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ANALYSIS

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2 Introduction

2.1 Experimental Procedures

In this report the author shall explore the theory behind the operation and function of heat exchangers to analyse data, using principals of fluid flow and heat transfer. Three experiments have been carried out in the University's Engineering Science Laboratory, each including a different independent variable against which to compare the effects on the performance and efficiency of the heat exchanger system.

These three experiments shall be carried out as follows:

- Exploring the effects of varying water flow rate.
- Exploring the effects of varying air flow rate at 60°C.
- Exploring the effects of varying air flow rate at 45°C.

2.2 Literature Review

A heat exchanger is a device used to remove heat from one medium, transferring it to another. Such device operates primarily on the law of conservation of energy, specifically the first law of thermodynamics:

$$\Delta U = Q - W$$

ΔU - Change in internal energy
 Q - Heat added to the system
 W - Heat removed by the system (work done)

Heat is a form of energy and thus cannot be destroyed; therefore, if the operating temperature of a system needs to be controlled, the heat energy must be removed and carried away from the system. The materials within the system interact, meaning the heat from each medium is exchanged by means of convection (Thermex, 2018). As is detailed below, the heat exchanger used can be operated by controlling the rate at which water and air enter the system, therefore showing this particular system works by means of forced convection. During this experiment the author shall monitor the heat transfer coefficient. It is hypothesised that as this value increases, more energy is able to be transferred; thus, more heat transferred (Rogers & Mayhew, 1992).

Heat exchangers are used frequently in every day life in a range of applications from the automotive to domestic appliance world. Arguably the most common is the radiator in an internal combustion engine. Fluid running through the radiator is cooled by air running over it, removing the unwanted heat from the system. Heat exchangers can also be found in a variety of oil coolers and refrigerators (Holman, 2010).

Various types of heat exchanger exist, each with different strengths and weaknesses. A key difference between designs is the flow configuration; this is the way in which the fluids flow through the system during the process of heat transfer. It can be said that there are four principal types of heat exchanger flow configurations:

- Concurrent (Parallel Flow) - Fluids move past each other in parallel, same direction.
- Counter-Current Flow - Fluids move past each other in parallel, opposite directions.
- Cross Flow - Fluids move perpendicular to each other.
- Hybrid Flow - Fluids move in a combination of the above ways (multiple flow passes).

Counter-current flow is the most common configuration seen as it is generally the most efficient. This configuration has the greatest amount of heat exchange surface area; thus producing the greatest possible temperature change (Kreith, et al., 2011; Thomas, 2017).

The construction of a heat exchanger also plays a key part in how it functions. Common differences between systems include:

- Recuperative and Regenerative

A recuperative heat exchanger consists of two fluid networks flowing simultaneously through the system. A Regenerative system allows alternative streams of warm and cool fluid through the same part of the system. Recuperative systems are generally more efficient as there is less risk of heat being lost to the surroundings, and a greater temperature change can be seen in a shorter amount of time (Kreith, et al., 2011).

- Direct vs Indirect

A direct heat exchanger will combine two or more fluids to transfer heat. There is no separation and heat energy is transferred by means of direct contact. An indirect system incorporates separate channels for the fluids to travel through. These channels are made from conductive materials that gain heat energy from the hotter fluid, then release the energy to the cooler fluid. Both systems are considered roughly equally efficient, however sometimes a direct system may be inappropriate as some fluids, once mixed, cannot be separated again (Thomas, 2017).

- Static vs Dynamic

A static heat exchanger includes internal components that stay stationary as the fluid moves through the system. A dynamic heat exchanger move around or with the fluid to enhance the heat transfer process. A dynamic system can be more efficient in certain applications as it contains separate moving sections, meaning each section moves through alternatively cooler and warmer regions, enhancing the heat transfer process. Because of this, both these types of systems will be regenerative and are most commonly direct heat exchangers (Kreith, et al., 2011; Thomas, 2017).

The heat exchanger used in the group's experiment was a TecQuipment TD1007 32 tube, cross-flow, recuperative, static, direct heat exchanger. The exchanger has two bundles of 16 tubes and the heated water passes through the system perpendicular to the air. This type of heat exchanger is sufficient for what is required from it, although as mentioned above, a counter-current flow system would be more efficient. Because the temperatures involved are not that large, the system is efficient enough to achieve reliable results quickly.



Figure 1 - TD1007 Heat Exchange (TecQuipment, 2017)r

3 Methodology

3.1 Thermodynamic Calculations

Before the experiment began the group made note of ambient pressure. The orifice diameter and area, as well as surface area of the heat exchanger were noted also. At each stage in the experiment, the author recorded the air and water inlet and outlet temperatures, as well as the water tank and atmospheric temperatures. From these raw data, the following could be calculated:

