NC STATE UNIVERSITY

Mechanical Engineering Systems
BSE At Havelock

(MES-400 Engineering Lab)

Heat Exchanger Analysis

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I have neither given nor received any unauthorized assistance on this report.

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Abstract

In this experiment the heat transfer for a tube in tube heat exchanger was evaluated. In this application the hot fluid flows on the inside tube while the cold fluid flows through the annular region between two tubes. Temperatures were measured from the tube in tube heat exchanger. The mass flow rate was calculated by running the water and measuring the time it took until 10 seconds were reached. This was done for both high and low flows. Water was used for the heated fluid and cooled fluid. The thermocouples were preset in the heat exchanger, there were 5 thermocouples for the hot and cold fluid, 10 total. The temperature measurements were taken at all the thermocouples as the hot fluid and cold fluid flowed counter and concurrent to each other at 25,35, and 45 percent of the flow rate and was repeated as the cold fluid mass flow increased. The overall heat transfer coefficient was plotted against the changing Reynolds number for the hot fluid. It was found that the heat transfer efficiency and the temperature efficiency are both increased as the cooling fluid flows counter to the hot fluid.

Introduction

Objective

The objective of this experiment is to compare the concurrent and counter flows in the heat exchanger. And to determine the heat transfer characteristics of the heat exchanger.

Background

In this experiment the tube in tube heat exchanger was used to observe the heat transfer characteristics of the hot and cold fluid as they flow concurrent and counter to each other.

Relevant Theory

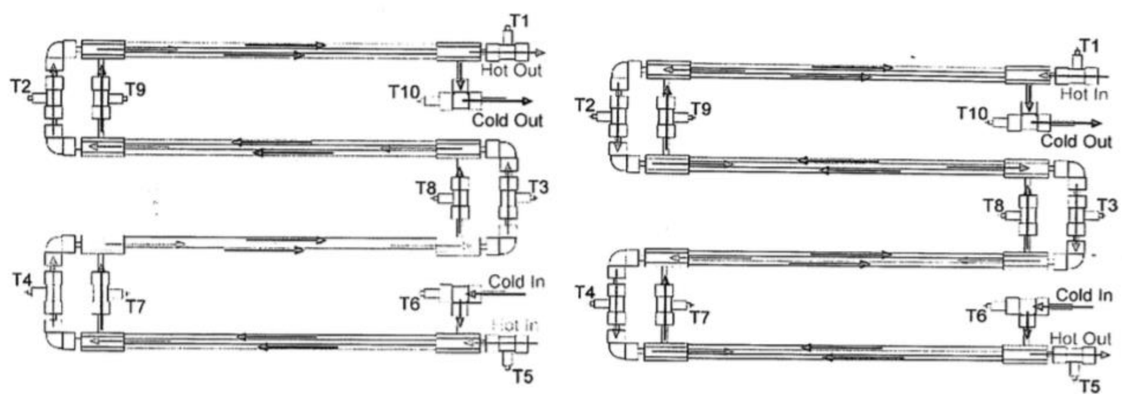


Figure 1: Concurrent Flow and Counter Flow [1]

In this experiment the heat exchanger was used in the two arrangements shown in figure 1. The thermocouples are fixed at various locations and there are 5 thermocouples each for the hot and cold fluid. T1-T5 are the hot fluid thermocouples, T6-T10 are the cold fluid thermocouples. When the fluids are flowing concurrently the cold and hot fluid flow in the same direction, the inlet and outlets are the same. However, for the counter flow, the flow in the opposite direction, the inlet and outlet are switched for the hot fluid. The temperatures are measured by the thermocouples in the heat exchanger.

