tc As Double
Dim Th As Double
Dim Thnew As Double
Dim Tcnew As Double
Range("G23").Value = Range("G18").Value + 273
Range("K23").Value = Range("K18").Value + 273
Th = Range("G17").Value
Tc = Range("K17").Value

'Range("G49").Value = ((Th - Thold) / Th) * 100
'Range("K49").Value = ((Tc - Tcold) / Tc) * 100
Call pt_b(0, (Th + Range("G16").Value) / 2)
Call pt_b(1, (Tc + Range("K16").Value) / 2)
Worksheets("pt_b").Calculate
Range("G17").Value = Range("G48").Value
Range("K17").Value = Range("K48").Value
Range("G49").Value = ((Range("G48").Value - Th) / Range("G48").Value) * 100
Range("K49").Value = ((Range("K48").Value - Tc) / Range("K48").Value) * 100
'Range("K49").Value = ((Tcnew - Tc) / Tcnew) * 100
'Call pt_b(1, Tc)

'k18
End
End Sub

Public Function GetTemp() As Integer

Dim flag As Boolean
flag = False
While flag = False
Dim temp_C As Variant
temp_C = InputBox("Enter a Temperature in Celsius between 10 and 100,
enter 999 to exit", "Water Properties")

If (temp_C <= 100) And (temp_C >= 10) Then
```

```
    flag = True
    GetTemp = CDbl(temp_C)
ElseIf temp_C = 999 Then
    flag = True
    End
Else
    MsgBox ("Out of Range Value")
End If
Wend
End Function
Public Function GetProperties(temp_C) As Double()
Dim ws As Worksheet
Set ws = ActiveSheet
Dim vals(1 To 7) As Double
Worksheets("Water Properties").Activate
Cells(8, 3).Value = temp_C
Worksheets("Water Properties").Calculate

Dim i As Integer
i = 1
While i <= 7
    vals(i) = Cells(i + 12, 3).Value
    i = i + 1
Wend

GetProperties = vals()
ws.Activate
End Function
Public Function innerOuter_selection() As Integer
Dim selection As Variant
Dim flag As Boolean
flag = False
While flag = False

selection = InputBox("Enter 0 if inner tube, 1 for outer tube, 999 to exit", "User
Selection")

If selection = 0 Or selection = 1 Then
    flag = True
```

```
    innerOuter_selection = CInt(selection)
ElseIf selection = 999 Then
    flag = True
    End
Else
    MsgBox ("You entered an invalid Response")
End If
Wend
End Function
Sub pt_b(selection As Integer, temp_C As Double)
Dim offset As Integer
Dim vals As Variant


If selection = 0 Then
    offset = 7
ElseIf selection = 1 Then
    offset = 11
End If

'temp_C = GetTemp()
vals = GetProperties(temp_C)

Dim i As Integer
i = 1
While i <= 7
    Cells(i + 22, offset).Value = vals(i)
    i = i + 1
Wend

End Sub
```