Air ΔTemp	$Air\ T_o - Air\ T_i$
Air average temp	$\frac{Air\ T_i + Air\ T_o}{2}$
Water ΔTemp	$Water\ T_o - Water\ T_i$
Water average temp	$\frac{Water\ T_i + Water\ T_o}{2}$
Density of air	$\left(\rho = \frac{P}{R.T}\right) \rightarrow \frac{Ambient\ P \times 10^5}{287.058 \times Ambient\ T + 273.15}$
Density of water	$\frac{999.839 + 16.952T - 7.990 \times 10^{-3}T^2 - 46.241 \times 10^{-6}T^3 + 105.846 \times 10^{-9}T^4 - 281.030 \times 10^{-12}T^5}{1 + 16.887 \times 10^{-3}T}$
Mass flowrate of air	$C_d \times A_o \times \sqrt{\Delta P \times 2 \times Ambient\ P}$
Mass flowrate of water	$\frac{Volume\ flow}{60000} \times Water\ density$
Specific heat capacity of water	$0.996185 + 0.0002874 \times \left(\frac{T + 100}{100}\right)^{5.26} + 0.011160 \times 10^{-0.036T} \times 4185.5$
Heat absorbed from air	$mass\ flow\ rate\ air \times spec.\ heat\ cap.\ air \times \Delta T_{air}$
Heat emitted from water	$Mass\ flow\ rate\ water \times spec.\ heat\ cap.\ water \times \Delta T_{water}$
Temperature efficiency air	$\frac{Air\ T_o - Air\ T_i}{Water\ T_i - Air\ T_i}$
Temperature efficiency water	$\frac{Water\ T_i - Water\ T_o}{Water\ T_i - Air\ T_i}$
Mean temperature efficiency	$\frac{\eta_{Water} + \eta_{Air}}{2}$
Logarithmic mean temperature difference (LMTD)	$\frac{(Water\ T_o - Air\ T_o) - (Water\ T_i - Air\ T_i)}{\ln\left(\frac{Water\ T_o - Air\ T_o}{Water\ T_i - Air\ T_i}\right)}$
Heat transfer coefficient	$\frac{Heat\ emitted\ from\ water}{Surface\ area \times LMTD}$
Energy Balance Coefficient	$\frac{Power\ Absorbed}{Power\ Emitted}$

Figure 2 - Equations Used

3.2 Experiment Set-up

Before the group arrived, the heating element in the water tank had been switched on with enough time for the water to reach a temperature of 60°C. The TD1007 has a control unit with a variable thermostat and live readout. Upon selecting the desired temperature, the operator must wait until the display temperature has stopped varying and the system holds constant temperature. The system had to be connected as for parallel flow for each experiment. This ensures the two banks of 16 tubes are connected by the top two tubes, and bottom two tubes (TecQuipment, 2017).

The group recorded the air and water inlet and outlet temperatures, as well as the water tank and atmospheric temperatures initially, as well as after each setup condition was reached. The data was inputted by the author onto a ready-made spreadsheet and this was handed to the rest of the group afterwards to ensure each participant had the same results.

This setup procedure was repeated for each experiment.

3.3 Experiment One - The Effect of Varying Water Flow Rate

Initially, the group noted the ambient conditions in the room at that current time and recorded the geometric conditions of the exchanger (Table 1).

The group then used the adjustable flap on the exit duct of the air channel; this set the air mass flow rate by altering the change in pressure for the air across the system. This was carefully altered until the pressure drop showed 250Pa (± 5 Pa tolerance) on the readout.

The water flow rate was set at the initial required level (2.25L/min $\pm$ 0.01L/min) by manually adjusting the valve to limit the amount of water that can enter. Once these values were set correctly, the group waited for five minutes for the system temperature to stabilise and took readings. This process was repeated for water flow rates of 1.75, 1.25, 0.75 and 0.25 L/min.

Table 1 - Experiment 1 Initial Data (BLUE = INDEPENDENT VARIABLE)

System Data				
EXPERIMENT	Ambient Pressure (Bar)	Orifice Diameter (m)	Orifice Area (m ²)	Surface Area (m ²)
1	1.0170	0.10011	0.0079	0.1558
2	1.0170	0.10011	0.0079	0.1558
3	1.0170	0.10011	0.0079	0.1558
4	1.0170	0.10011	0.0079	0.1558
5	1.0170	0.10011	0.0079	0.1558

Air Data				
EXPERIMENT	Pressure Difference (Pa)	Ambient Air Temp (°C)	Air Temp In (°C)	Air Temp Out (°C)
1	249.0000	23.3000	23.5000	29.3000
2	250.0000	23.2000	23.6000	29.2000
3	249.0000	23.1000	23.6000	28.9000
4	250.0000	23.3000	23.6000	28.4000
5	250.0000	23.4000	23.8000	27.3000

Water Data				
EXPERIMENT	Water Flow (L/min)	Water Tank Temp (°C)	Water Temp In (°C)	Water Temp Out (°C)
1	2.2500	59.9000	60.9000	56.6000
2	1.7500	59.9000	60.8000	55.5000
3	1.2500	60.2000	60.4000	53.3000
4	0.7500	60.1000	59.7000	49.3000
5	0.2500	60.1000	60.4000	38.3000

Prior to carrying out the experiment, the author had created a spreadsheet not only for the data (table 1) but also for the data analysis (table 2). This section was not shared with the rest of the group. With the formulae already in the appropriate cells, the analysis equations produced an instant result as soon as the data was inputted into the table. This saved time during the writeup phase and was a good opportunity for the author to gain a better understanding of exactly what was required from the group before starting the experiment.

