Double Pipe Heat Exchanger: Final Report
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Thursday B1

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Nomenclature

Variable	Definition	Units
V_{EG}, V_w	Volumetric flow rates of ethylene glycol and water, respectively	L/min
m_{EG}, m_w	Mass flow rates of ethylene glycol, water	kg/s
m_{steam}	Calculated mass flow rate of steam	kg/hr
T	Temperature	ºC
P_{steam}	Steam pressure	volts/bars
C_p	Specific heat	kJ/kgK
Q_{EG}, Q_w	Heat duties of ethylene glycol, water	kW
Q_L	Heat loss in the cooling section	kW
U	Overall heat transfer coefficient	W/m^2K
A	Heat transfer surface area	m^2
ΔTlm	Log mean temperature difference	K

1.0 Introduction

Heat exchangers are devices used in industrial and commercial contexts for either heating or cooling fluids of interest. These machines typically involve a fluid of low temperature and a fluid of high temperature flowing in a system without direct contact. The temperature difference between the two fluids is the driving force for the heat exchange, which occurs because energy spontaneously flows from higher to lower temperatures. The second law of thermodynamics states that the total entropy of the universe increases for all processes [1]. Entropy, S, is defined as Q/T, where Q is heat emitted and T is temperature of a system. For a spontaneous process, such as heat exchange, there is a positive change in entropy. In a given system where energy is given as heat, a low energy to high energy transfer would result in a negative value for entropy, which violates the second law of thermodynamics and is thus impossible.

There are many different types of designs used for heat exchangers in industry, which are chosen based on cost, maintenance, fluid properties, temperature differences, etc. Shell and tube heat exchangers consist of a larger outer tube flowing a fluid over an array of smaller tubes in which another fluid flows [2]. Plate heat exchangers consist of a series of flat metal plates through which fluids flow through all four corners. The increase in surface area of contact of the fluids leads to a more efficient transfer of heat [3]. The helical coil heat exchanger is a hybrid of the shell and tube and double pipe heat exchangers and is commonly used in processes requiring high pressures due to its compact design [4]. Figure 1 shows illustrations of these three types of heat exchangers.

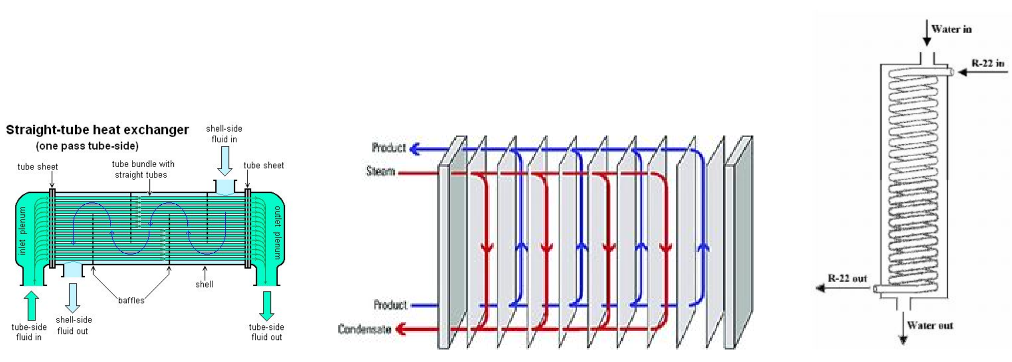


Figure 1. Schematics of a) a shell and tube heat exchanger [5] b) a plate heat exchanger [6] and c) a helical coil heat exchanger [7]

Double pipe exchangers are the simplest type of heat exchanger with a basic design of a "pipe-in-pipe" configuration, with an outer pipe flowing one fluid and the inner pipe flowing another [8]. Figure 2 depicts the general design of double pipe heat exchangers, and Figure 3 shows a 3D model of this piece of equipment.

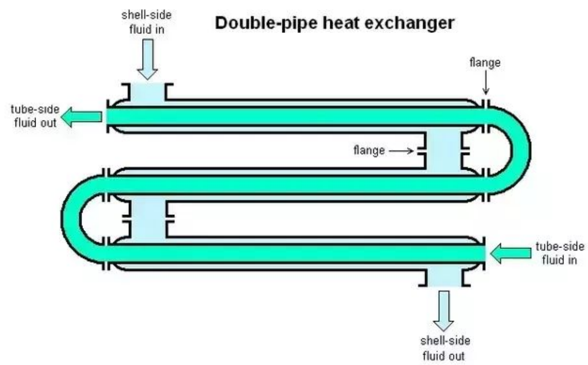


Figure 2. Schematics of a double pipe heat exchanger [9]

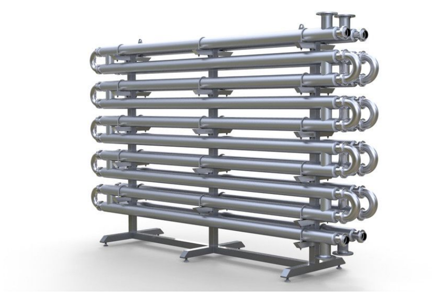


Figure 3. CAD model of a double pipe heat exchanger [10]

The flow arrangement in these devices can either be described as either co-current (parallel) or countercurrent flow. In co-current flow, both the inner and outer fluids enter the system on the same side and exit from another, while countercurrent flow involves the inner and outer fluids entering and exiting the system on opposite sides. Countercurrent flows are considered more efficient because the larger temperature difference between the two fluids creates a greater driving force for heat transfer [10]. Figure 4 illustrates the differences between co-current and countercurrent flows in a double pipe heat exchanger.

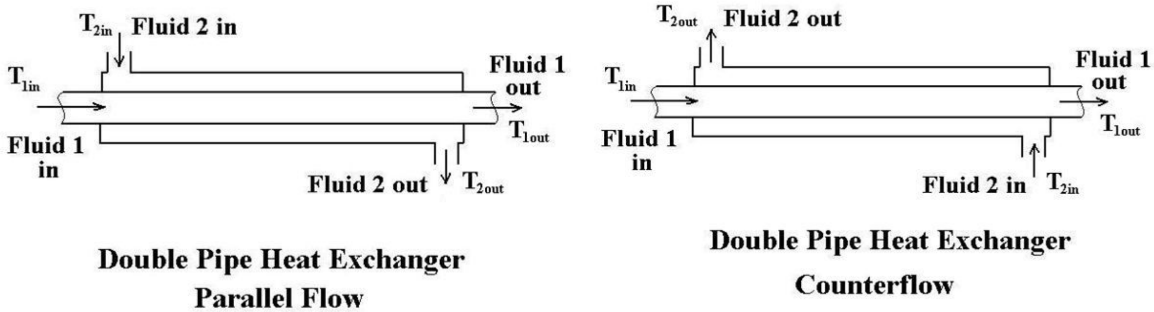


Figure 4. Cross-section of a) co-current and b) countercurrent flow [11]

Heat transfer occurs through the walls of the pipes via convection. In this process, heat is transferred from one fluid to another by the movement of their streams. For a double pipe heat exchanger, the flow of the working fluids over the inner pipe allows heat to diffuse through its surface.

The simple design of the double pipe model makes it an economical option for small scale operations occurring at high temperatures and pressures. These devices are also relatively easy to maintain; however, because they occupy large amounts of space, these heat exchangers can be rather expensive for large scale operations, so other heat exchanger designs are often selected in industry [12]. The double pipe experiment utilizes ethylene glycol (EG) as the inner pipe fluid, and steam and liquid water as the outer pipe fluid in the heating and cooling sections, respectively.

In order to calculate the heat duty of ethylene glycol, the equation used is

$$Q_{EG} = m_{EG} * C_{p,EG} * \Delta T_{EG} \tag{1}$$

where ΔT is the temperature difference of the fluid between the inlet and outlet. Similarly, the heat duty of water is given by the following equation

$$Q_W = m_w * C_{P,W} * \Delta T_W. \tag{2}$$

In the cooling section, the difference between Q_W and Q_{EG} gives the rate of heat loss as

$$\text{Rate of Heat Loss} = |\, Q_W - Q_{EG} \,|. \tag{3}$$

The overall heat transfer coefficient U can be found using

$$U = Q_{EG}/(A*\Delta Tlm) \tag{4}$$

where ΔTlm is the log mean temperature difference between the inlet and outlet of the inner and outer pipes of each section. The equation used to calculate ΔTlm is

$$\Delta Tlm = (\Delta T2 - \Delta T1)/\ln(\Delta T2/\Delta T1) \tag{5}$$

where $\Delta T2$ is the temperature difference between the EG inlet and water outlet, and $\Delta T1$ is the temperature difference between the EG outlet and water inlet.

Finally, to find the mass flow rate of steam in the heating sections, the relationship between Q_w and Q_{EG} is used. Saturated steam enters each heating section, and condenses when it comes in contact with the inner pipe containing cold EG. Therefore, the sum of the heat of condensation of the steam and the heat duty of water after the phase change is equal to the heat duty of EG, assuming the system is adiabatic, meaning no heat escapes the system. In the equation

$$Q_{steam} = m_{steam}\Delta H_{cond} + m_{steam}C_{P,\ H2O(l)}\Delta T_{steam}\ , \tag{6}$$

m_{steam} is the only unknown and can thus be easily solved for.

These calculations were used to accomplish the four technical objectives of this experiment. The objectives were focused on analyzing data that demonstrates the impact of varying the flow rates of the various fluids on the overall system. Technical Objective 1 sought to examine the effect that the tube side EG flow rate had on the steady-state heat duty in each of the three heating sections, to calculate the overall heat transfer coefficient for each heating section, and to estimate the amount of steam used in each heating section for each EG flow rate. Objective 2 examined the effect that the tube side EG flow rate had on the steady-state EG and water heat duties and the rate of heat loss in the cooling section, and aimed to calculate the overall heat transfer coefficient for the cooling section. Objective 3 investigated the effect of shell side water flow rate on the steady-state EG and water heat duties, the rate of heat loss in the cooling section, and the overall heat transfer coefficient for the cooling section. Finally, Objective 4 analyzed the effect that steam pressure had on the steady-state heat duty in each heating section, calculated the overall heat transfer coefficient in each heating section, and estimated the amount of steam used in each heating section.

2.0 Experimental Methodology

2.1 Equipment and Apparatus

Before beginning testing, the condensate release valve, shown in Figure 5, must be opened. Doing so releases steam condensate, which is necessary to prevent build-up from affecting the results.

Figure 5. Steam condensate release valves

The software LabView is used to record, measure, and control the measured properties of the steam, ethylene glycol, and water, and its interface is depicted in Figure 6.

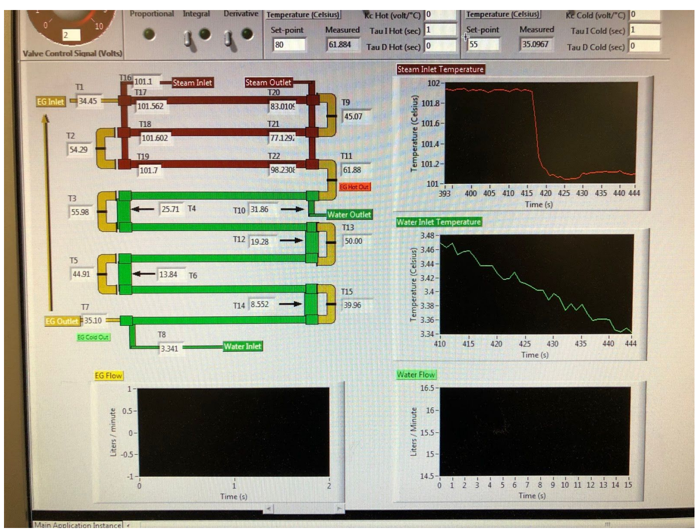


Figure 6. The LabView shows the measured properties of EG and water.

LabView indicates the pipes within the heating section as the top three red pipes. The cooling section is indicated by the bottom five green pipes. In the heating sections, the steam consistently enters from the left and exits on the right. The ethylene glycol in the heating section enters from the top left and exits the bottom right. As a result, the ethylene glycol and steam run co-current to each other in the first and third heating sections, while in the second heating section, the two fluids run countercurrent. Because of the changes in flow direction, each of the three heating sections must be considered as separate systems. In the green cooling section, the ethylene glycol and water run countercurrent in each of the five pipes, so this whole section can be treated as one continuous system.

In LabView, temperatures measured at the yellow bends correspond to the EG temperatures. For the heating section, temperature is measured at the steam inlets and outlets. For the cooling section, water temperature is measured at the water inlet and outlet, as well as at each corner. Temperature measurements are taken at the circled bends using thermocouples, as indicated in Figure 7.