For this experiment, it must be assumed that the heat exchanger is 100% efficient. And the heat transfer is defined as:

$$Q_{cold} = Q_{hot} \tag{1}$$

$$Q = C_p \dot{m}(T_1 - T_2) \tag{2}$$

Where:

C_p is the specific heat

$\dot{m}$ is the mass flow rate

T_1 is the inlet temperature of the fluid

T_2 is the exit temperature of the fluid

The overall heat transfer coefficient is:

$$U = \frac{Q}{A\Delta T_m} \tag{3}$$

Where:

Q is the heat transfer rate

A is the mean area

ΔT_m is the log mean temperature difference

$$\Delta T_m = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} \tag{4}$$

Where:

ΔT_2 is the temperature difference at side 1

ΔT_1 is the temperature difference at side 2

The heat efficiency is defined as:

$$n_Q = \frac{Q_{avg}}{Q_{max}} * 100 \tag{5}$$

Where:

Q_{avg} is the average heat transfer of the hot and cold fluids

Q_{max} is the max heat transfer

$$n_h = \frac{T_{in\ hot} - T_{out\ hot}}{T_{in\ hot} - T_{T_{in\ cold}}} \tag{6}$$

Methods

1. The cold fluid mass flow was measured by counting the time it took for the water to fill up a container and weighing it on a scale. The average mass flow rate was taken.
2. The heat exchanger was operated and in the initial setup the fluids concurrently flowed against each other.
3. The thermocouple's temperatures were recorded after waiting for the temperatures to reach steady state.
4. This was repeated for the mass flow at 25 percent, 35 percent, and 45 percent.
5. The heat exchanger was set so the fluids move counter to each other, and steps 2-4 were repeated.
6. The cold fluid flow was set to high, and steps 1-5 were repeated.

Results/Discussion

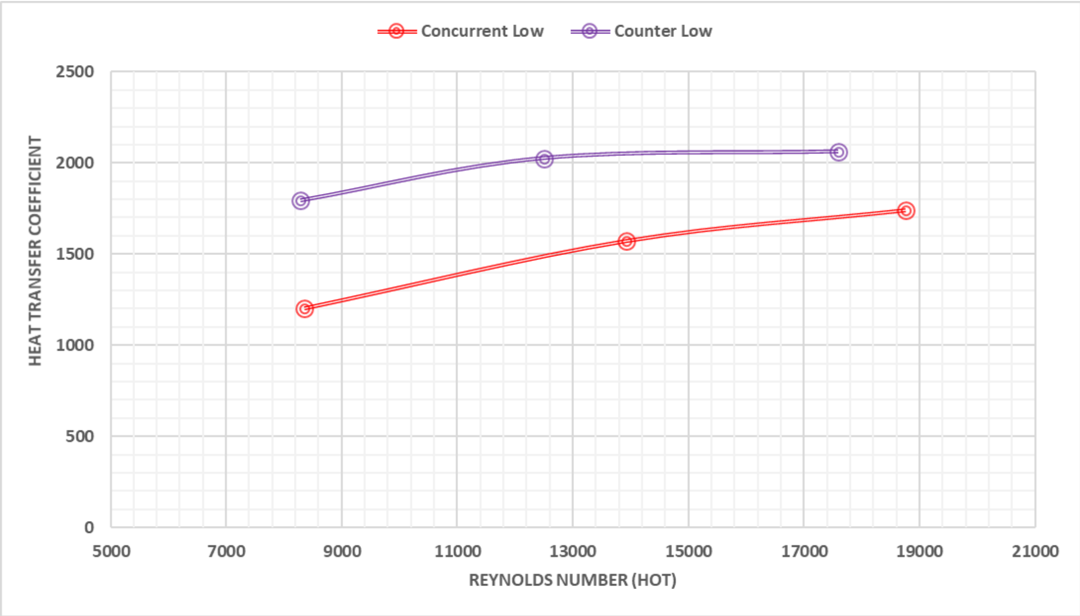


Figure 2: Overall Heat Transfer vs Reynolds Number (Low Flow)

Figure 2 is the overall heat transfer vs Reynolds number for the low flow experiment. The overall heat transfer for the counter flow is greater than the heat transfer when the flows are concurrent. Counter flow is more efficient than concurrent flow because there is a greater uniform temperature difference between the two fluids along the length of the heat exchanger [3].