Table 2 - Experiment 1 Data Analysis

Overall Flow Results Analysis				
EXPERIMENT	Logarithmic Mean ΔT (LMTD) ($^{\circ}\text{C}$)	Absolute Heat Transfer Coefficient (U) ($\text{W}/\text{m}^2\cdot\text{K}$)	Mean Temperature Efficiency (%)	Energy Balance Coefficient
1	32.0855	131.3136	13.5027	0.9426
2	31.4357	128.5263	14.6505	0.9510
3	30.1766	128.2000	16.8478	0.9381
4	27.8111	122.4009	21.0526	0.9675
5	21.2951	113.5235	34.9727	0.9933

Air Results Analysis							
EXPERIMENT	ΔTemp ($^{\circ}\text{C}$)	Average Temp ($^{\circ}\text{C}$)	Density of Air (kg/m^3)	Mass Flowrate (kg/s)	Spec. Heat Capacity ($\text{J}/\text{Kg}/\text{K}$)	Power Absorbed (W)	Temperature Efficiency (%)
1	5.8000	26.4000	1.1951	0.1062	1005.0000	618.8533	15.5080
2	5.6000	26.4000	1.1955	0.1064	1005.0000	598.7122	15.0538
3	5.3000	26.2500	1.1959	0.1062	1005.0000	565.5039	14.4022
4	4.8000	26.0000	1.1951	0.1064	1005.0000	513.1819	13.2964
5	3.5000	25.5500	1.1947	0.1064	1005.0000	374.1951	9.5628

Water Results Analysis							
EXPERIMENT	ΔTemp ($^{\circ}\text{C}$)	Average Temp ($^{\circ}\text{C}$)	Density of Water (kg/m^3)	Mass Flowrate (kg/s)	Spec. Heat Capacity ($\text{J}/\text{Kg}/\text{K}$)	Absolute Power Emitted (W)	Temperature Efficiency (%)
1	-4.3000	58.7500	973.2030	0.0365	4183.5677	656.5230	11.4973
2	-5.3000	58.1500	973.5609	0.0284	4183.3162	629.5736	14.2473
3	-7.1000	56.8500	974.3309	0.0203	4182.7895	602.8227	19.2935
4	-10.4000	54.5000	975.7035	0.0122	4181.8998	530.4383	28.8089
5	-22.1000	49.3500	978.6239	0.0041	4180.2346	376.7016	60.3825

3.4 Experiment Two - The Effect of Varying Air Flow Rate

For this experiment the heat exchanger was set up as per experiment one (table 3), however for this experiment the water flow rate would be constantly set to 0.25L/min (± 0.01 L/min) using the control valve. the air flow rate would then be altered by setting the pressure drop across the system to 250Pa (± 5 Pa tolerance). Once Again, five minutes was taken to let the system temperature stabilise then a reading was taken. This process was repeated for system pressure drop values of 200, 150, 100, 50 and 25 Pa.

Table 3 - Experiment 2 Initial Data (BLUE = INDEPENDENT VARIABLE)

System Data				
EXPERIMENT	Ambient Pressure (Bar)	Orifice Diameter (m)	Orifice Area (m ²)	Surface Area (m ²)
1	1.0170	0.10011	0.0079	0.1558
2	1.0170	0.10011	0.0079	0.1558
3	1.0170	0.10011	0.0079	0.1558
4	1.0170	0.10011	0.0079	0.1558
5	1.0170	0.10011	0.0079	0.1558
6	1.0170	0.10011	0.0079	0.1558

Air Data				
EXPERIMENT	Pressure Difference (Pa)	Ambient Air Temp (°C)	Air Temp In (°C)	Air Temp Out (°C)
1	250.0000	23.4000	23.8000	27.3000
2	199.0000	23.7000	23.8000	27.3000
3	149.0000	23.6000	23.8000	27.4000
4	101.0000	23.2000	24.0000	27.9000
5	50.0000	23.3000	24.2000	28.9000
6	25.0000	23.3000	24.7000	30.2000

Water Data				
EXPERIMENT	Water Flow (L/min)	Water Tank Temp (°C)	Water Temp In (°C)	Water Temp Out (°C)
1	0.2500	60.1000	60.4000	38.3000
2	0.2400	60.1000	58.3000	38.0000
3	0.2500	60.0000	58.1000	38.5000
4	0.2500	60.1000	58.2000	39.4000
5	0.2500	60.0000	58.6000	41.4000
6	0.2500	60.1000	58.9000	43.3000

In the same way as experiment one, the inputted data was automatically put into each calculation via the pre-made table:

Table 4 - Experiment 2 Data Analysis

Overall Flow Results Analysis				
EXPERIMENT	Logarithmic Mean ΔT (LMTD) (°C)	Heat Transfer Coefficient (U)	Mean Temperature Efficiency (%)	Energy Balance Coefficient
1	21.2951	113.5235	34.9727	0.9933
2	20.3294	104.9241	34.4928	1.0044
3	20.5637	104.3170	33.8192	0.8889
4	20.8280	98.7650	33.1871	0.8268
5	21.6333	86.9437	31.8314	0.7667
6	21.9880	77.5411	30.8480	0.6999

Air Results Analysis							
EXPERIMENT	Δ Temp (°C)	Average Temp (°C)	Density of Air (kg/m ³)	Mass Flowrate (kg/s)	Spec. Heat Capacity (J/Kg/K)	Power Absorbed (W)	Temperature Efficiency (%)
1	3.5000	25.5500	1.1947	0.1064	1005.0000	374.1951	9.5628
2	3.5000	25.5500	1.1935	0.0949	1005.0000	333.8525	10.1449
3	3.6000	25.6000	1.1939	0.0821	1005.0000	297.1363	10.4956
4	3.9000	25.9500	1.1955	0.0676	1005.0000	265.0241	11.4035
5	4.7000	26.5500	1.1951	0.0476	1005.0000	224.7206	13.6628
6	5.5000	27.4500	1.1951	0.0336	1005.0000	185.9485	16.0819