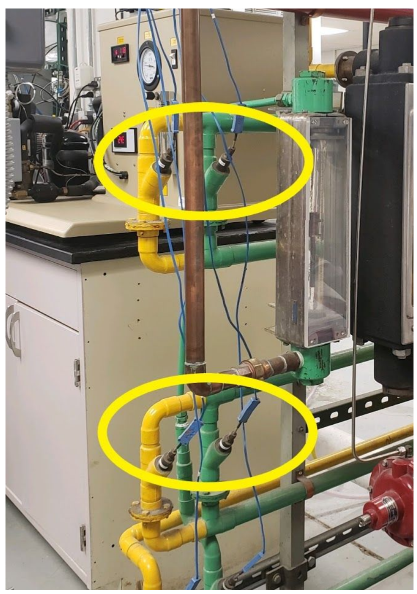


Figure 7. Double pipe HX thermocouples

As shown in Figure 8, the data inputs transmit the measured values for the various temperatures to LabView. The electro-pneumatic transducers are responsible for converting the LabView output voltages into air pressure levels that are used to control fluid flow and steam pressure in response to user input, as shown in Figure 9.

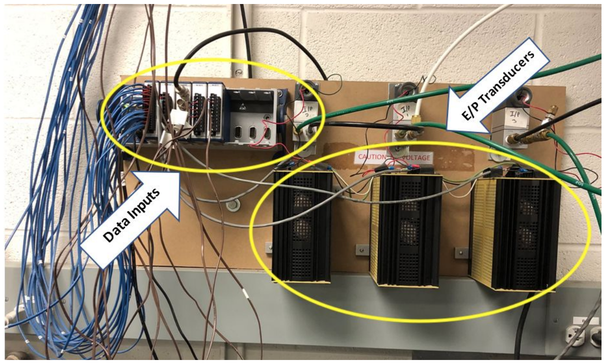


Figure 8. System electro-pneumatic transducers

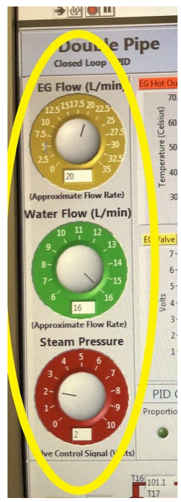


Figure 9. The settings in LabView for the EG flow, water flow, and steam pressure

LabView inputs for EG flow, water flow, and steam pressure change the corresponding traits in the heat exchanger. The user inputs within LabView are sent to the transducers in Figure 8, which then change the pressure within the air actuated valve in Figure 10.

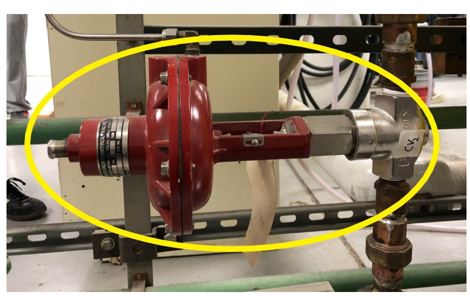


Figure 10. Air actuated valve controlling flow rate of water

The air actuated valve controls both fluid flow rates as well as the steam pressure by correspondingly increasing or decreasing the diameter of the tube contained within. Pneumatics cause the tube inside to change diameter inversely proportional to the pressure applied.

The flow rate of the water is read from the rotameter shown in Figure 11. Since the rotameter does not measure the volumetric flow rate in L/min, the read value must be converted using

$$V_W = 0.269 * R + 0.5231 \quad (7)$$

where R represents the rotameter reading and V_2 represents the volumetric flow rate of water.

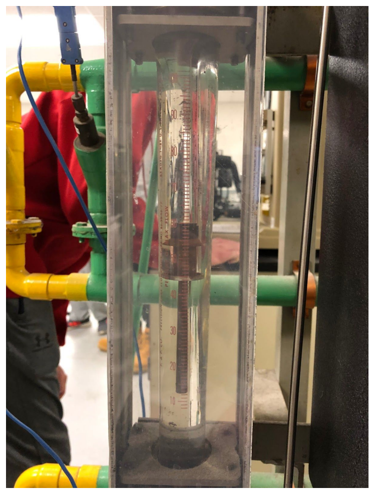


Figure 11. Water rotameter

2.2 Experimental Procedures

At the beginning of each experimental session, the double pipe heat exchanger was prepared by opening the appropriate steam and air supply valves. This was done to remove steam condensate from the system and to supply air to the air actuated valve used to control the various flow rates. It was also ensured that the LabView data-collecting software was running properly. Throughout the experimental sessions, the water flow rate was measured using a rotameter to get a more accurate value of the actual flow rate, and this number was then converted to L/min using Equation 7.

During the first experimental session, the EG and water flow rates were set at 10 L/min and 16 L/min, respectively, and the steam pressure was set at 2 V. The EG stream temperatures in and out of the heating sections were monitored until they reached steady-state, which was identified by the graphs of these temperatures stabilizing to horizontal lines in the LabView program. The same procedure was repeated for EG flow rates of 15, 20, 25, 30, and 35 L/min, while the water flow rate and steam pressure remained constant. Data was collected in LabView and saved as an Excel file.

For the second experimental session, the EG flow rate was set at 30 L/min, and the water flow rate and steam pressure were again set at 16 L/min and 2 V. Then the EG and water stream temperatures in and out of the cooling section were allowed to reach steady-state. The same procedure was then repeated for water flow rates of 14, 12, 10, 8, and 6 L/min, while EG flow rate and steam pressure were held constant.

For the third experimental session, the steam pressure was set at 2 V, and the EG and water flow rates were set at 35 L/min and 16 L/min, respectively. Once the EG temperatures reached steady-state, the steam pressure was changed to 5 V and then 8 V, while the EG and water flow rates remained constant.

3.0 Results

Technical Objective 1 evaluated the effects that varying the tube-side EG flow rate had on each of the three heating sections. The values in Tables 1, 2, and 3 were calculated using data from the first trial on January 31st. Steam pressure was held constant at 2V, and water flow rate at 14.78 L/min. The heat transfer surface area in each heating section was calculated to be $0.2534 m^2$. It can be seen that as the EG flow rate increased in each heating section, so did the EG heat duty, the overall heat transfer coefficient, and the amount of steam used.

Table 1. Steady-state calculations of EG heat duty, overall heat transfer coefficient, and amount of steam used for the first heating section. Specific gravity = 1.04. C_p = 3.45 kJ/kg K.

V_{EG} (L/min)	m_{EG} (kg/s)	ΔT_{EG} = T9-T1 (ºC)	ΔT_{steam} = T16-T20 (ºC)	Q_{EG} (kW)	U (W/m^2K)	m_{steam} (kg/hr)
10	0.17	14.57	5.98	8.71	702.09	13.75
15	0.26	12.19	17.3	10.93	881.11	16.90
20	0.34	10.56	20.06	12.63	1017.72	19.42
25	0.43	9.43	24.16	14.10	1136.03	21.52
30	0.52	8.53	23.36	15.30	1233.12	23.40
35	0.60	7.82	22.99	16.37	1318.90	25.04

Table 2. Steady-state calculations of EG heat duty, overall heat transfer coefficient, and amount of steam used for the second heating section. Specific gravity = 1.064. C_p = 3.48 kJ/kg K.

V_{EG} (L/min)	m_{EG} (kg/s)	ΔT_{EG} = T2-T9 (ºC)	ΔT_{steam} = T16-T21 (ºC)	Q_{EG} (kW)	U (W/m^2K)	m_{steam} (kg/hr)
10	0.17	11.73	10.30	7.24	733.10	11.33
15	0.26	10.13	20.62	9.38	949.65	14.41
20	0.35	9.05	23.67	11.17	1131.21	17.07
25	0.44	8.24	22.16	12.71	1287.45	19.48
30	0.53	7.59	19.24	14.05	1423.07	21.64
35	0.62	7.05	16.48	15.23	1542.13	23.57

Table 3. Steady-state calculations of EG heat duty, overall heat transfer coefficient, and amount of steam used in the third heating section. Specific gravity = 1.055. C_p = 3.52 kJ/kg K.

V_{EG} (L/min)	m_{EG} (kg/s)	ΔT_{EG} = T11-T2 (ºC)	ΔT_{steam} = T16-T22 (ºC)	Q_{EG} (kW)	U (W/m^2K)	m_{steam} (kg/hr)
10	0.17	9.86	3.38	6.10	37.39	9.67
15	0.26	8.59	3.29	7.97	48.86	12.64
20	0.35	7.51	3.00	9.30	56.95	14.75
25	0.44	6.62	3.17	10.24	62.75	16.24
30	0.52	6.00	2.64	11.14	68.25	17.68
35	0.61	5.48	2.63	11.87	72.72	18.84

Objective 2 examined the effect of the EG flow rate on the steady state heat duties for water and EG along with the rate of heat loss in the cooling section. The results in Table 4 were calculated using data from Trial 1. Steam pressure was kept constant at 2V, the volumetric flow rate for water was calculated to be constant at 14.78 L/min, and the mass flow rate of water was calculated to be 0.25 kg/s.

Table 4. Steady-state calculations of EG heat duty, water heat duty, overall heat transfer coefficient, and rate of heat loss. Specific gravity = 1.00. C_p = 4.18 kJ/kg K.

V_{EG} (L/min)	m_{EG} (kg/s)	ΔT_{EG} = T11-T7 (ºC)	ΔT_W = T10-T8 (ºC)	Q_{EG} (kW)	Q_w (kW)	U (W/m^2K)	Heat Loss $\lvert Q_W - Q_{EG} \rvert$ (kW)
10	0.17	34.07	18.81	20.37	19.66	447.61	0.72
15	0.26	31.21	25.11	27.99	26.25	623.61	1.75
20	0.34	26.91	29.23	32.18	30.55	772.43	1.64
25	0.43	24.39	32.30	36.46	33.76	889.80	2.70
30	0.52	22.26	34.60	39.93	36.16	986.77	3.78
35	0.60	20.77	36.60	43.47	38.25	1068.48	5.22

Technical Objective 3 investigated the effect of water flow rate on the steady-state heat duties for water and EG along with the rate of heat loss in the cooling section. The flow rate of EG and steam pressure were kept constant at 30 L/min and 2V respectively, and the contact surface area of the entire cooling section was calculated to be 1.27 m^2. Table 5 contains results calculated from data collected during the second trial on February 28th. In general, the rate of heat loss as well as heat duties of water and EG decreased as water flow rate decreased.

Table 5. Steady-state calculations of heat duty of water and EG, overall heat transfer coefficient, and rate of heat loss. Specific gravity of water: 1.00. $C_{p,W}$= 4.18 kJ/kg K. m_{EG} = 0.52 kg/s.

V_W (L/min)	m_W (kg/s)	ΔT_W T10 - T8	ΔT_{EG} T11-T7	U (W/m^2-K)	Q_W (kW)	Q_{EG} (kW)	Heat loss $\lvert Q_W - Q_{EG}\rvert$ (kW)
14.92	0.25	29.39	19.32	938.12	30.59	34.66	4.07
12.72	0.21	37.08	20.29	980.06	32.91	36.40	3.49
11.99	0.20	40.94	19.47	1058.81	34.26	34.93	0.66
10.22	0.17	43.56	19.24	971.32	31.05	34.52	3.46
8.08	0.13	50.9	17.83	960.69	28.72	31.99	3.27
5.61	0.09	63.91	14.52	961.47	25.01	26.05	1.04

Objective 4 focused on the effect of steam pressure on the steady-state heat duty in each of the three heating sections. The EG flow rate and water flow rates remained constant at 35 L/min and 14.915 L/min, respectively. The heat transfer surface area for each section was calculated as 0.230 m^2. Tables 6, 7, and 8 contain results calculated from data collected during the third trial on April 4th. These results show that as steam pressure increased so did the EG heat duty and steam usage within each section, while the overall heat transfer coefficient decreased.

Table 6. Steady-state calculations of EG heat duty, overall heat transfer coefficient, and amount of steam used for the first heating section. Specific gravity = 1.04. C_p = 3.45 kJ/kg K. m_{EG}=.173 kg/s. m_W=2.77 kg/s.

Steam Pressure (V)	ΔT_{EG} =T9-T1 (C)	ΔT_W = T16-T20	Q_{EG} (kW)	U (W/m^2K)	m_{steam} (kg/hr)
2	7.11	43.60	4.33	571.17	6.39
5	7.54	40.71	4.59	563.38	6.82
8	8.27	40.14	5.04	561.72	7.48

Table 7. Steady-state calculations of EG heat duty, overall heat transfer coefficient, and amount of steam used for the second heating section. Specific gravity = 1.04. C_p = 3.45 kJ/kg K. m_{EG}=.173 kg/s. m_W=2.77 kg/s.

Steam Pressure (V)	ΔT_{EG} =T2-T9 (C)	ΔT_W = T16-T21	Q_{EG} (kW)	U (W/m^2K)	m_{steam} (kg/hr)
2	6.14	44.87	3.74	590.15	5.51
5	6.69	37.36	4.08	537.55	6.08
8	7.23	33.07	4.41	501.29	6.63

Table 8. Steady-state calculations of EG heat duty, overall heat transfer coefficient, and amount of steam used for the third heating section. Specific gravity = 1.04. C_p = 3.45 kJ/kg K. m_{EG}=.173 kg/s. m_W=2.77 kg/s.

Steam Pressure (V)	ΔT_{EG} =T11-T2 (C)	ΔT_W = T16-T22	Q_{EG} (kW)	U (W/m^2K)	m_{steam} (kg/hr)
2	5.78	5.33	3.52	336.27	5.56
5	5.88	2.67	3.58	336.88	5.69
8	6.15	2.68	3.75	339.36	5.98

4.0 Analysis & Discussion

Objective 1

The purpose of Technical Objective 1 was to examine the effect that the tube side EG flow rate had on the steady-state heat duty in each of the three heating sections, to calculate the overall heat transfer coefficient for each heating section, and to estimate the amount of steam used in each heating section for each EG flow rate.