Table 1: Low Flow Concurrent vs Counter Heat Transfer

Overall Heat Transfer Coefficient (Cold Low)			
	Concurrent	Counter	Percent Difference
25%	1203	1285	7
35%	1572	1748	11
45%	1740	1919	10

Table 1 is the percent difference between the heat transfer values for counter and concurrent flow. The counter heat transfer coefficient is always greater than the concurrent heat transfer and this is due to the reason mentioned above. The percent difference of the two flows should roughly be 10-15 percent [3].

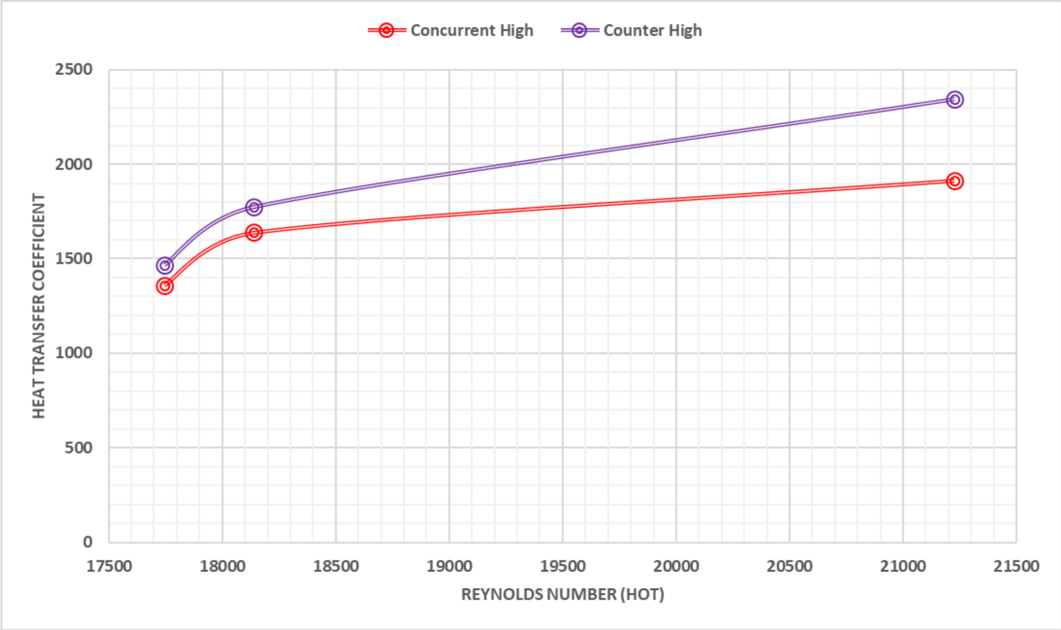


Figure 3: Overall Heat Transfer vs Reynolds Number (High Flow)

Figure 3 is the heat transfer coefficient plotted against the Reynolds number. It can be noted that the last data point for the counter flow is significantly higher than the concurrent flow. This is most likely due to an error in waiting for heat exchanger to reach steady state and the values were not given the proper time to adjust or there was an error in a thermocouple.

Table 2: High Flow Concurrent vs Counter Heat Transfer

Overall Heat Transfer Coefficient (Cold High)			
	Concurrent	Counter	Percent Difference
25%	1360	1467	8
35%	1638	1775	8
45%	1914	2345	20

Table 2 is the overall heat transfer coefficient for when the cold fluid flow is high. The percent differences are on average 15 percent the difference between counter and concurrent flows should be about 10-15 percent [3]. There is a 20 percent difference between the concurrent and counter 45 percent, and this is most likely due to variations in the ambient air since the outside pipes were not insulated and this can prevent heat gain from the ambient air to the cold fluid which affects the overall heat transfer coefficient.

Table 3: Heat Transfer Efficiency

Heat Transfer Efficiency %			
Flow Type	25%	35%	45%
Concurrent Low	105	100	100
Counter Low	100	105	103
Concurrent High	181	181	181
Counter High	119	194	366

Table 3 is the heat transfer efficiency for all the flows separated by flow type. It is noted that the flow is in all cases 100 percent, or above which means that there was heat gained from the environment. The concurrent and counter low flows are stable as the flow percentage changes, but the high flow values are extremely high, and this is because of the errors mentioned before, temperature error, reading error, recording error, equipment error.