Water Results Analysis							
EXPERIMENT	Δ Temp (°C)	Average Temp (°C)	Density of Water (kg/m ³)	Mass Flowrate (kg/s)	Spec. Heat Capacity (J/Kg/K)	Absolute Power Emitted (W)	Temperature Efficiency (%)
1	-22.1000	49.3500	978.6239	0.0041	4180.2346	376.7016	60.3825
2	-20.3000	48.1500	979.2868	0.0039	4179.9041	332.3780	58.8406
3	-19.6000	48.3000	979.2043	0.0041	4179.9442	334.2633	57.1429
4	-18.8000	48.8000	978.9286	0.0041	4180.0803	320.5400	54.9708
5	-17.2000	50.0000	978.2620	0.0041	4180.4228	293.0843	50.0000
6	-15.6000	51.1000	977.6452	0.0041	4180.7560	265.6742	45.6140

3.5 Experiment 3 - Effect of Varying Temperature (Driving Force)

Experiment 3 used the previous settings aside from water tank temperature, which the group set to 45°C. Once more, time was allowed for the system temperature to stabilise.

Table 5 - Experiment 3 Initial Data (BLUE = INDEPENDENT VARIABLE)

System Data				
EXPERIMENT	Ambient Pressure (Bar)	Orifice Diameter (m)	Orifice Area (m ²)	Surface Area (m ²)
1	1.0170	0.10011	0.0079	0.1558
2	1.0170	0.10011	0.0079	0.1558
3	1.0170	0.10011	0.0079	0.1558
4	1.0170	0.10011	0.0079	0.1558
5	1.0170	0.10011	0.0079	0.1558
6	1.0170	0.10011	0.0079	0.1558

Air Data				
EXPERIMENT	Pressure Difference (Pa)	Ambient Air Temp (°C)	Air Temp In (°C)	Air Temp Out (°C)
1	249.0000	23.1000	23.6000	26.1000
2	200.0000	23.4000	23.9000	26.4000
3	150.0000	23.2000	23.9000	26.5000
4	100.0000	23.1000	23.9000	26.8000
5	50.0000	23.2000	24.3000	27.7000
6	25.0000	23.2000	24.7000	28.5000

Water Data				
EXPERIMENT	Water Tank Temp (°C)	Water Flow (L/min)	Water Temp In (°C)	Water Temp Out (°C)
1	45.0000	0.2500	48.6000	33.6000
2	45.2000	0.2500	48.1000	33.8000
3	44.7000	0.2500	48.1000	34.2000
4	44.7000	0.2500	48.2000	34.9000
5	45.1000	0.2500	48.3000	36.4000
6	45.5000	0.2500	48.5000	37.6000

As previously stated, the inputted data was automatically put into each calculation via the pre-made table

Table 6 - Experiment 3 Data Analysis

Overall Flow Results Analysis				
EXPERIMENT	Logarithmic Mean ΔT (LMTD) (°C)	Heat Transfer Coefficient (U)	Mean Temperature Efficiency (%)	Energy Balance Coefficient
1	14.5352	113.3481	35.0000	1.0390
2	14.1787	110.7834	34.7107	0.9767
3	14.4088	105.9547	34.0909	0.9051
4	14.7459	99.0443	33.3333	0.8616
5	15.0779	86.6332	31.8750	0.7987
6	15.2900	78.2253	30.8824	0.6893

Air Results Analysis							
EXPERIMENT	Δ Temp (°C)	Average Temp (°C)	Density of Air (kg/m ³)	Mass Flowrate (kg/s)	Spec. Heat Capacity (J/Kg/K)	Power Absorbed (W)	Temperature Efficiency (%)
1	2.5000	24.8500	1.1959	0.1062	1005.0000	266.7471	10.0000
2	2.5000	25.1500	1.1947	0.0952	1005.0000	239.0645	10.3306
3	2.6000	25.2000	1.1955	0.0824	1005.0000	215.3174	10.7438
4	2.9000	25.3500	1.1959	0.0673	1005.0000	196.0912	11.9342
5	3.4000	26.0000	1.1955	0.0476	1005.0000	162.5639	14.1667
6	3.8000	26.6000		0.0336	1005.0000	128.4735	15.9664

Water Results Analysis							
EXPERIMENT	Δ Temp (°C)	Average Temp (°C)	Density of Water (kg/m ³)	Mass Flowrate (kg/s)	Spec. Heat Capacity (J/Kg/K)	Absolute Power Emitted (W)	Temperature Efficiency (%)
1	-15.0000	41.1000	983.0445	0.0041	4178.4382	256.7244	60.0000
2	-14.3000	40.9500	983.1219	0.0041	4178.4166	244.7619	59.0909
3	-13.9000	41.1500	983.0187	0.0041	4178.4456	237.8921	57.4380
4	-13.3000	41.5500	982.8117	0.0041	4178.5058	227.5788	54.7325
5	-11.9000	42.3500	982.3955	0.0041	4178.6352	203.5432	49.5833
6	-10.9000	43.0500	982.0288	0.0041	4178.7580	186.3746	45.7983