The calculated results presented in Tables 1, 2, and 3 show that as the EG flow rate increased, so did the heat duty of EG in each of the three heating sections. In the first heating section between EG flow rates of 10 L/min and 35 L/min, the calculated value for Q_{EG} increased by almost 88% from 8.71 kW to 16.37 kW. In the second and third heating sections between the same flow rates, Q_{EG} was found to have increased by 110% and 95%, respectively. This trend can be explained logically by considering Equation 1. Within each individual heating section, C_p remained constant while m_{EG} increased and ΔT_{EG} decreased for each flow trial. Since the magnitude by which m_{EG} increased was larger than that by which ΔT_{EG} decreased, Q_{EG} increased for each flow trial. As expected, a similar trend was found in the calculated values for the overall heat transfer coefficient since U is directly proportional to Q_{EG}, as shown in Equation 4. For each heating section, U increased by 88%, 110%, and 95%, respectively, between EG flow rates of 10 and 35 L/min.

As the ethylene glycol flow rate was increased, it was found that the amount of steam used within each heating section also increased. Between EG flow rates of 10 and 35 L/min in the first heating section, the estimated value for m_{steam} increased by 82% from 13.75 kg/hr to 25.04 kg/hr. In the second and third heating sections between the same flow rates, the amount of steam used increased by 108% and 95%, respectively. Referring back to Equation 6 can help explain this trend. Assuming the system is adiabatic, all heat that is lost by the steam is completely absorbed by the ethylene glycol within each heating section. For each successive flow trial, $C_{p,EG}$, $C_{p,H2O(L)}$, and ΔH_{cond} remained constant, while m_{EG} and ΔT_{steam} increased and ΔT_{EG} decreased. Since m_{EG} increased at a faster rate than ΔT_{EG} decreased, m_{steam} also had to increase in order for the expression $Q_{EG} = Q_{steam}$ to remain true.

When comparing the heat duties between the three heating sections, it is evident that as the ethylene glycol traveled through each successive heating section, it absorbed less and less heat from the steam. For example, at an EG flow rate of 15 L/min, Q_{EG} decreased from 10.93kW in Section 1 to 9.38 kW in Section 2 to 7.97 kW in Section 3. This trend can be explained by considering the driving force for heat transfer within the heating sections: the temperature gradient between the tube-side ethylene glycol and the shell-side steam. The temperature of the ethylene glycol increased as it passed from one heating section to the next. Since the inlet steam temperature remained roughly constant, the temperature gradient between the steam and the ethylene glycol became smaller in each successive heating section. This reduction in the driving force for heat transfer resulted in a decrease in Q_{EG} between the individual heating sections at a constant EG flow rate. Figure 12 shows the relationship between Q_{EG} in each heating section and EG flow rate.

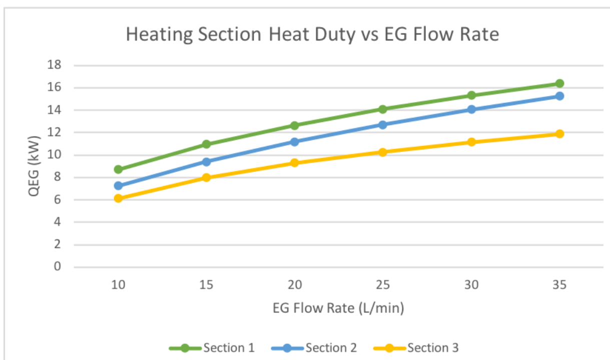


Figure 12. Plot of Q_{EG} vs EG flow rate

When comparing each heating section's overall heat transfer coefficients at a constant flow rate, an unexpected trend is noticeable between Sections 1 and 2: at a constant EG flow rate, the calculated values for U increased. For example, when the EG flow rate was 15 L/min, U increased from 881.11 W/m^{2}K in Section 1 to 949.65 W/m^{2}K in Section 2. At first glance, this seems to be a discrepancy since U is directly proportional to Q_{EG}. If Q_{EG} decreased between Sections 1 and 2, then it seems logical for U to have decreased as well; however, this was not the case. An explanation of this unexpected reality can be given upon further consideration of Equation 4, which shows that U is also inversely proportional to ΔTlm, the log mean temperature difference. Since the heat transfer surface area A remained constant and Q_{EG} decreased, in order for U to increase ΔTlm must have decreased between Sections 1 and 2. Calculations for ΔTlm showed that this was indeed the case: between Sections 1 and 2, the log mean temperature difference decreased from 48.98 K to 38.97 K. A graphical comparison between the overall heat transfer coefficients in Sections 1 and 2 is shown in Figure 13.

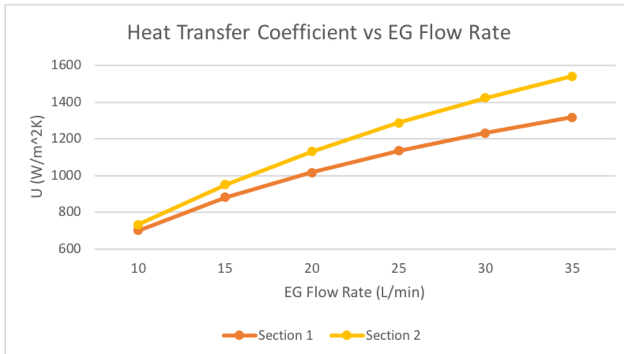


Figure 13. Plot of U vs EG flow rate for Sections 1 and 2

As the ethylene glycol made its way through the heating sections, the calculated results for Objective 1 show that the mass flow rate of steam decreased. For example, at an EG flow rate of 15 L/min between Sections 1 and 2, the amount of steam used decreased by about 15% from 16.90 kg/hr to 14.41 kg/hr. Similarly, at the same EG flow rate between Sections 2 and 3, the amount of steam decreased by 12% to 12.64 kg/hr. This trend can also be explained by the reduction in the temperature gradient between the ethylene glycol and the steam. In Heating Section 1, the incoming ethylene glycol was at a much lower temperature (T1) than the incoming steam (T16), so more steam was needed to transfer a sufficient amount of heat to the ethylene glycol. This heated ethylene glycol then entered Section 2 at a temperature (T9) closer to that of the fresh inlet steam resulting in a smaller temperature gradient and thus a smaller driving force for heat transfer, so less steam was required. The same explanation holds true for Section 3. Figure 14 shows a graphical comparison between the amounts of steam used within each heating section at the varying EG flow rates.

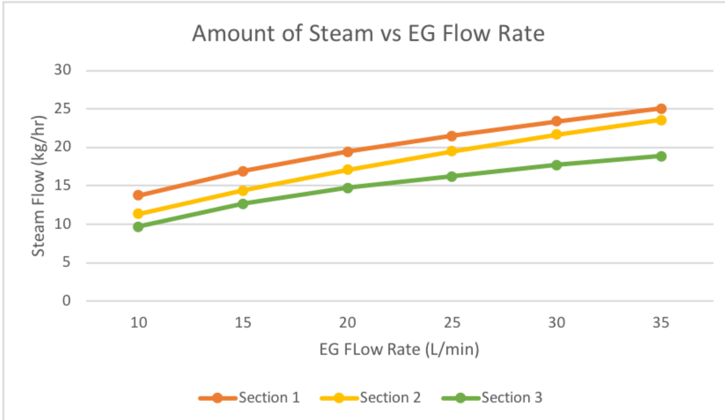


Figure 14. Plot of amount of steam vs EG flow rate

Objective 2

The purpose of Technical Objective 2 was to examine the effect that the tube side EG flow rate had on the steady-state EG and water heat duties and the rate of heat loss in the cooling section, and to calculate the overall heat transfer coefficient for the cooling section.

For Objective 2, it was determined that as the EG flow rate increased from 10 to 35 L/min, both the heat duty of water and EG also increased. Q_W increased by 94.6% from 19.66 kW to 38.25 kW while Q_{EG} increased by 113% from 20.4 kW to 43.5 kW. According to Equations 1 and 2, this was expected due to the dependence of the heat duty on the mass flow rate of the fluids and temperature difference between inlet and outlet fluids, since the heat capacity is constant. For Q_{EG}, ΔT, when converted to Kelvin, did not contribute to any large deviations (large jumps in temperature, negative difference, etc.), thus making the mass flow rate the major contributor to the heat duty. For Q_W, since the mass flow rate of water was relatively constant, the increase in Q_W can be attributed to the increasing temperature difference as m_{EG} increased. This increase in temperature difference between the inlet cooling water and outlet cooling water can be attributed to increasing rates of convection, with more EG being able to be cooled by the water as its mass flow rate increased. When looking at Figure 15, both Q_{EG} and Q_W increased in a largely linear fashion, with an R-squared value of 0.97 and 0.95, respectively.

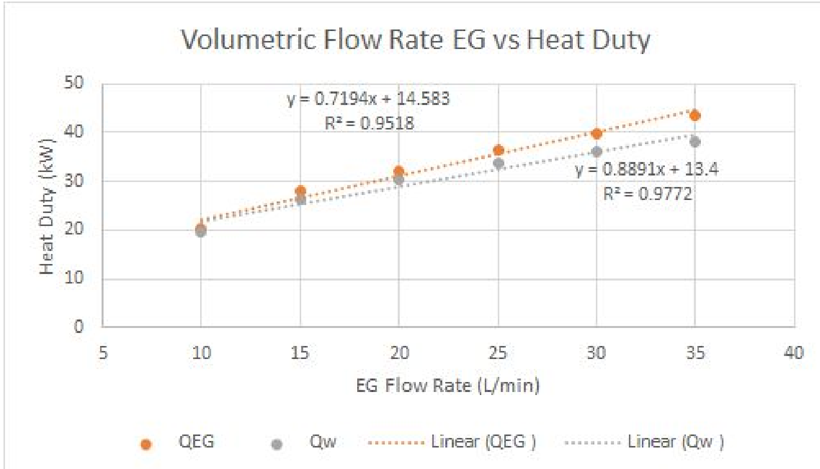


Figure 15. Plot of volumetric flow rate vs. heat duty in the cooling section.

Although Q_{EG} and Q_w both increased as the EG flow rate increased, when comparing the slopes of the linear regression lines, the heat duty for EG increased slightly faster than that of water. This is also due to the mass flow rates of water and EG, as the EG mass flow rate increased while the water mass flow rate remained relatively constant.

It was also determined that as the EG flow rate increased, the rate of heat loss, which was calculated as the absolute difference between Q_W and Q_{EG}, increased due to the increasing difference between the EG and water heat duties. Figure 16 shows this trend between the volumetric flow rate of EG and rate of heat loss.

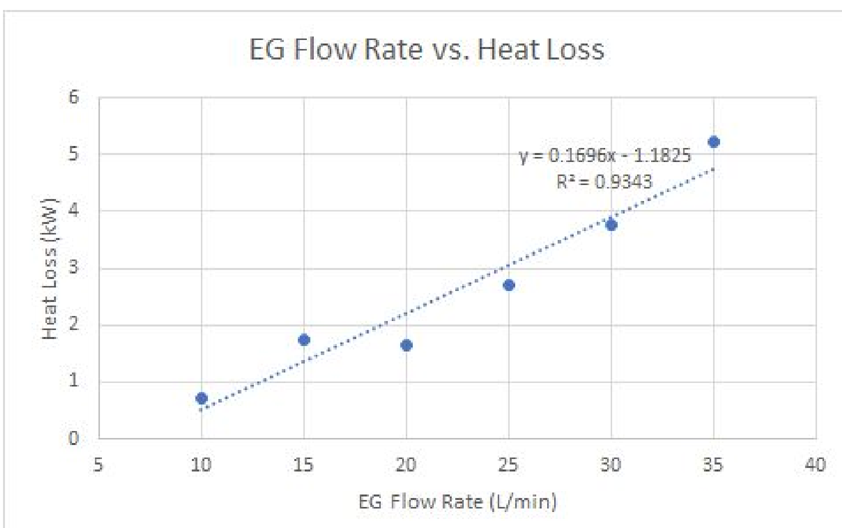
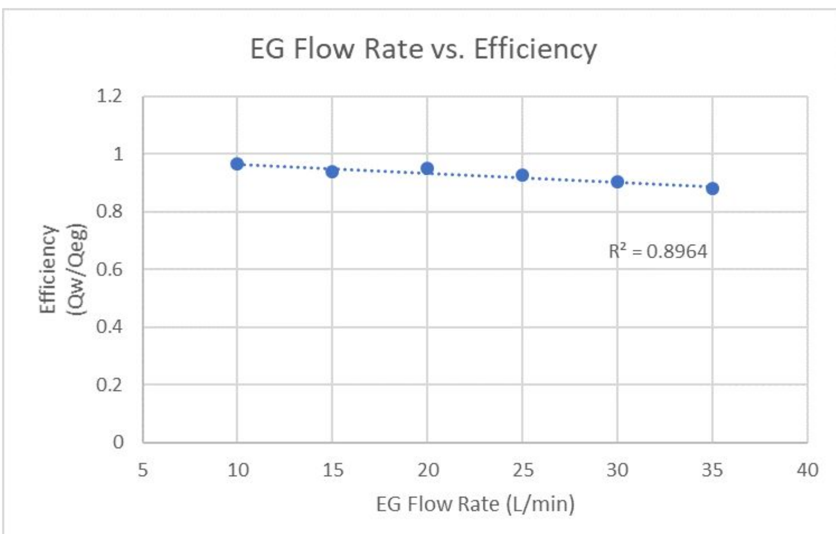


Figure 16. Plot of heat loss vs. EG flow rate in the cooling section.