Table 4: Temperature Efficiencies

Temperature Efficiencies				
	Efficiency Type	25%	35%	45%
Concurrent Low	Hot Efficiency	39	31	26
	Cold Efficiency	40	49	54
	Mean Efficiency	39	40	40
Counter Low	Hot Efficiency	47	39	31
	Cold Efficiency	44	54	61
	Mean Efficiency	45	47	46
Concurrent High	Hot Efficiency	71	63	59
	Cold Efficiency	24	29	35
	Mean Efficiency	48	46	47
Counter High	Hot Efficiency	45	54	65
	Cold Efficiency	91	154	406
	Mean Efficiency	68	104	235

Table 4 is the temperature efficiencies and mean efficiency. In all cases the mean efficiency is greater in the counter flow compared to concurrent flow. This is also visually confirmed per figure 2 and 3. There are also possible errors in the last mean efficiency for the counter high. This is most likely due to an error in the recording or not allowing enough time for the temperatures to reach steady state.

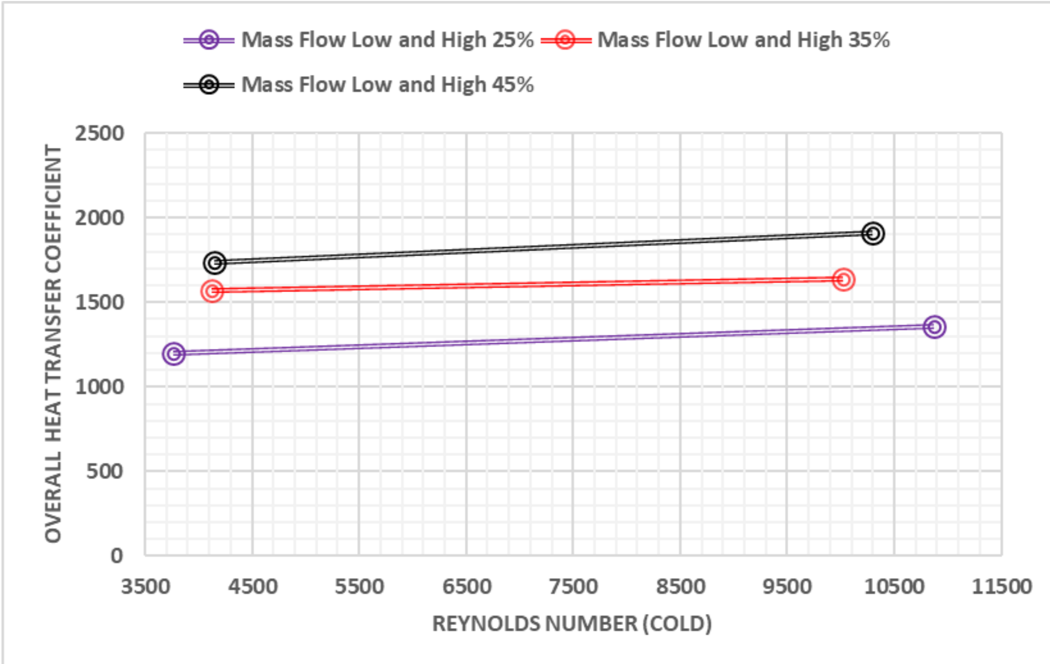


Figure 4: Low and High Cold Mass Concurrent Flow

Figure 4 is the low and high concurrent flow rates as the cold fluid mass flow rate increases. There is a consistent increase in the overall heat transfer coefficient as the flow rate and Reynolds number increases.