4 Data Analysis and Evaluation

4.1 Experiment One Analysis - The Effect of Varying Water Flow Rate

4.1.1 Power vs Water Mass Flow Rate

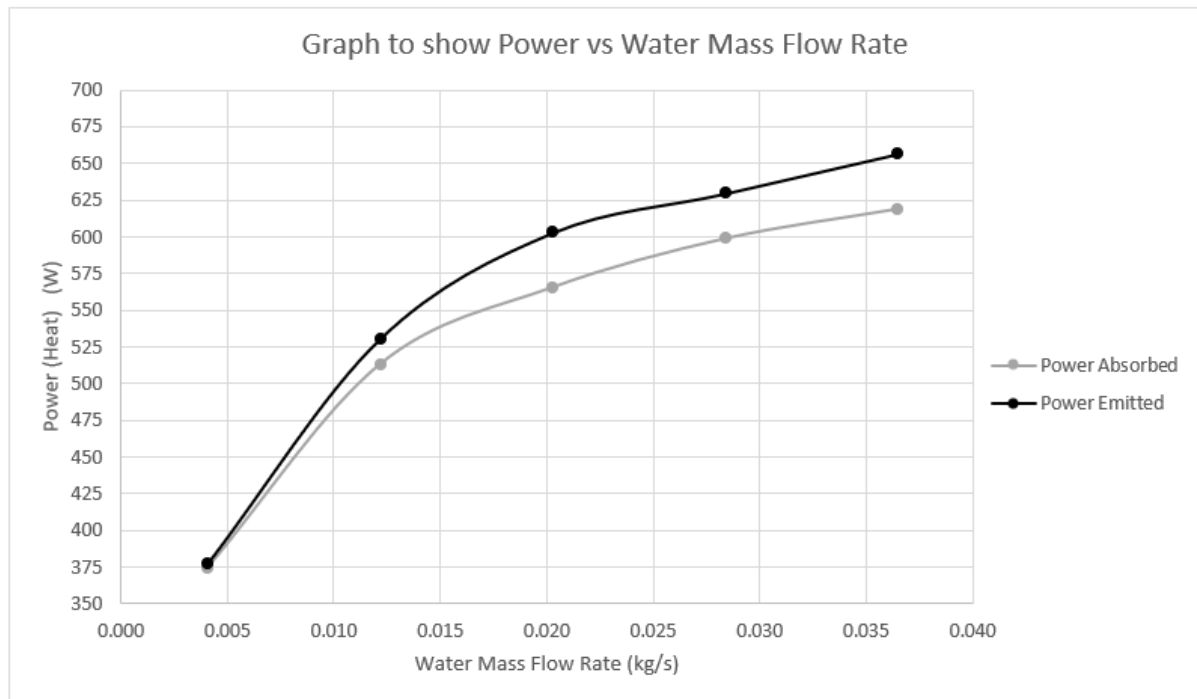


Figure 3 - Experiment 1 Power Graph

Figure three shows that there is an overall positive correlation between water mass flow rate and magnitude of power. It should be noted that the values of power emitted are absolute values. The gradient is much larger between 0.0041 and 0.0122 kg/s than seen on the rest of the graph, which shows a relatively constant, smaller gradient. At all times the power emitted is larger than power absorbed. This shows the inefficiencies of the system, explained further in figure 4, proving that energy is being lost to the surroundings. As the mass flow rate increases and more power is produced, the two lines diverge noticeably, thus showing efficiency and mass flow rate share an overall negative correlation.