The rate of heat loss increased 626% from .72 kW to 5.22 kW as V_{EG} increased from 10 to 35 L/min. This increase resulted from the heat duty of water staying relatively constant as the heat duty of EG steadily increased. In theory, if there were a perfectly efficient cooling system, then the heat duty of both water and EG would have been equal. However, in practice, differences arise with heat being lost by the EG to the surroundings. This was especially true due to the lack of insulation on the pipes in the cooling section. A comparison can be made between a perfectly efficient system where $Q_{EG} = Q_W$ and the actual values calculated. Efficiency can be defined as

$$(Q_W/Q_{EG}) * 100 \tag{7}$$

where a perfect system has an efficiency of 100%. According to Figure 17, the efficiency of the cooling system decreases slightly from 96.5% to 88% as V_{EG} increased from 10 to 35 L/min.



V_{EG}	Efficiency
(L/min)	(Qw/Qeg)
10	0.965
15	0.937
20	0.949
25	0.926
30	0.905
35	0.880

Figure 17. Plot of EG volumetric flow rate vs efficiency in the cooling section.

This outcome leads to the conclusion that the increase in heat loss means that the cooling system becomes less efficient and its performance decreases as the mass flow rate of EG increases. Also, since the cooling section utilizes countercurrent flow, the system is the more efficient option compared to a theoretical cocurrent flow system.

Lastly, as the EG flow rate increased, the overall heat transfer coefficient increased. U increased from 447.61 W/m^2 K to 1068.48 W/m^{2}K as the V_{EG} increased from 10 to 35 L/min, resulting in a 139% increase. According to Equation 4, this is expected to occur due to the proportionality of U to Q_{EG}. Theoretically, this can be explained by the overall heat transfer coefficient, which describes how well heat is conducted through the pipe wall. A higher U means that more heat is being transferred through the pipe given an amount of temperature difference. Since an increasing Q_{EG} is dependent on an increase in the heat transferred through the pipe wall and an increase in m_{EG} correlates with an increase in the rate of convection, the overall heat transfer coefficient is expected to increase.

Objective 3

The purpose of Technical Objective 3 was to investigate the effect of shell-side water flow rate on the steady-state EG and water heat duties, the rate of heat loss in the cooling section, and the overall heat transfer coefficient for the cooling section.

The results in Table 5 indicate that both the heat duties of water and ethylene glycol generally decreased as the water flow rate decreased in the cooling section. Inversely, the temperature change of water (ΔT_W) was smallest for a water flow rate of 14.92 L/min but increased significantly by 34.5 ºC when the flow rate was decreased to 5.61 L/min. In the cooling section, the ΔT_W occurs as the cold water absorbs heat from the hot EG. For this objective, the flow rate of EG was constant. The results show that the slower the water flowed over the surface of the EG pipe, the less heat it absorbed. However, the ΔT_W was smallest at 29.39 ºC for Trial 1 and greatest at 63.91ºC for Trial 6, which seems to contradict the trend. This can be explained by Equation 2. Heat duty depends on the temperature change and mass flow rate for a species with constant heat capacity. In this case, the heat transfer occurs through convection, as water carries heat away from the EG. Therefore, a higher volumetric flow rate should allow a greater number of water molecules to travel over the EG pipe and thus remove more heat. It can be seen in Table 5 that Q_W decreased by 5.58 kW when the flow rate decreased by 9.31 L/min despite the large temperature change. Similarly, Q_{EG} decreased by 8.61 kW between the first and last trials because the slower-traveling water absorbed less heat from the EG, which again flowed at a constant rate between trials. The trend of heat duty versus water flow rate is displayed in Figure 18.

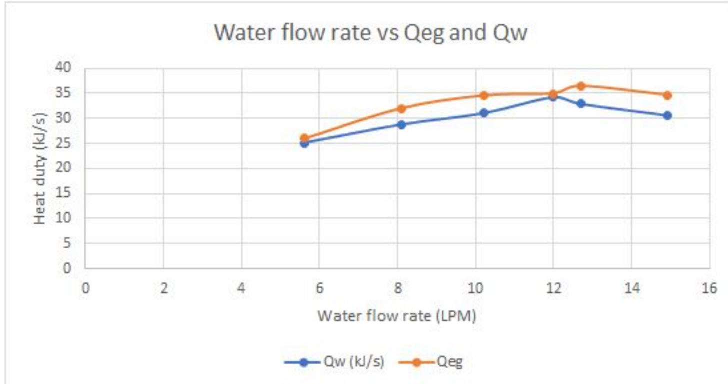


Figure 18. Plot of water flow rate vs heat duty of EG and water in the cooling section

Despite the heat duty of water and EG following the same general trend, Q_{EG} was greater than Q_w in every trial. The difference between these values represents the heat loss in the cooling section. The average was calculated as 2.67 kW for all six trials. This loss is a result of the exposed lengths of yellow EG piping in the cooling section visible in Figure 11. In the green sections also pictured in Figure 11, cooled water flows over the surface of the yellow pipe containing the heated EG, and heat is transferred from the EG to the water. If the entire cooling section was insulated, the heat duty of water and EG would be equal since water would absorb all the heat lost by the EG. Instead, Q_{EG} is greater than Q_W because, in the yellow sections, the EG releases heat to the surroundings which the water does not capture. As mentioned, the water captured more heat from the EG when the flow rate was higher. Therefore, if water were hypothetically surrounding the exposed sections, it could absorb more heat from the EG at a higher velocity. This is indicated in Table 5 by the generally decreasing heat loss as water flow rate decreased. The outlying data point that correlates to a water flow rate of about 11.99 L/min, however, resulted in an unexpectedly low heat loss. One possibility for this odd data point could be that the trial was ended early and therefore the temperatures did not stabilize. This could result in a low ΔT_{EG}, leading to a low Q_{EG}, which ultimately would cause the quantity Q_{EG} - Q_W to be a very small value. For a high flow rate of 14.92 L/min, the heat loss was 4.07 kW, but at 5.61 L/min, only 1.04 kW was lost. The plot of water flow rate versus heat lost is shown in Figure 19.

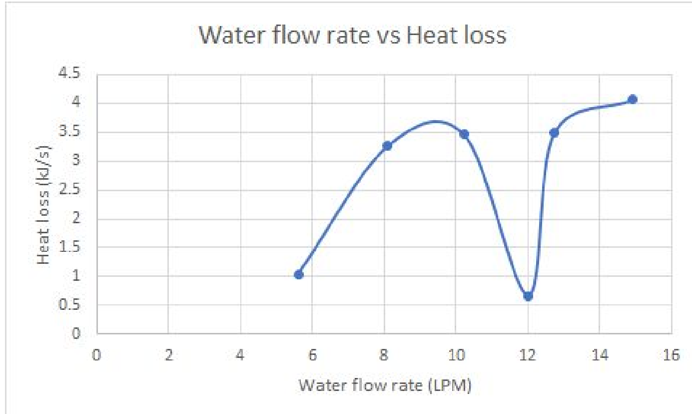


Figure 19. Plot of water flow versus rate of heat loss in the cooling section

The heat transfer coefficient, U, represents the efficiency of rate of heat transfer from one fluid to another through a surface, in this case the EG pipe. Since the heat loss generally increased with increasing flow rate, the U value decreased by about 23 W/m^{2}K or approximately 2.5%. This slight decrease in U indicates the efficiency of the heat exchanger increased with decreasing flow rate, as shown in Figure 20. The trend agrees with the earlier discussion. At a higher water flow rate the EG loses more heat in the exposed parts of the cooling section, meaning that a higher flow rate corresponds to a less efficient process and thus a lower U value. The outlying data point corresponds to the large heat loss for a flow rate of 11.99 L/min. As mentioned earlier, this error was likely because the heat exchanger was not allowed to reach steady-state.

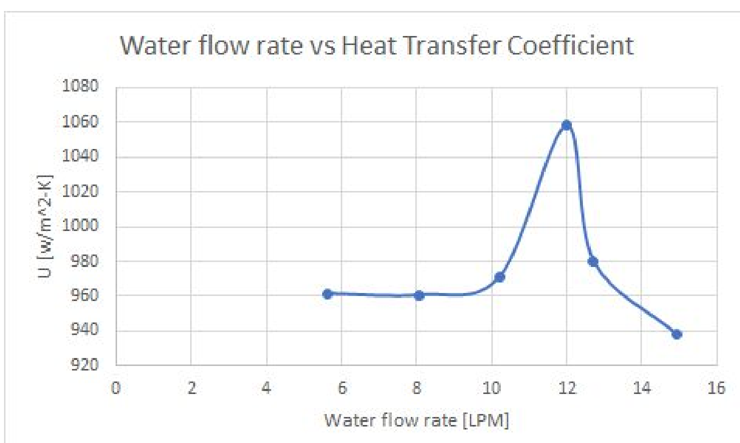


Figure 20. Plot of V_w vs overall heat transfer coefficient in the cooling section

Objective 4

The purpose of Technical Objective 4 was to evaluate the effect of steam pressure on the EG heat duty, the amount of steam used, and the overall heat transfer coefficient in each of the three heating sections. The results in Tables 6, 7, and 8 show an increase in steam usage and an increase in heat duty of EG as steam pressure increased, while the overall heat transfer coefficient decreased. Between steam pressures of 2V and 8V there was a 16% increase in Q_{EG} in the first heating section, a 17% increase in Q_{EG} for the second heating section, and a 6% increase for the third heating section. The trend is represented in Figure 21.

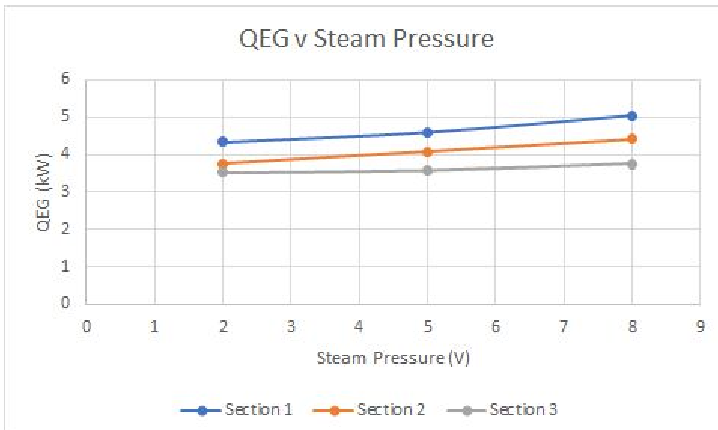


Figure 21. Q_{EG} vs steam pressure

Equation 1 explains this trend. The mass flow rate of EG and Cp_{EG} were kept constant, but the ΔT_{EG} changed. The ΔT_{EG} value for all three heating sections was positive which means the temperature of EG increased with increasing steam pressure. For heating section 1, ΔT_{EG} was 1.16℃ which accompanied a steam pressure increase from 2V to 8V. The heat duty of EG is directly proportional to the change in EG temperature. ΔT_{EG} is positive since cold EG enters the pipes and heat is transferred from the steam surrounding the inner pipe. This heat transfer increased the temperature of the EG and decreased the temperature of the steam. Between heating sections, the Q_{EG} dropped and had a less significant change. The increase in Q_{EG} in heating section 3 was 6% and the ΔT_{EG} only increased by 0.37℃.

Steam usage decreased between sections in the heat exchanger as the pressure was increased. Between heating sections the change in temperature of steam decreased due to the heat from the steam transferred to the EG. The increase in steam pressure caused an increase in steam usage since more steam was required to create a higher pressure in the outer pipe. Figure 22 shows that the steam usage decreased from section 1 to section 3. The driving force for heat transfer between the steam and the EG is the average temperature difference between the two, represented by ΔTlm. As the EG neared the last section, it gained heat from the steam and consequently the ΔTlm decreased between sections. Therefore, less steam was required because as the temperature difference between the two fluids decreased, so did the driving force for heat transfer. Between section 1 and section 2 at 2V there was a 12% decrease, and between section 2 and 3 at 2V the mass usage increased by 0.09%. The steam usage between sections varied by very little. As shown in Figure 22, the difference in steam usage between heating sections was not very significant.