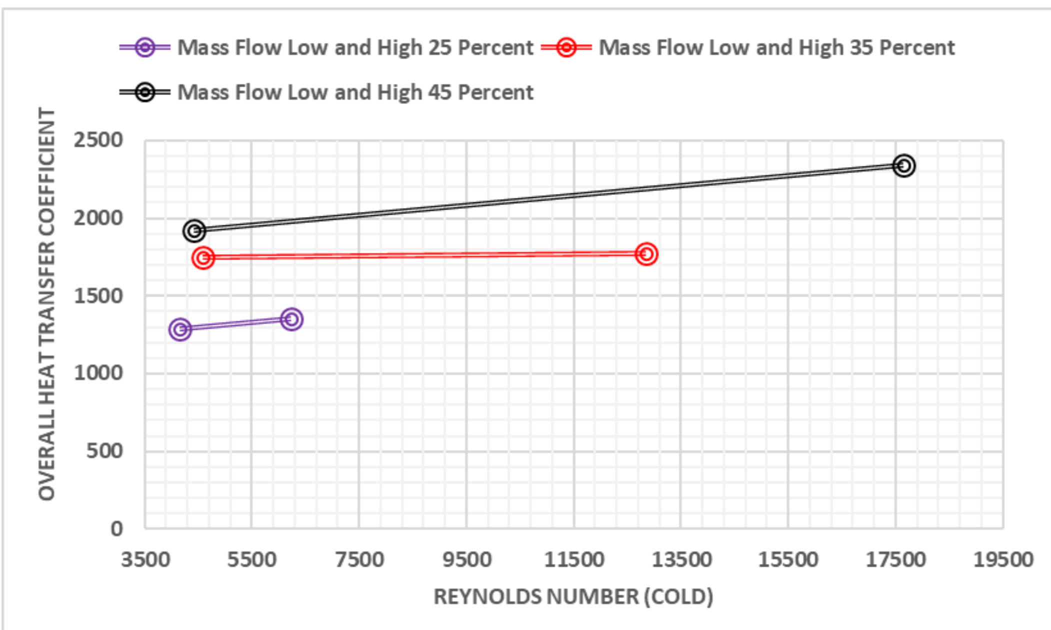


Figure 5: Low and High Cold Mass Counter Flow

Figure 5 is the low and high counter flow rates as the cold fluid flow increases. As in figure 4, there is a consistent increase as the Reynolds number increases. The Reynolds number for the 25 percent high flow has a less difference than the 35 and 45 percent and this is most likely because there is an error in the temperature reading or recording since the mass flow rate and Reynolds numbers are a function of the temperature changes.

Conclusions

The overall heat transfer coefficient was also dependent on the cold fluid mass flow rate. In figure 2 and 3 the changes in the heat coefficient can be observed, as the flow rate of the cold fluid increased, the heat transfer coefficient increased.

Table 1 and 2 is the heat transfer coefficient values for the concurrent and counter flow arrangements. The counter flow consistently has higher heat transfer coefficients than the concurrent flows. The efficiency of the counter flow in table 2 seems too high and this is most likely due to the temperatures not reaching steady state and it is also possible that the thermocouple readings are incorrect. But due to the data in table 1 being correct and the research conducted, it can be concluded that the counter flow transfers heat more efficiently than the concurrent flow.

Running the cooling fluid counter to the hot fluid yields an increased overall heat transfer and temperature efficiency. This is because the heat is distributed more evenly throughout the heat exchanger and the cold fluid also maintains its temperature, so it can cool more because of this [4].

Insulating the outer tubes would have decreased the heat transfer efficiency from the environment to the cold fluid and thus providing more accurate efficiencies from the hot and cold fluids. Overall in most cases the efficiency of the counter and concurrent flows were around 10-15 percent and this does coincide with the research conducted on the difference between the two flows which means that the data was correct with a few errors.

References

1. https://moodlecourses2122.wolfware.ncsu.edu/mod/resource/view.php?id=172948
2. https://moodlecourses2122.wolfware.ncsu.edu/mod/resource/view.php?id=172951
3. https://en.wikibooks.org/wiki/Heat_Transfer/Heat_Exchangers#:~:text=Counter%20flow%20heat%20exchangers%20are,length%20of%20the%20fluid%20path.&text=For%20example%2C%20one%20fluid%20may,passes%2C%20the%20other%204%20passes
4. https://www.anandseamless.com/why-are-counter-flow-heat-exchanger-tubes-more-efficient/