4.1.2 System Efficiencies vs Water Mass Flow Rate

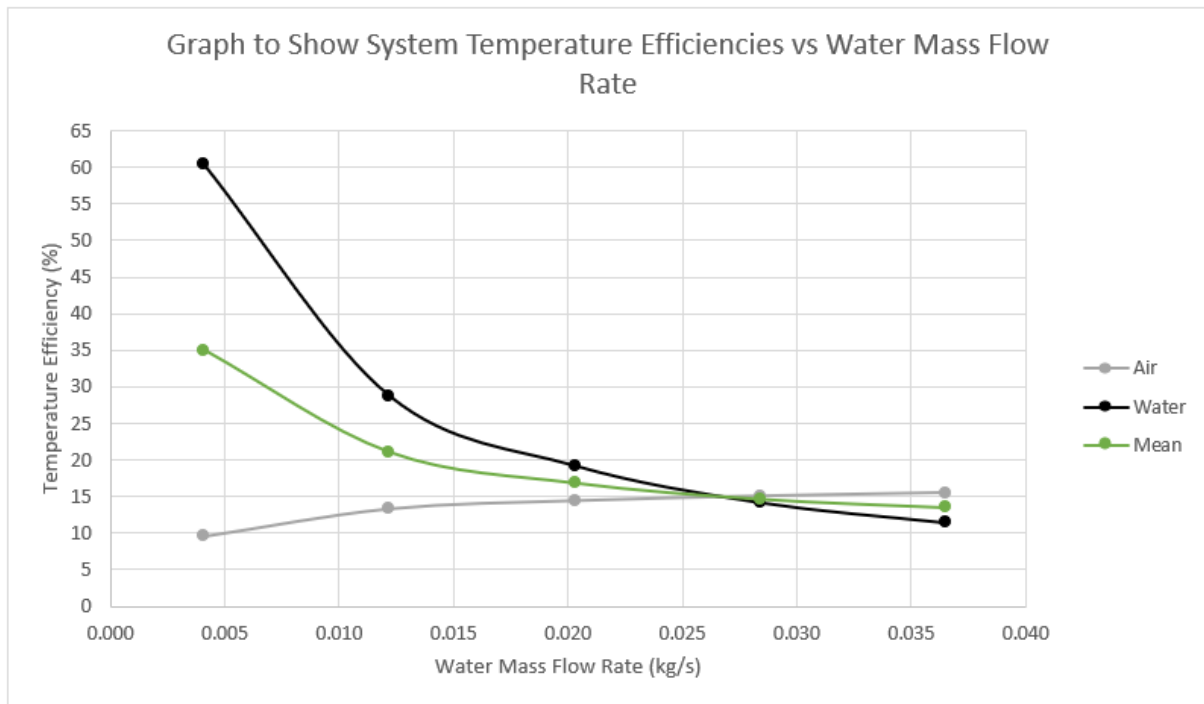


Figure 4 - Experiment 1 Efficiencies Graph

Figure 4 supports figure 3, showing an overall negative correlation between water mass flow rate and water temperature efficiency and an overall positive correlation between water mass flow rate and air temperature efficiency. Of these, the water values are affected more drastically than the air values; these factors result in an overall 21.5% decrease in system efficiency. This is an expected trend as the water flow rate is being altered and the air flow rate is constant, and there are evidently higher temperature changes in the air.

The raw data collected, and figures 3 and 5, show that as the water mass flow rate is increased, the amount of heat transfer experienced also increases. This shows that although the system as a whole performs much less efficiently at higher water mass flow rate, the system is capable of a higher amount of heat transfer. The amount of work done by the system counteracts the inefficiency it experiences; this is likely due to the amount that the flow rate can be increased. Between the first and last point on figure 3, the flow increases by 88%. This means nearly 43% more power can be emitted, which is work done by the system, overcoming the inefficiencies shown in figure 4.

The inefficiencies seen are likely due to the design of the heat exchanger. A crossflow configuration limits the time that the air can come into contact with the water; thus, there is a maximum amount of water the system can effectively use. After this maximum, the system still exchanges the same amount of heat, but the water it cannot use is wasted, thus explaining the results of figures 4 and 5. A counter-flow parallel configuration would most likely also show an increase in efficiency. Figures 3 and 5 suggest without the anomaly; the line would level out at high flow rate meaning a maximum heat transfer amount is reached (Holman, 2010). Again, this confirms the above suggestion.

4.1.3 Heat Transfer Coefficient vs Mass Flow Rate

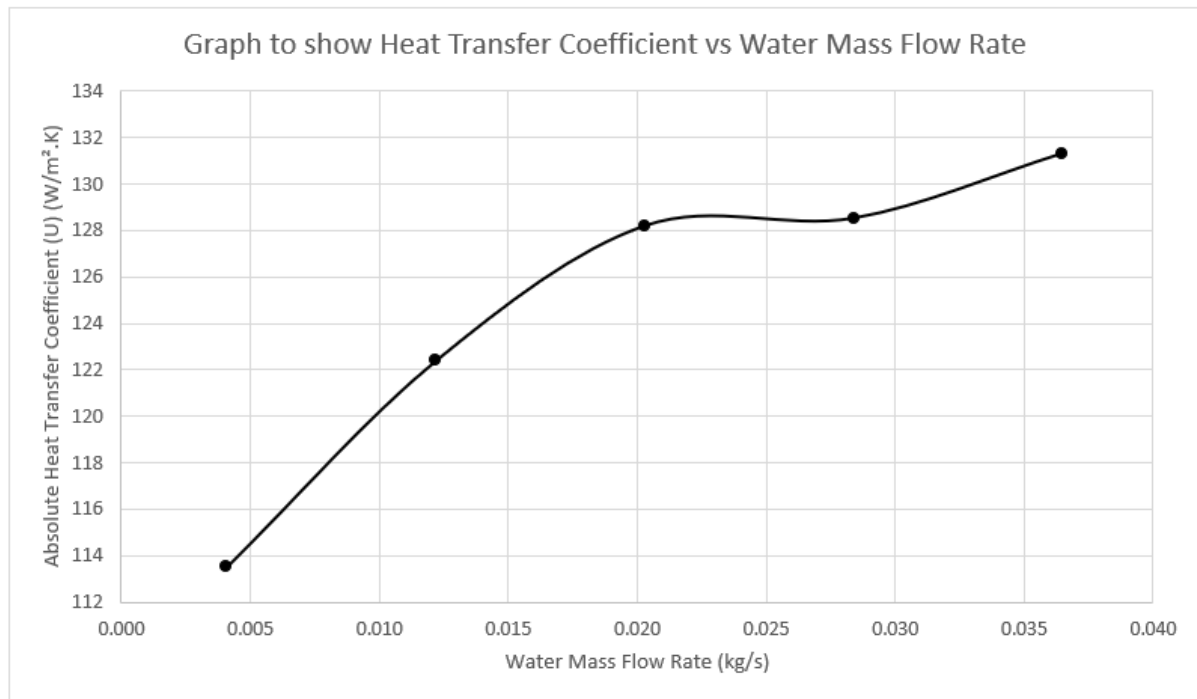


Figure 5 - Experiment 1 Heat Transfer Coefficient Graph

Figure 5 shows a clear positive correlation between water mass flow rate and heat transfer coefficient. It would appear that the heat transfer coefficient value at mass flow rate of 0.028 is outside of the expected trend, showing a possible anomaly. The values of heat transfer coefficient for flow rates of 0.0203 and 0.0284 are only 0.25% different. This could hint that it is likely the group did not let the system temperature stabilise between readings and effectively took the same reading twice. The experiment would have to be re-run to confirm this.

Despite the anomaly it is clear that an increased water mass flow rate increases the heat transfer coefficient. Because of how the heat transfer coefficient (U) is calculated with relation to heat emitted from the water (Q):

$$U = \frac{Q}{A \times LMTD}, \text{ meaning that, } Q = U \times LMTD$$

This shows that U is a constant of proportionality for Q . Therefore it can be concluded that figure five shows that the higher water mass flow rate, the more heat the system will transfer.