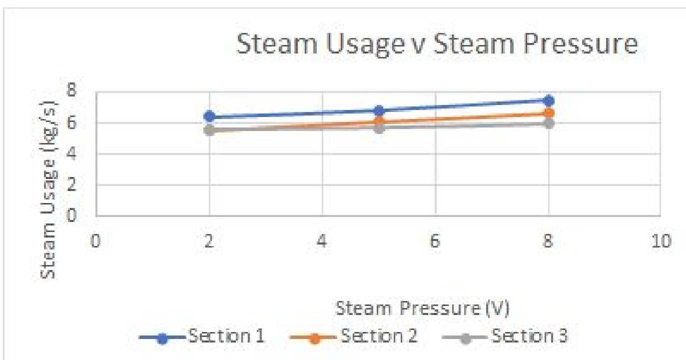


Figure 22. Mass flow rate of steam vs steam pressure

The overall heat transfer coefficient did not change significantly with the changes in pressure. The lack of change in U can be seen in Figure 23 as the trendlines are straight with slopes of almost zero. The change in U from 2V to 5V was a 7.79 (W/m^2-K) decrease. The higher U indicated more efficient heat transfer from the hot steam to the cold EG through the inner pipe. Since sections 1 and 2 had higher U values, those sections had greater efficiencies in transferring heat. Section 3 had lower U values due to the heat loss that occurred as the steam and EG flowed through the heat exchanger. Section 3 also had the lowest trend of Q_{EG} therefore it would have the lowest U value since equation 2 shows the direct proportionality between Q_{EG} and U.

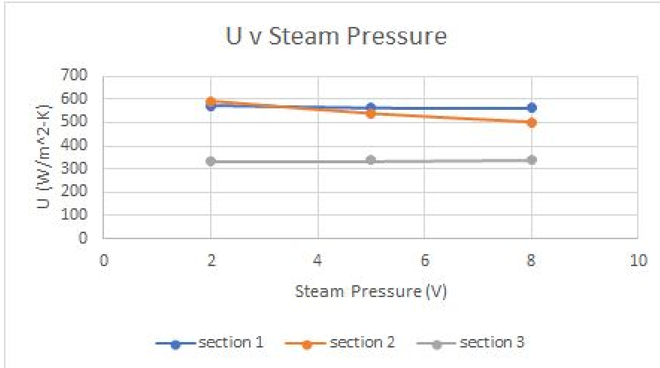


Figure 23. U vs steam pressure

U is directly proportional the heat duty of EG so as Q_{EG} increased the U should have increased. The reason U decreased most likely has to do with the fact that ΔTlm increased. In Equation 4, ΔTlm is inversely proportional to U. So as ΔTlm increased, U decreased. From 2V to 8V in section 1, ΔTlm had an 18% increase while Q_{EG} had a 16% increase. Since ΔTlm had a more significant increase the trend showed U decreasing. However, the much lower U value for the third heating section corresponds to the significant difference between Q_{EG} in section 1 versus section 2. At 2V of pressure, the Q_{EG} of section 1 was 4.33 kW and in section 3 it was 3.52 kW, which is a 0.8 kW difference. Between section 1 and section 2 at 2V of pressure U changed by 3% from 571.17 (W/m^2-K) to 590.15(W/m^2-K). This represented the direct relationship between Q_{EG} and U as well as represented that as the heat duty of EG decreased in each section U also decreased. Thus, a lower Q_{EG} corresponded to less effective heat transfer as the EG moved from section to section.

5.0 Summary & Conclusion

The purpose of this experiment was to evaluate the effects that changing the flow rates of EG, water, and steam had on the heat duty of the double pipe heat exchanger within the heating and cooling sections.

The purpose of Technical Objective 1 was to determine how EG flow rate affected the steady-state heat duty of each heating section and to calculate the overall heat transfer coefficient for each section. The results showed that the EG absorbed less heat from the shell-side steam as it traveled through each successive heating section. For instance, Q_{EG} decreased from heating section 1 to 3 by approximately 30% for an EG flow rate of 10 L/min. This was a result of the decreasing temperature gradient between the steam and ethylene glycol, which is the driving force for heat transfer. Since this driving force decreased, the calculated values for Q_{EG} decreased as well. In addition, it was found that as EG flow rate increased, the amount of steam within each heating section also increased. Comparing EG flow rates of 10 and 35 L/min, the value of m_{steam} in the first heating section increased by approximately 82%. Q_{EG} depended on mass flow rate as well as the change in temperature; however, the change in mass flow rate was greater than the change in temperatures. Therefore, the mass flow rate drove the change in Q_{EG}, which is equivalent to Q_{steam}.

The purpose of Objective 2 was to determine how the EG flow rate affected the steady-state heat duties of EG and water, the rate of heat loss, and the overall heat transfer coefficient in the cooling section. The results showed that as the EG flow rate increased, both Q_W and Q_{EG} increased. For instance, increasing the EG flow rate from 10 to 35 L/min resulted in a 94% increase in Q_W and a 113% increase in Q_{EG}. This was due to the dependence of the EG heat duty on the mass flow rate of the EG and the dependence of the water heat duty on the temperature difference between the inlet stream and outlet stream. It was also determined that as the EG flow rate increased from 10 to 35 L/min, the rate of heat loss increased by 626%. This was due to the increase in heat loss with increasing flow rate. The EG lost more heat as the rate of convection increased, and thus more heat was lost in the uninsulated sections. It was also determined that as Q_W increased between Trials 1 and 6, the U value also increased since according to Equation 4 the Q_W is in the numerator of the equation.

In Objective 3, the purpose was to determine how water flow rate affected the steady-state heat duty and heat loss in the cooling section and to calculate the cooling section's heat transfer coefficient. The results showed that as the water flow rate in the cooling sections decreased, the heat duty decreased. For instance, decreasing the water flow rate from 14.92 to 5.61 L/min resulted in approximate decreases of 18% in Q_W and 25% in Q_{EG} values. This is because heat duty is dependent upon temperature change and mass flow rate. With a lower mass flow rate, convection was less efficient since there was less movement of molecules. The more molecules of water which flowed over the inner EG pipe, the more heat could be removed from the ethylene glycol. The flow rate had a greater influence on heat duty compared to the change in temperatures. The Q_{EG} was greater than Q_w for every trial. This was caused by heat loss through the exposed sections of pipe. In these sections, heat was lost to the surroundings, as opposed to being transferred to water. In applications of double pipe heat exchangers, this loss could be mitigated by insulating the exposed sections to prevent heat loss.

In Objective 4, the purpose was to determine how steam pressure affected the steady-state heat duty of the heating sections, and to calculate the heat transfer coefficient in each section. Increasing the steam pressure from 2V to 8V resulted in increases in Q_{EG} of 16%, 17%, and 6% in each successive heating section. The results also showed that increasing the steam pressure caused the mass of steam required to increase and the heat transfer coefficient to decrease. The increased steam pressure resulted in a higher mass flow rate, since more steam was needed to drive the higher pressure. The results also showed that in each subsequent section, the coefficient of heat transfer decreased. This was because the driving force for heat transfer is the temperature gradient between steam and ethylene glycol. As heat is transferred from steam to EG from section 1 to 3 while the pressure is held constant, the temperature difference between the two (quantified by ΔTlm) increased. According to Equation 4, ΔTlm is in the denominator when calculating U, the U value decreased between sections. This indicated that the heat exchanger was less efficient in subsequent sections.

Overall, the evaluation of heat duty is important because it indicates the efficiency of the double pipe heat exchanger system. In order to have a more cost-and-material-efficient system, the heat duty should be higher and the heat loss should be lower. The results from Objectives 1-4 showed that by varying the flow rates of respective fluids, heat duty can be increased. The heat loss determined in Objective 3 shows that insulation is important to improve the efficiency of the system.

6.0 References

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Appendix A-1: Experimental Data

Table 9. Day 1 steady-state temperature readings T1-T11 for EG flow rate of 10 L/min, water flow rate of 14.78 L/min, steam pressure of 2 V.

V_{EG} (L/min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
10.	29.06	55.84	55.65	17.90	41.49	10.19	31.54	4.96	44.77	22.93	64.74
10.	29.26	55.76	56.00	17.91	41.45	10.18	31.76	4.93	43.05	22.99	65.68
10.	29.44	56.15	56.19	18.01	41.53	10.20	31.94	4.88	45.15	23.07	66.08
10.	29.61	55.74	56.28	18.03	41.78	10.18	31.84	4.85	44.60	23.12	65.69
10.	29.79	55.14	56.05	18.00	41.82	10.17	31.83	4.82	44.27	23.15	66.05
10.	29.96	56.51	56.10	18.08	41.80	10.15	32.06	4.77	44.91	23.20	66.23
10.	30.13	56.57	56.49	18.07	41.81	10.12	32.13	4.75	42.87	23.23	66.53
10.	30.30	56.06	56.59	18.06	41.88	10.11	31.98	4.73	43.99	23.28	66.13
10.	30.46	57.02	56.42	18.15	41.97	10.14	32.00	4.70	44.93	23.35	66.90
10.	30.60	56.74	56.80	18.19	41.92	10.10	31.97	4.62	44.84	23.43	66.62

Table 10. Day 1 steady-state temperature readings T12-T22 for EG flow rate of 10 L/min, water flow rate of 14.78 L/min, steam pressure of 2V.

V_{EG} (L/min)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
10.	13.37	47.36	7.26	35.97	102.53	102.02	101.48	102.74	96.23	92.36	99.32
10.	13.40	47.38	7.22	36.07	102.50	102.01	101.26	102.74	96.37	92.32	98.95

10.	13.43	47.74	7.19	36.09	102.51	101.96	101.32	102.73	96.30	91.77	99.01
10.	13.41	47.78	7.15	36.30	102.49	102.01	101.38	102.75	96.44	91.76	99.27
10.	13.41	47.80	7.17	36.1	102.51	101.98	101.29	102.78	96.56	92.44	99.28
10.	13.43	47.96	7.12	36.30	102.51	102.03	101.32	102.76	96.93	91.52	99.23
10.	13.38	48.14	7.09	36.32	102.52	101.98	101.34	102.80	96.87	92.30	99.21
10.	13.41	48.21	7.06	36.43	102.54	101.99	101.21	102.82	96.73	92.27	99.15
10.	13.45	48.21	7.05	36.48	102.60	102.12	101.39	102.87	96.75	92.45	99.13
10.	13.45	48.38	7.02	36.55	102.57	102.11	101.36	102.85	96.87	92.48	98.91

Table 11. Day 1 steady-state temperature readings T1-T11 for EG flow rate of 15 L/min, water flow rate of 14.78 L/min, steam pressure of 2V.

V_{EG} (L/min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
15	33.76	56.02	56.95	22.40	43.86	11.81	33.62	3.53	46.09	28.49	64.69
15	33.81	56.25	57.03	22.43	43.93	11.79	33.63	3.53	45.95	28.52	64.61
15	33.83	56.02	57.02	22.47	43.89	11.83	33.63	3.51	46.01	28.54	64.78
15	33.89	56.21	57.02	22.44	43.93	11.80	33.63	3.51	45.96	28.54	64.73
15	33.93	56.33	57.06	22.51	43.96	11.83	33.65	3.49	46.11	28.62	64.85
15	33.97	56.31	57.05	22.39	43.98	11.78	33.66	3.49	46.16	28.50	64.93
15	34.01	56.22	57.12	22.44	43.98	11.81	33.63	3.50	46.14	28.54	64.93
15	34.03	56.25	57.15	22.48	43.99	11.83	33.68	3.48	46.22	28.58	64.98

15	34.06	56.41	57.15	22.50	44.00	11.85	33.58	3.46	46.38	28.63	64.97
15	34.08	56.51	57.12	22.43	43.95	11.76	33.69	3.45	46.22	28.57	64.97

Table 12. Day 1 steady-state temperature readings T12-T22 for EG flow rate of 15 L/min, water flow rate of 14.78 L/min, steam pressure of 2V.

V_{EG} (L/min)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
15	16.48	49.67	7.46	38.53	101.89	102.31	100.80	102.41	84.39	81.53	98.58
15	16.48	49.75	7.45	38.56	101.92	102.32	100.93	102.39	84.65	81.06	98.66
15	16.51	49.77	7.48	38.54	101.89	102.35	101.13	102.40	84.44	80.91	98.76
15	16.51	49.75	7.44	38.54	101.92	102.36	101.01	102.42	85.47	80.83	98.80
15	16.56	49.81	7.45	38.55	101.94	102.36	100.79	102.43	84.10	81.89	98.91
15	16.46	49.77	7.43	38.61	101.92	102.37	100.88	102.45	85.23	81.53	98.79
15	16.51	49.84	7.44	38.58	101.93	102.35	100.79	102.40	84.31	81.53	98.48
15	16.54	49.86	7.44	38.60	101.91	102.33	100.89	102.40	84.96	81.30	98.47
15	16.56	49.89	7.47	38.62	101.91	102.32	101.00	102.40	84.42	81.06	98.33
15	16.48	49.87	7.41	38.62	101.92	102.35	100.86	102.43	84.23	81.28	98.49

Table 13. Day 1 steady-state temperature readings T1-T11 for EG flow rate of 20 L/min, water flow rate of 14.78 L/min, steam pressure of 2V.