<u>A: Data Collection Sheet With Calculations and Notes</u>

	Concurrent Low					Counter Low			
	Thermocouple	**25%**	**35%**	**45%**		Thermocouple	**25%**	**35%**	**45%**
Hot Out	**1**	29.1	42.2	41.5	Hot In	**1**	53.9	50.5	47.7
	2	43.3	43.3	43		**2**	49	47.1	45.8
	3	46.8	45.8	45		**3**	45.6	45.4	43.9
	4	51.2	48.9	46.8		**4**	42	43	42.1
Hot In	**5**	58	52.5	49	Hot Out	**5**	38	38.6	39.1
Cold In	**6**	19.3	19.4	19.7	Cold In	**6**	19.9	19.8	19.7
	7	25.5	25.8	26		**7**	23.3	23.8	24.3
	8	29.2	29.7	29.8		**8**	26.5	27.5	28.1
	9	31.8	32.6	32.9		**9**	30.1	31.5	32.1
Cold Out	**10**	34.3	35.5	35.5	Cold Out	**10**	34.7	36.5	36.7

Hot Flow	25 Percent				35 Percent				45 Percent	
	Temperature (C)		LMTD	X (m)	Temperature (C)		LMTD	X (m)	Temperature (C)	
Hot Out	1	33.3		2.68	1	42.2		2.68	1	41.5
	3	38.4		1.34	3	45.8		1.34	3	45
	4	43.7		0.67	4	48.9		0.67	4	46.8
Hot In	5	50		0	5	52.5		0	5	49
Cold In	6	19.6		0	6	19.4		0	6	19.7
	7	22.6		0.67	7	25.8		0.67	7	26
	8	24.4		1.34	8	29.7		1.34	8	29.8
	9	25.2		2.01	9	32.6		2.01	9	32.9
Cold Out	10	26.7		2.68	10	25.5		2.68	10	25.5

Counter High										
Hot Flow	25 Percent				35 Percent				45 Percent	
	Temperature (C)			X (m)	Temperature (C)			X (m)	Temperature (C)	
Hot In	1	39		0	1	32.8		0	1	32.3
	2	36.5		0.67	2	34.1		0.67	2	33.3
	3	34.5		1.34	3	36.1		1.34	3	35.1
	4	32.5		2.01	4	40		2.01	4	37.6
Hot Out	5	29.8		2.68	5	43.4		2.68	5	40.1
Cold In	6	19.6		2.68	6	19.6		2.68	6	19.7
	7	21		2.01	7	22.6		2.01	7	22.4
	8	22.3		1.34	8	24.1		1.34	8	24.1
	9	23.8		0.67	9	25.3		0.67	9	25.2
Cold Out	10	26.6		0	10	26.6		0	10	26.8

	25	35	45
Mass Flow hot	0.027	0.045	0.061
mass flow cold	0.02628	0.028789	0.028956
Mass Flow	0.027	0.045	0.061
mass flow cold	0.029007	0.032066	0.030859
Mass Flow	0.033237	0.050169	0.069152
mass flow cold	0.07597	0.069972	0.071918
Mass Flow	0.033237	0.050169	0.069152
mass flow cold	0.043464	0.089696	0.123271
Mass Flow	0.027	0.045	0.061
mass flow cold	0.02628	0.028789	0.028956
Q hot (Watts)	1648.15	1937.894	1912.808
Q cold	1819.153	1952.558	1916.175
Q avg	1733.652	1945.226	1914.491
U hot	1143.271	1565.641	1738.269
u cold	1261.891	1577.488	1741.329
U average	1202.581	1571.565	1739.799
Mass Flow	0.027	0.045	0.061
mass flow cold	0.029007	0.032066	0.030859
Q hot (Watts)	1794.903	2238.926	2193.353
Q cold	1794.898	2025.324	2061.707
Q avg	1794.901	2132.125	2127.53
U hot	1285.386	1835.992	1978.095
u cold	1285.382	1660.832	1859.369
U average	1285.384	1748.412	1918.732
Mass Flow	0.033237	0.050169	0.069152
mass flow cold	0.07597	0.069972	0.071918
Q hot (Watts)	2223.414	2223.414	2255.177
Q cold	848.9381	921.7042	909.5766
Q avg	1536.176	1572.559	1582.377
U hot	1967.984	2316.556	2728.288
u cold	751.4104	960.3156	1100.396
U average	1359.697	1638.436	1914.342
Mass Flow	0.033237	0.050169	0.069152
mass flow cold	0.043464	0.089696	0.123271
Q hot (Watts)	1181.189	2475.121	3556.241
Q cold	788.2997	800.4274	836.8104
Q avg	984.7442	1637.774	2196.526
U hot	1387.004	2682.97	3796.714
u cold	925.6562	867.6433	893.3956
U average	1156.33	1775.306	2345.055