4.2 Experiment Two Analysis - The Effect of Varying Air Flow Rate

4.2.1 Power vs Water Mass Flow Rate

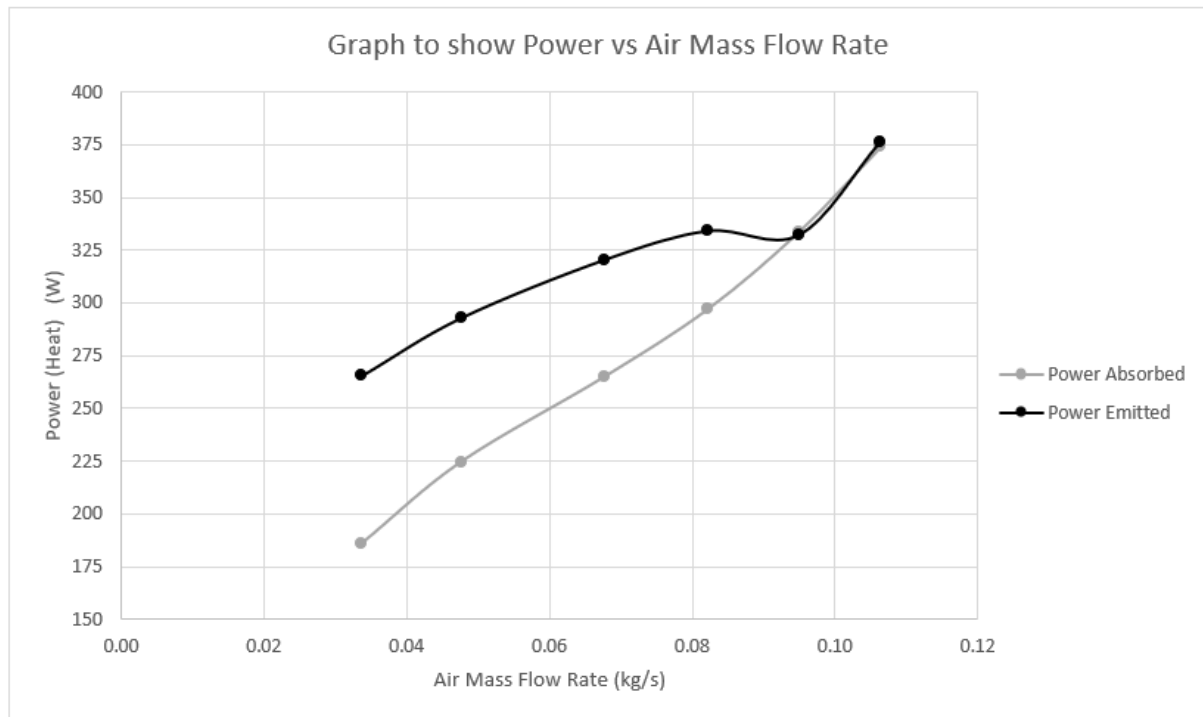


Figure 6 - Experiment 2 Power Graph

Figure 6 shows an overall positive correlation between power and air mass flow rate. It should again be noted that the values of power emitted are absolute values. It is clear that the values converge at higher air mass flow rate showing an overall increase in efficiency at higher air mass flow rate, supporting the results shown in figure 7. It is also clear that the trend is still increasing towards the higher air flow rates. Contrary to water flow rate, this suggests that if air mass flow rate was increased further, amount of heat transfer would still rise.

It is again clear that an anomaly is present at an air mass flow rate of 0.0949kg/s. Not only is there a noticeable deformation in the line, but shortly after this point the power absorbed by the air is temporarily higher than the power emitted from the air, this suggests that the system has gained energy from an external source. As it is a closed system, this goes against the law of conservation of energy and the first law of thermodynamics, as detailed in section 2.2. This may, however, be caused by inefficient insulation around the system, causing it to absorb heat from its surroundings.