V_{EG} (L/min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
20.	34.89	54.52	56.18	26.02	45.13	13.97	35.29	3.32	45.48	32.18	62.03

20.	34.97	54.58	56.24	26.00	45.16	13.93	35.25	3.30	45.48	32.16	62.10
20.	35.05	54.65	56.26	26.01	45.20	13.96	35.34	3.29	45.68	32.19	62.15
20.	35.12	54.73	56.37	26.05	45.26	13.95	35.39	3.27	45.67	32.27	62.24
20.	35.20	54.88	56.37	26.09	45.29	13.96	35.40	3.26	45.87	32.29	62.32
20.	35.29	54.94	56.46	26.12	45.35	13.99	35.45	3.26	45.77	32.34	62.40
20.	35.36	54.96	56.55	26.15	45.39	14.01	35.47	3.25	45.89	32.40	62.40
20.	35.41	54.97	56.55	26.14	45.39	13.98	35.51	3.23	45.95	32.40	62.47
20.	35.48	55.06	56.60	26.20	45.44	14.01	35.51	3.22	46.03	32.45	62.56
20.	35.52	55.05	56.66	26.20	45.48	13.99	35.53	3.22	46.01	32.45	62.59

Table 14. Day 1 steady-state temperature readings T12-T22 for EG flow rate of 20 L/min, water flow rate of 14.78 L/min, steam pressure of 2V.

V_{EG} (L/min)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
20.	19.49	50.18	8.62	40.23	101.05	101.52	101.59	101.58	81.14	76.71	98.03
20.	19.48	50.26	8.60	40.16	101.04	101.50	101.59	101.62	80.68	76.98	98.01
20.	19.51	50.32	8.61	40.26	101.08	101.53	101.62	101.63	80.55	77.31	97.98
20.	19.52	50.35	8.61	40.27	101.10	101.56	101.63	101.66	80.73	77.28	98.46
20.	19.55	50.41	8.61	40.29	101.11	101.60	101.65	101.67	82.20	77.67	98.36
20.	19.57	50.48	8.61	40.36	101.14	101.58	101.67	101.66	80.88	77.58	98.08
20.	19.58	50.51	8.61	40.38	101.15	101.63	101.73	101.71	80.16	77.82	98.02

20.	19.58	50.53	8.60	40.40	101.18	101.65	101.73	101.73	80.47	77.67	97.88
20.	19.61	50.58	8.62	40.45	101.20	101.65	101.74	101.74	81.69	77.87	97.89
20.	19.61	50.62	8.61	40.479	101.20	101.66	101.76	101.74	81.35	78.27	98.00

Table 15. Day 1 steady-state temperature readings T1-T11 for EG flow rate of 25 L/min, water flow rate of 14.78 L/min, steam pressure of 2V.

V_{EG} (L/min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
25	36.99	54.68	56.48	28.90	46.57	15.73	36.97	3.05	46.42	35.15	61.33
25	37.05	54.74	56.55	28.94	46.59	15.74	37.01	3.05	46.48	35.19	61.37
25	37.09	54.77	56.57	28.96	46.62	15.77	37.01	3.06	46.52	35.21	61.39
25	37.13	54.82	56.59	28.99	46.65	15.79	37.04	3.05	46.55	35.25	61.44
25	37.21	54.84	56.62	29.02	46.70	15.81	37.09	3.092	46.60	35.28	61.49
25	37.24	54.89	56.66	29.07	46.71	15.85	37.11	3.09	46.66	35.32	61.53
25	37.28	54.90	56.70	29.08	46.75	15.84	37.13	3.11	46.67	35.34	61.57
25	37.30	54.98	56.72	29.09	46.75	15.86	37.15	3.10	46.75	35.36	61.55
25	37.37	54.99	56.76	29.16	46.80	15.89	37.16	3.12	46.79	35.43	61.61
25	37.39	55.02	56.76	29.15	46.82	15.88	37.18	3.11	46.80	35.42	61.60

Table 16. Day 1 steady-state temperature readings T12-T22 for EG flow rate of 25 L/min, water flow rate of 14.78 L/min, steam pressure of 2V.

V_{EG} (L/min)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)

25	21.93	51.18	9.541	41.841	100.55	101.09	101.18	101.23	77.59	78.59	97.40
25	21.96	51.23	9.55	41.85	100.59	101.12	101.18	101.23	77.38	78.69	97.34
25	21.98	51.27	9.57	41.89	100.61	101.12	101.21	101.20	76.19	78.74	97.59
25	22.02	51.29	9.58	41.91	100.60	101.10	101.19	101.23	75.87	78.29	97.55
25	22.02	51.32	9.59	41.95	100.60	101.12	101.22	101.21	74.77	78.11	97.33
25	22.08	51.36	9.62	41.97	100.60	101.13	101.24	101.23	78.48	78.90	97.31
25	22.06	51.38	9.62	41.98	100.61	101.14	101.23	101.23	75.28	77.89	97.19
25	22.09	51.41	9.63	42.00	100.61	101.12	101.20	101.25	76.49	78.51	97.56
25	22.13	51.46	9.66	42.03	100.63	101.13	101.22	101.28	76.36	78.33	97.52
25	22.12	51.48	9.65	42.06	100.66	101.18	101.24	101.25	75.61	78.37	97.30

Table 17. Day 1 steady-state temperature readings T1-T11 for EG flow rate of 30 L/min, water flow rate of 14.78 L/min, steam pressure of 2V.

V_{EG} (L/min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
30.	38.34	54.50	56.47	31.25	47.57	17.41	38.32	3.04	46.90	37.39	60.53
30.	38.39	54.54	56.51	31.30	47.61	17.44	38.34	3.03	46.98	37.45	60.60
30.	38.46	54.60	56.59	31.34	47.65	17.45	38.37	3.043	47.01	37.50	60.60
30.	38.50	54.64	56.58	31.32	47.66	17.43	38.37	3.037	47.05	37.47	60.61
30.	38.56	54.65	56.63	31.35	47.70	17.45	38.411	3.022	47.09	37.52	60.65
30.	38.58	54.71	56.64	31.36	47.71	17.47	38.40	3.006	47.10	37.54	60.68

30.	38.62	54.71	56.67	31.39	47.72	17.47	38.42	2.995	47.13	37.56	60.71
30.	38.64	54.73	56.67	31.38	47.74	17.425	38.44	2.973	47.18	37.57	60.72
30.	38.68	54.75	56.68	31.37	47.74	17.43	38.43	2.957	47.16	37.55	60.73
30.	38.71	54.77	56.70	31.38	47.76	17.43	38.45	2.955	47.23	37.55	60.77

Table 18. Day 1 steady-state temperature readings T12-T22 for EG flow rate of 30 L/min, water flow rate of 14.78 L/min, steam pressure of 2V.

V_{EG} (L/min)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
30.	24.05	51.75	10.57	43.08	100.12	100.67	100.75	100.78	76.73	80.44	97.34
30.	24.10	51.82	10.58	43.14	100.17	100.72	100.77	100.81	76.78	80.72	97.52
30.	24.13	51.86	10.59	43.16	100.15	100.67	100.74	100.79	77.73	80.88	97.46
30.	24.10	51.86	10.57	43.15	100.11	100.64	100.72	100.75	77.71	80.95	97.69
30.	24.13	51.89	10.57	43.18	100.09	100.64	100.73	100.77	76.66	80.70	97.98
30.	24.16	51.89	10.60	43.21	100.08	100.64	100.70	100.76	77.17	81.41	97.64
30.	24.15	51.94	10.57	43.21	100.09	100.65	100.68	100.74	75.89	80.61	97.32
30.	24.11	51.95	10.54	43.26	100.07	100.60	100.68	100.73	76.01	80.71	97.21
30.	24.12	51.95	10.52	43.25	100.01	100.59	100.66	100.70	76.16	81.04	97.23
30.	24.13	51.97	10.54	43.24	100.02	100.56	100.64	100.68	76.48	81.28	97.10

Table 19. Day 1 steady-state temperature readings T1-T11 for EG flow rate of 35 L/min, water flow rate of 14.78 L/min, steam pressure of 2V.

V_{EG} (L/min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
35	39.96	54.82	56.78	33.18	48.60	18.70	39.57	2.72	47.81	39.33	60.33
35	40.00	54.88	56.83	33.23	48.64	18.74	39.59	2.74	47.83	39.36	60.37
35	39.98	54.85	56.82	33.23	48.63	18.71	39.60	2.71	47.83	39.36	60.36
35	40.00	54.88	56.83	33.26	48.64	18.75	39.59	2.70	47.83	39.38	60.36
35	40.02	54.90	56.84	33.27	48.66	18.76	39.60	2.71	47.82	39.39	60.35
35	40.02	54.89	56.85	33.30	48.67	18.74	39.62	2.71	47.84	39.42	60.34
35	40.04	54.88	56.85	33.22	48.63	18.70	39.59	2.71	47.83	39.34	60.36
35	40.05	54.92	56.85	33.21	48.64	18.68	39.58	2.70	47.86	39.32	60.37
35	40.02	54.89	56.83	33.20	48.66	18.68	39.57	2.68	47.79	39.31	60.36
35	40.00	54.90	56.83	33.16	48.61	18.64	39.56	2.68	47.82	39.28	60.37

Table 20. Day 1 steady-state temperature readings T12-T22 for EG flow rate of 35 L/min, water flow rate of 14.78 L/min, steam pressure of 2V.

V_{EG} (L/min)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
35	25.81	52.54	11.30	44.35	99.74	100.24	100.32	100.37	75.85	82.89	97.60
35	25.85	52.57	11.32	44.36	99.75	100.28	100.32	100.39	76.09	82.70	97.18
35	25.82	52.56	11.30	44.37	99.76	100.27	100.34	100.39	76.08	82.79	97.06
35	25.86	52.56	11.31	44.36	99.72	100.28	100.34	100.37	77.69	82.99	96.96
35	25.85	52.57	11.31	44.36	99.71	100.29	100.35	100.38	76.80	83.27	97.04

35	25.88	52.59	11.29	44.38	99.75	100.29	100.34	100.37	75.99	83.34	96.94
35	25.76	52.54	11.25	44.33	99.73	100.32	100.37	100.41	78.32	84.05	97.05
35	25.77	52.55	11.23	44.32	99.74	100.30	100.34	100.38	78.85	83.50	97.18
35	25.76	52.54	11.23	44.31	99.77	100.34	100.37	100.39	75.81	83.58	97.06
35	25.74	52.53	11.22	44.32	99.74	100.30	100.37	100.39	76.07	83.79	96.97

Table 21. Day 2 steady-state temperature readings T1-T11 for water flow rate of 14.91 L/min, EG flow of 30 L/min, steam pressure of 2 V.

V_W (L/min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
14.91	32.17	47.40	50.40	28.07	42.83	16.58	34.98	4.58	40.27	33.12	53.84
14.91	32.55	47.72	50.68	28.22	43.08	16.65	35.17	4.55	40.62	33.32	54.14
14.91	32.91	48.02	50.96	28.41	43.30	16.76	35.35	4.54	40.93	33.55	54.43
14.91	33.35	48.45	51.27	28.59	43.52	16.83	35.50	4.52	41.34	33.78	54.79
14.91	33.65	48.69	51.49	28.73	43.75	16.90	35.68	4.50	41.64	33.95	55.05
14.91	33.96	48.94	51.71	28.88	43.93	16.95	35.81	4.48	41.89	34.13	55.27
14.91	34.22	49.21	51.96	29.07	44.12	17.07	35.94	4.47	42.13	34.34	55.49
14.91	34.49	49.42	52.13	29.17	44.27	17.10	36.06	4.44	42.39	34.47	55.68
14.91	34.72	49.61	52.28	29.23	44.40	17.11	36.17	4.43	42.55	34.58	55.87
14.91	34.95	49.80	52.49	29.38	44.52	17.18	36.26	4.40	42.81	34.74	56.04

Table 22. Day 2 steady-state temperature readings T12-T22 for water flow rate of 14.915 L/min, EG flow of 30 L/min, steam pressure of 2 V.

V_W (L/min)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
14.91	22.03	46.29	10.78	38.92	100.02	100.64	100.71	100.54	58.19	57.02	96.62
14.91	22.14	46.57	10.81	39.13	100.04	100.69	100.75	100.56	58.64	57.64	95.94
14.91	22.30	46.81	10.85	39.32	100.06	100.67	100.74	100.55	59.03	58.22	96.77
14.91	22.41	47.07	10.89	39.53	100.08	100.71	100.78	100.58	59.41	58.74	96.27
14.91	22.53	47.29	10.92	39.74	100.11	100.74	100.83	100.61	59.71	59.15	97.09
14.91	22.62	47.51	10.95	39.90	100.12	100.77	100.83	100.64	59.99	59.63	96.50
14.91	22.77	47.72	10.99	40.06	100.12	100.78	100.84	100.68	60.25	60.02	97.29
14.91	22.85	47.88	11.01	40.19	100.14	100.76	100.85	100.71	60.51	60.35	97.01
14.91	22.89	48.04	11.02	40.32	100.16	100.75	100.84	100.65	60.63	60.58	96.63
14.91	22.98	48.20	11.05	40.44	100.19	100.82	100.91	100.74	60.87	60.90	96.75

Table 23. Day 2 steady-state temperature readings T1-T11 for water flow rate of 12.718 L/min, EG flow of 30 L/min, steam pressure of 2 V.