Appendix B: Hand Calculations

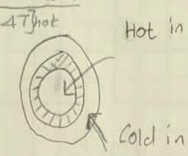
- Find U of heat exchanger & compare actual and theoretical values.
- Find if U is dependent on flow rate and direction
- Find thermal efficiencies of heat exchanger with both flows

Reynolds Number

$Re_i = \frac{\rho V ID}{\mu}$, inner tube $\quad Re_o = \frac{\rho V I D_h}{\mu}$, $D_h = \frac{\pi((ID_{shell})^2 - (OD_{tube})^2)}{\pi(ID_{shell} + OD_{tube})}$

Heat Transfer Efficiency

$Q_{cold} = Q_{hot} \quad Q = [C_p \dot{m} \Delta T]_{cold} = [C_p \dot{m} \Delta T]_{hot} \quad \dot{m}_{hot} = \frac{[C_p \dot{m} \Delta T]_{cold}}{[C_p \Delta T]_{hot}}$



$Q_{max} = min[C_{cold}, C_{hot}](T_{hot\,in} - T_{cold\,in})$

Temperature Efficiency

$\eta_h = \frac{T_{in\,hot} - T_{hot\,out}}{T_{in\,hot} - T_{in\,cold}} \times 100$, $\eta_c = \frac{T_{in\,cold} - T_{out\,cold}}{T_{in\,hot} - T_{in\,cold}} \times 100$

Tube
ID = 0.0083 m
OD = 0.0095 m

Shell
ID = 0.014 m

$$U = \frac{1}{\left(\frac{1}{h_o}\right) + \left((r_o - r_i)/k\right) + \left(\frac{1}{h_i}\right)}$$

25%

Water Properties @ 58°C

$\rho = 1000 \frac{kg}{m^3}$

$\mu = 4.8 \cdot 10^{-4}$ Pa-S

$Re = \frac{\rho v d}{\mu}$, $U = \frac{\dot{m}_{hot}}{\rho A}$ $\quad \dot{m}_{hot} = \frac{[C_p \dot{m} \Delta T]_{cold}}{[C_p \Delta T]_{hot}}$

$Q = UA\Delta T_m \rightarrow U = \frac{Q}{A \Delta T_m}$

$$\dot{m}_{hot} = \frac{4184 \frac{J}{kg\text{-}K} \cdot [34.3 - 19.3]C \cdot 0.029 \frac{kg}{s}}{4184 \frac{J}{kg\text{-}K} \cdot [58 - 29.1]C} = \boxed{0.015 \frac{kg}{s}}$$

$$h = 1.32\left(\frac{\Delta T}{d}\right)^{1/4}$$

$$V = \frac{0.015 \frac{kg}{s}}{1000 \frac{kg}{m^3} \cdot (\pi(0.0083/2)^2)} = \boxed{0.277 \frac{m}{s}}$$

$$h_i = 1.32\left(\frac{58 - 29}{0.0083}\right)^{1/4}$$

$$Re = \frac{1000 \frac{kg}{m^3} \cdot 0.277 \frac{m}{s} \cdot 0.0083\,m}{4.8 \cdot 10^{-4} \frac{kg\text{-}m\text{-}s}{s^2\,m^2}} = \boxed{4789.8}$$

$$U = \frac{1}{\frac{1}{h_i} + \frac{(r_o - r_i)}{k} + \frac{1}{h_2}}$$

Equipment

Equipment used:
HT 36 Heat Exchanger
Thermocouples