V_W (L/min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
12.71	40.35	54.48	56.98	35.35	49.04	20.79	40.05	4.29	47.74	41.31	60.31
12.71	40.36	54.49	57.00	35.34	49.04	20.791	40.01	4.27	47.75	41.32	60.31
12.71	40.37	54.45	56.99	35.35	49.03	20.77	40.02	4.28	47.77	41.32	60.32

12.71	40.37	54.51	56.99	35.34	49.04	20.77	40.02	4.27	47.78	41.31	60.35
12.71	40.39	54.48	57.01	35.37	49.05	20.80	40.04	4.28	47.80	41.34	60.34
12.71	40.41	54.52	56.99	35.38	49.04	20.79	40.04	4.24	47.80	41.35	60.34
12.71	40.40	54.51	57.02	35.35	49.06	20.76	40.04	4.24	47.79	41.33	60.34
12.71	40.43	54.52	57.02	35.43	49.09	200.81	40.07	4.24	47.79	41.38	60.34
12.71	40.42	54.54	57.01	35.40	49.07	20.81	40.07	4.23	47.83	41.39	60.35
12.71	40.42	54.52	57.02	35.42	49.08	20.84	40.07	4.23	47.81	41.41	60.35

Table 24. Day 2 steady-state temperature readings T12-T22 for water flow rate of 12.718 L/min, EG flow of 30 L/min, steam pressure of 2 V.

V_W (L/min)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
12.71	27.97	52.83	13.12	44.76	100.62	101.15	101.24	101.07	63.67	65.40	97.25
12.71	27.97	52.83	13.11	44.75	100.62	101.12	101.21	101.14	63.749	65.43	97.36
12.71	27.97	52.84	13.12	44.76	100.62	101.18	101.25	101.11	63.75	65.43	97.41
12.71	27.95	52.84	13.11	44.75	100.61	101.17	101.25	101.11	63.77	65.46	97.50
12.71	27.98	52.85	13.11	44.75	100.60	101.14	101.23	101.08	63.67	65.37	97.38
12.71	27.99	52.83	13.10	44.762	100.61	101.18	101.24	101.11	63.70	65.40	97.43
12.71	27.96	52.86	13.08	44.756	100.58	101.16	101.26	101.07	63.71	65.43	97.31
12.71	28.04	52.86	13.14	44.79	100.63	101.19	101.24	101.14	63.76	65.51	97.37
12.71	28.00	52.87	13.09	44.786	100.61	101.18	101.24	101.09	63.75	65.52	97.42

12.71	28.03	52.89	13.12	44.81	100.60	101.16	101.25	101.10	63.78	65.60	97.37

Table 25. Day 2 steady-state temperature readings T1-T11 for water flow rate of 11.992 L/min, EG flow of 30 L/min, steam pressure of 2 V.

V_W (L/min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
11.99	41.73	55.65	58.48	39.46	51.12	23.68	42.08	4.30	49.00	45.33	61.33
11.99	41.82	55.73	58.5	39.30	51.10	23.61	42.05	4.30	49.06	45.23	61.40
11.99	41.91	55.75	58.57	39.33	51.15	23.62	42.07	4.31	49.15	45.27	61.45
11.99	41.98	55.82	58.64	39.35	51.19	23.66	42.10	4.32	49.23	45.31	61.53
11.99	42.04	55.89	58.65	39.30	51.20	23.60	42.09	4.31	49.29	45.28	61.56
11.99	42.11	55.96	58.72	39.32	51.23	23.58	42.11	4.31	49.34	45.29	61.61
11.99	42.15	56.01	58.72	39.30	51.25	23.56	42.10	4.31	49.40	45.27	61.63
11.99	42.18	56.01	58.76	39.34	51.27	23.62	42.14	4.29	49.40	45.31	61.66
11.99	42.24	56.06	58.80	39.37	51.30	23.60	42.17	4.30	49.46	45.34	61.68
11.99	42.26	56.08	58.80	39.36	51.31	23.61	42.18	4.31	49.49	45.35	61.73

Table 26. Day 2 steady-state temperature readings T12-T22 for water flow rate of 11.99 L/min, EG flow of 30 L/min, steam pressure of 2 V.

V_W (L/min)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
11.99	31.70	54.70	14.88	46.91	100.75	101.28	101.33	101.37	64.24	66.41	97.63
11.99	31.57	54.71	14.87	46.88	100.73	101.25	101.32	101.33	64.19	66.43	97.65

11.99	31.58	54.76	14.87	46.92	100.77	101.29	101.38	101.41	64.24	66.45	97.86
11.99	31.59	54.83	14.86	46.96	100.79	101.29	101.36	101.38	64.24	66.48	98.21
11.99	31.53	54.82	14.83	46.94	100.77	101.29	101.37	101.39	64.25	66.46	97.89
11.99	31.53	54.86	14.80	46.96	100.77	101.33	101.40	101.38	64.27	66.52	97.62
11.99	31.52	54.88	14.82	46.96	100.75	101.33	101.39	101.40	64.31	66.51	97.83
11.99	31.57	54.92	14.83	47.00	100.73	101.32	101.37	101.36	64.30	66.51	97.78
11.99	31.57	54.91	14.82	47.01	100.72	101.32	101.37	101.38	64.31	66.49	97.79
11.99	31.57	54.95	14.82	47.01	100.72	101.35	101.42	101.38	64.32	66.49	97.84

Table 27. Day 2 steady-state temperature readings T1-T11 for water flow rate of 10.21 L/min, EG flow of 30 L/min, steam pressure of 2 V.

V_W (L/min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
10.21	43.76	57.32	60.14	41.91	52.88	25.47	43.60	4.32	50.76	47.83	62.81
10.21	43.78	57.31	60.14	41.91	52.90	25.46	43.63	4.32	50.77	47.85	62.82
10.21	43.80	57.34	60.17	41.93	52.90	25.49	43.63	4.33	50.81	47.88	62.83
10.21	43.81	57.32	60.18	41.94	52.92	25.49	43.65	4.32	50.79	47.91	62.85
10.21	43.86	57.41	60.20	42.00	52.94	25.56	43.67	4.32	50.87	47.95	62.92
10.21	43.86	57.40	60.22	42.05	53.00	25.58	43.71	4.32	50.86	48.01	62.91
10.21	43.87	57.41	60.23	42.00	52.97	25.52	43.70	4.32	50.85	47.98	62.94
10.21	43.89	57.41	60.20	41.85	52.92	25.36	43.64	4.32	50.87	47.86	62.93

10.21	43.89	57.40	60.18	41.79	52.88	25.30	43.61	4.31	50.90	47.81	62.97
10.21	43.91	57.43	60.19	41.80	52.92	25.37	43.62	4.34	50.92	47.83	62.95

Table 28. Day 2 steady-state temperature readings T12-T22 for water flow rate of 10.21 L/min, EG flow of 30 L/min, steam pressure of 2 V.

V_W (L/min)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
10.21	33.88	56.42	15.98	48.58	100.88	101.48	101.53	101.51	64.388	67.98	97.83
10.21	33.89	56.44	15.97	48.60	100.90	101.47	101.53	101.53	64.38	67.99	97.88
10.21	33.34	56.47	16.01	48.61	100.88	101.47	101.53	101.51	64.413	67.96	97.74
10.21	33.94	56.48	16.01	48.64	100.92	101.47	101.56	101.57	64.427	67.93	97.78
10.21	34.01	56.52	16.07	48.66	100.93	101.47	101.54	101.52	64.44	67.90	97.73
10.21	34.04	56.57	16.07	48.72	100.93	101.47	101.55	101.53	64.34	67.84	97.96
10.21	34.01	56.56	16.06	48.73	100.97	101.47	101.54	101.50	64.41	67.82	97.89
10.21	33.83	56.53	15.95	48.66	100.93	101.45	101.51	101.5	64.41	67.93	97.83
10.21	33.80	56.52	15.94	48.64	100.96	101.46	101.56	101.53	64.41	67.97	97.82
10.21	33.84	56.53	15.97	48.66	100.96	101.47	101.53	101.54	64.36	68.01	97.60

Table 29. Day 2 steady-state temperature readings T1-T11 for water flow rate of 8.06 L/min, EG flow of 30 L/min, steam pressure of 2 V.

V_W (L/min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
8.06	48.09	60.83	63.97	49.67	57.66	31.74	48.21	4.38	54.74	55.18	65.95

8.06	48.13	60.87	64.01	49.71	57.69	31.76	48.20	4.38	54.75	55.20	66.02
8.06	48.17	60.91	64.05	49.71	57.71	31.77	48.25	4.37	54.80	55.24	66.04
8.06	48.22	60.98	64.08	49.77	57.76	31.83	48.28	4.37	54.86	55.28	66.08
8.06	48.24	61.00	64.12	49.81	57.80	31.84	48.30	4.37	54.90	55.34	66.12
8.06	48.30	61.00	64.12	49.82	57.83	31.83	48.32	4.39	54.92	55.34	66.12
8.06	48.33	61.06	64.17	49.82	57.82	31.85	48.34	4.42	54.96	55.34	66.17
8.06	48.37	61.09	64.17	49.86	57.85	31.90	48.36	4.45	54.98	55.39	66.21
8.06	48.37	61.10	64.20	49.88	57.88	31.92	48.36	4.44	55.00	55.41	66.22
8.06	48.40	61.14	64.23	49.93	57.90	31.94	48.40	4.45	55.06	55.46	66.24

Table 30. Day 2 steady-state temperature readings T12-T22 for water flow rate of 8.06 L/min, EG flow of 30 L/min, steam pressure of 2 V.

V_W (L/min)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
8.06	41.41	60.87	19.98	53.42	101.21	101.79	101.81	101.81	65.69	73.15	97.75
8.06	41.43	60.91	19.99	53.46	101.22	101.81	101.85	101.83	65.73	73.86	97.86
8.06	41.47	60.94	20.00	53.46	101.20	101.78	101.82	101.80	65.76	74.17	97.74
8.06	41.52	60.97	20.03	53.51	101.22	101.80	101.87	101.83	65.77	74.36	97.87
8.06	41.55	61.00	20.01	53.55	101.20	101.82	101.86	101.84	65.82	74.12	97.85
8.06	41.54	61.02	20.04	53.56	101.21	101.84	101.89	101.85	65.83	73.52	97.87
8.06	41.56	61.03	20.05	53.56	101.22	101.85	101.89	101.85	65.81	74.31	97.87

8.06	41.58	61.08	20.09	53.596	101.22	101.83	101.87	101.84	65.84	74.47	97.78
8.06	41.65	61.10	20.12	53.63	101.21	101.85	101.89	101.86	65.85	74.55	97.72
8.06	41.67	61.13	20.15	53.66	101.25	101.84	101.89	101.85	65.86	74.58	97.74

Table 31. Day 2 steady-state temperature readings T1-T11 for water flow rate of 5.60 L/min, EG flow of 30 L/min, steam pressure of 2 V.

V_W (L/min)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
5.60	58.26	68.99	72.29	64.75	68.08	46.96	58.76	4.61	63.92	68.33	73.25
5.60	58.32	69.05	72.33	64.82	68.13	47.02	58.80	4.60	64.00	68.39	73.30
5.60	58.40	69.12	72.42	64.89	68.21	47.081	58.86	4.63	64.0	68.48	73.36
5.60	58.45	69.14	72.45	64.92	68.24	47.09	58.88	4.64	64.104	68.50	73.40
5.60	58.49	69.19	72.47	64.96	68.28	47.13	58.93	4.63	64.13	68.55	73.43
5.60	58.55	69.21	72.51	65.00	68.32	47.19	58.95	4.63	64.20	68.58	73.47
5.60	58.58	69.27	72.54	65.05	68.35	47.161	58.97	4.60	64.24	68.62	73.51
5.60	58.61	69.29	72.57	65.07	68.37	47.23	59.02	4.62	64.27	68.66	73.56
5.60	58.66	69.31	72.59	65.14	68.43	47.34	59.08	4.61	64.34	68.71	73.59
5.60	58.73	69.34	72.65	65.18	68.47	47.36	59.08	4.63	64.38	68.76	73.61

Table 32. Day 2 steady-state temperature readings T12-T22 for water flow rate of 5.60 L/min, EG flow of 30 L/min, steam pressure of 2 V.

V_W (L/min)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)

5.60	57.74	70.41	30.67	64.31	101.91	102.43	102.48	102.43	85.23	95.19	98.24
5.60	57.79	70.45	30.67	64.34	101.92	102.41	102.47	102.40	85.96	95.43	98.22
5.60	57.88	70.52	30.74	64.42	101.94	102.43	102.48	102.41	85.72	95.23	98.20
5.60	57.90	70.56	30.74	64.45	101.97	102.42	102.46	102.43	86.11	95.37	98.23
5.60	57.93	70.60	30.81	64.51	101.97	102.44	102.5	102.44	86.195	95.543	98.279
5.60	57.99	70.64	30.86	64.55	101.97	102.43	102.50	102.41	86.21	95.46	98.19
5.60	58.02	70.68	30.86	64.58	101.98	102.43	102.49	102.43	86.13	95.64	98.21
5.60	58.07	70.72	30.90	64.62	102.02	102.46	102.52	102.43	86.23	95.51	98.18
5.60	58.16	70.76	30.99	64.71	102.03	102.44	102.50	102.43	85.89	95.49	98.19
5.60	58.19	70.79	30.96	64.71	102.03	102.47	102.50	102.44	85.56	95.52	98.22

Table 33. Day 3 steady-state temperature readings T1-T11 for steam pressure of 2V, EG flow of 35 L/min, water flow of 14.915 L/min.

P_{steam} (V)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
2	39.73	52.53	54.96	34.40	47.87	22.00	39.90	8.03	46.49	39.61	58.07
2	39.80	52.54	54.99	34.45	47.91	22.05	39.92	8.00	46.52	39.67	58.09
2	39.84	52.62	55.02	34.46	47.93	22.04	39.93	7.99	46.60	39.68	58.12
2	39.92	52.68	55.07	34.50	47.98	22.06	39.96	8.00	46.62	39.73	58.19
2	39.96	52.74	55.13	34.52	48.00	22.07	39.97	7.97	46.68	39.76	58.23
2	40.01	52.78	55.15	34.54	48.03	22.07	39.98	7.94	46.73	39.78	58.26

2	40.05	52.80	55.20	34.58	48.08	22.08	40.03	7.93	46.76	39.83	58.28
2	40.07	52.83	55.22	34.57	48.07	22.06	40.02	7.93	46.78	39.84	58.32
2	40.15	52.88	55.25	34.59	48.11	22.07	40.05	7.93	46.84	39.84	58.35
2	40.18	52.92	55.30	34.62	48.14	22.12	40.07	7.93	46.87	39.87	58.39

Table 34. Day 3 steady-state temperature readings T12-T22 for steam pressure of 2V, EG flow of 35 L/min, water flow of 14.915 L/min.

P_{steam} (V)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
2	28.13	51.27	15.58	44.13	100.60	101.06	101.04	101.03	60.93	63.06	97.32
2	28.15	51.31	15.60	44.17	100.60	101.03	101.05	101.08	60.98	63.25	97.59
2	28.14	51.35	15.58	44.19	100.61	101.05	101.06	101.09	60.99	63.39	98.28
2	28.19	51.39	15.58	44.22	100.62	101.09	101.07	101.08	60.97	63.46	98.36
2	28.21	51.42	15.59	44.22	100.60	101.07	101.07	101.07	60.93	63.47	98.20
2	28.20	51.42	15.56	44.24	100.62	101.06	101.09	101.04	61.01	63.54	98.78
2	28.22	51.49	15.56	44.30	100.63	101.06	101.07	101.09	61.01	63.61	97.79
2	28.21	51.49	15.54	44.32	100.64	101.10	101.09	101.10	61.03	63.56	98.13
2	28.23	51.54	15.57	44.32	100.63	101.10	101.13	101.07	61.09	63.58	98.80
2	28.25	51.55	15.58	44.35	100.66	101.09	101.12	101.11	61.11	63.65	98.23

Table 35. Day 3 steady-state temperature readings T1-T11 for steam pressure of 5V, EG flow rate 35 L/min, water flow rate of 14.95 L/min

P_{steam} (V)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
5	42.58	56.79	59.21	37.25	51.35	23.41	42.46	7.78	50.11	43.04	62.63
5	42.59	56.82	59.21	37.25	51.36	23.42	42.48	7.76	50.10	43.04	62.65
5	42.64	56.82	59.26	37.32	51.40	23.47	42.52	7.77	50.16	43.12	62.67
5	42.66	56.85	59.28	37.35	51.44	23.51	42.52	7.79	50.15	43.13	62.72
5	42.69	56.87	59.29	37.35	51.46	23.49	42.53	7.80	50.20	43.14	62.75
5	42.71	56.93	59.32	37.35	51.46	23.47	42.54	7.80	50.25	43.15	62.73
5	42.75	56.95	59.37	37.37	51.48	23.51	42.59	7.80	50.28	43.19	62.78
5	42.76	56.94	59.35	37.34	51.47	23.47	42.56	7.79	50.29	43.15	62.80
5	42.77	56.97	59.36	37.37	51.49	23.50	42.58	7.79	50.27	43.17	62.80
5	42.77	56.96	59.34	37.33	51.48	23.45	42.57	7.76	50.27	43.15	62.79
5	42.79	57.00	59.37	37.37	51.51	23.50	42.59	7.77	50.32	43.18	62.80

Table 36. Day 3 steady-state temperature readings T12-T22 for steam pressure 5V, EG flow rate 35 L/min, water flow rate of 14.95 L/min

P_{steam} (V)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
5	30.24	30.24	30.24	30.24	30.24	107.43	107.47	107.46	67.13	70.54	103.71
5	30.26	30.26	30.26	30.26	30.26	107.43	107.48	107.47	67.14	70.61	104.08
5	30.32	30.32	30.32	30.32	30.32	107.42	107.47	107.47	67.15	70.69	103.67
5	30.35	30.35	30.35	30.35	30.35	107.42	107.48	107.48	67.20	70.79	103.46
5	30.34	30.34	30.34	30.34	30.34	107.42	107.48	107.47	67.22	70.82	103.41
5	30.33	30.33	30.33	30.33	30.33	107.43	107.49	107.47	67.21	70.86	103.30

5	30.36	30.36	30.36	30.36	30.36	107.43	107.47	107.46	67.23	70.88	103.25
5	30.32	30.32	30.32	30.32	30.32	107.44	107.48	107.48	67.25	70.95	103.25
5	30.36	30.36	30.36	30.36	30.36	107.45	107.48	107.51	67.29	70.97	103.35
5	30.32	30.32	30.32	30.32	30.32	107.44	107.48	107.49	67.33	70.92	103.44
5	30.35	30.35	30.35	30.35	30.35	107.43	107.46	107.45	67.28	71.01	103.38

Table 37. Day 3 steady-state temperature readings T1-T11 for steam pressure of 8V, EG flow rate 35 L/min, water flow rate of 14.95 L/min

P_{steam} (V)	T1 (ºC)	T2 (ºC)	T3 (ºC)	T4 (ºC)	T5 (ºC)	T6 (ºC)	T7 (ºC)	T8 (ºC)	T9 (ºC)	T10 (ºC)	T11 (ºC)
8	44.63	60.11	62.58	39.59	54.13	24.67	44.53	7.77	52.92	45.82	66.25
8	44.66	60.15	62.61	39.62	54.16	24.68	44.56	7.78	52.92	45.87	66.26
8	44.69	60.17	62.62	39.64	54.17	24.70	44.59	7.77	52.95	45.88	66.29
8	44.72	60.21	62.66	39.72	54.22	24.77	44.61	7.77	52.98	45.95	66.32
8	44.77	60.22	62.70	39.71	54.24	24.76	44.62	7.78	53.01	45.95	66.35
8	44.80	60.27	62.71	39.70	54.23	24.71	44.62	7.78	53.02	45.93	66.38
8	44.84	60.29	62.74	39.71	54.25	24.72	44.64	7.79	53.06	45.94	66.38
8	44.83	60.30	62.74	39.74	54.27	24.74	44.65	7.78	53.07	45.96	66.38
8	44.87	60.34	62.74	39.75	54.29	24.76	44.65	7.77	53.06	45.96	66.39
8	44.89	60.36	62.76	39.78	54.30	24.76	44.65	7.76	53.11	45.99	66.40

Table 38. Day 3 steady-state temperature readings T11-T22 for steam pressure of 8V, EG flow rate 35 L/min, water flow rate of 14.95 L/min

P_{steam} (v)	T12 (ºC)	T13 (ºC)	T14 (ºC)	T15 (ºC)	T16 (ºC)	T17 (ºC)	T18 (ºC)	T19 (ºC)	T20 (ºC)	T21 (ºC)	T22 (ºC)
8	32.05	58.24	17.00	49.72	112.31	112.89	72.89	80.79	108.89	112.85	112.94
8	32.06	58.26	16.99	49.73	112.29	112.89	72.98	80.57	108.94	112.84	112.93
8	32.09	58.28	17.00	49.76	112.29	112.92	73.06	80.54	108.84	112.83	112.91
8	32.11	58.30	16.99	49.77	112.31	112.91	73.06	80.73	108.79	112.85	112.92
8	32.18	58.34	17.02	49.83	112.30	112.93	73.08	80.47	108.86	112.85	112.92
8	32.14	58.34	17.01	49.82	112.29	112.91	73.08	80.72	108.74	112.85	112.90

8	32.13	58.35	16.99	49.80	112.28	112.94	73.08	80.46	109.37	112.86	112.93
8	32.14	58.38	17.00	49.81	112.29	112.91	73.11	81.02	108.56	112.86	112.91
8	32.16	58.39	17.01	49.84	112.31	112.92	73.17	81.34	108.78	112.86	112.95
8	32.17	58.38	17.01	49.84	112.29	112.94	73.24	81.42	108.76	112.90	112.97
8	32.16	58.38	17.00	49.83	112.27	112.92	73.22	81.28	108.54	112.87	112.92

Appendix A-2: Example Calculations

Sample calculation of actual water flow rate for a rotameter reading of 53.5 L/min:

$V_W = 0.26 * 53.5 + 0.52 = 14.91$ L/min

Heating Sections

1. Calculate Q_{EG} of Heating Section 1 for $V_{EG} = 10$ L/min

$Q_{EG} = m_{EG}*C_p*\Delta T_{EG}$ (kW)

$m_{EG} = 0.17$ kg/s

$C_p = 3.45$ (kJ/kg*ºC)

ΔT_{EG} = T9-T1= 44.34 ºC-29.77 ºC = 14.57 ºC

Q_{EG} = (0.17 kg/s)*(3.45 kJ/kg*ºC)*(14.57 ºC)

Q_{EG} = 8.71 kW

2. Steam Usage Estimate for Heating Section 1, $V_{EG} = 10$ L/min

$m_{steam} = Q_{EG} / (\Delta H_{cond} + C_{p,EG}*\Delta T)$

Q_{EG} = 8.71 kJ/s

ΔH_{cond} = 2257 kJ/kg

$C_{p,EG}$ = 4.18 kJ/kg*C

ΔT = T16-T20= 102.53C-96.55C = 5.98C

m_{steam} = (8.71 kJ/s) /(2257(kJ/kg) + ((4.18 kJ/kgºC * 5.98 ºC)*3600 s/hr)

m_{steam} = 13.75 kg/hr

3. Calculating Log Mean Temperature Difference in Heating Section 1

ΔTlm = (ΔT2-ΔT1)/ln(ΔT2/ΔT1)

ΔT2 = T16 - T1 = 100.9 ºC - 35.25 ºC = 65.65 ºC

ΔT1 = T20 - T9 = 80.06 ºC - 44.66 ºC = 35.4 ºC

$\Delta Tlm = (65.65\ ºC - 35.45\ ºC)/\ln(65.65\ ºC/35.4\ ºC) = 48.98\ ºC$

4. Overall Heat Transfer Coefficient for Heating Section 1 at $V_{EG} = 10$ L/min

$Q_{EG} = U*A*\Delta Tlm$

$U = Q_{EG}/(A*\Delta Tlm)$

$Q_{EG} = 8.71$ kJ/s

$A = $(inner pipe OD * π * pipe length) = .0286 m * π * 2.82 m = .253 m^2

$\Delta Tlm = 48.98\ ºC$

$U = 8.71\ (kJ/s) / (.253\ m^2 * 48.98\ ºC)$

$U = 0.70\ kW/m^2*K$

Cooling Section

1. Calculate area of cooling section

A = inner pipe OD * pi *length * 5

Inner pipe OD = 0.0286 m

Length = 2.82 m

A = 0.0286 [m] * π * 2.82 [m] * 5 = 1.27 m^2

2. Calculate log mean temperature difference

$\Delta Tlm = (\Delta T2-\Delta T1)/\ln(\Delta T2/\Delta T1)$ where $\Delta T2 = T11 - T10$ and $\Delta T1 = T7 - T8$

$\Delta T2 = 61.88\ ºC - 31.86\ ºC = 30.02\ ºC$

$\Delta T1 = 35.1\ ºC - 3.341\ ºC = 35.76\ ºC$

$\Delta Tlm = (30.02\ ºC - 35.76\ ºC)/\ln(30.02\ ºC/35.76\ ºC) = 30.88\ ºC$

3. Calculate overall heat duty of water

$Q_w = m_w * C_{p,w} * \Delta T$

$m_w = 14.92$ LPM / (60s/M) = 0.27 kg/s

$C_{p,\,W} = 4.18$ kJ/kg K

$\Delta T = T10 - T8 = 33.89\ ºC - 4.5\ ºC = 29.39\ ºC$

$Q_w = 0.27$ [kg/s] * 4.18 [kJ/kg K] * 29.39 [ºC] = 32.82 kW

4. Calculate overall heat transfer coefficient

$U = Q_w / (A * \Delta Tlm)$

$Q_w = 30.59$ kW

$A = 1.27\ m^2$

$\Delta Tlm = 30.88\ ^oC$

$U = 30.59\ [kW] / (1.27\ [m^2] * 30.88\ [^oC]) = 781.89\ W/m^2\ K$