4.2.2 System Efficiencies vs Water Mass Flow Rate

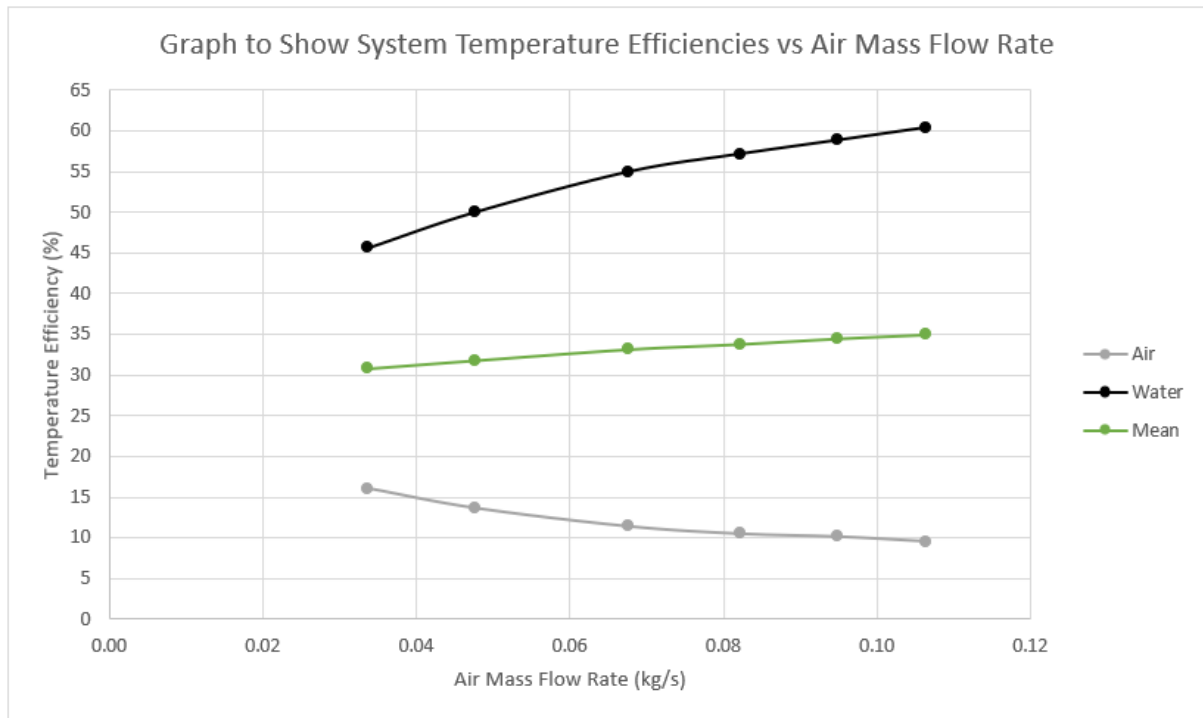


Figure 7 - Experiment 2 Efficiencies Graph

Figure 7 shows that with increased air mass flow rate, the air temperature efficiency decreases whilst the water temperature increases at a slightly higher rate. Because of this the overall efficiency of the system is slightly increased, but only by 11%, a small increase compared to other efficiency changes such as those seen in figure four, thus showing the changes in flow rate experienced have little effect on system efficiency.

4.2.3 Heat Transfer Coefficient vs Mass Flow Rate

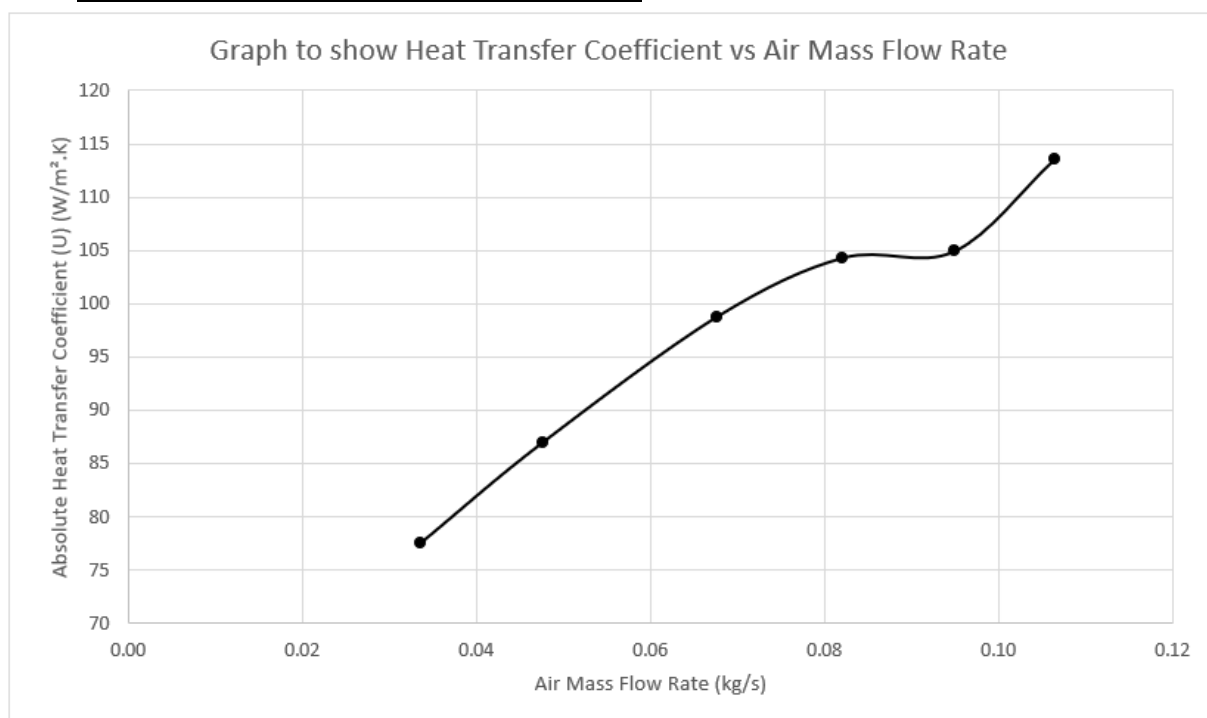


Figure 8 - Experiment 2 Heat Transfer Coefficient Graph

Figure 8 shows a clear positive correlation between air mass flow rate and heat transfer coefficient. This supports figure 6, as it shows the heat exchanger becomes more effective when more air is put into the system. This data also correlates to figure 5, showing an increase in air or water mass flow rate both increase the amount of heat transferred by the system.

Unlike experiment one, the increase of heat transfer coefficient does not show the opposite trend to efficiency. Increasing air mass flow rate makes the system more efficient overall, hence it is full expected more heat transfer will be possible.

4.3 Experiment Three Analysis - Effect of Varying Temperature (Driving Force)

4.3.1 Power vs Water Mass Flow Rate

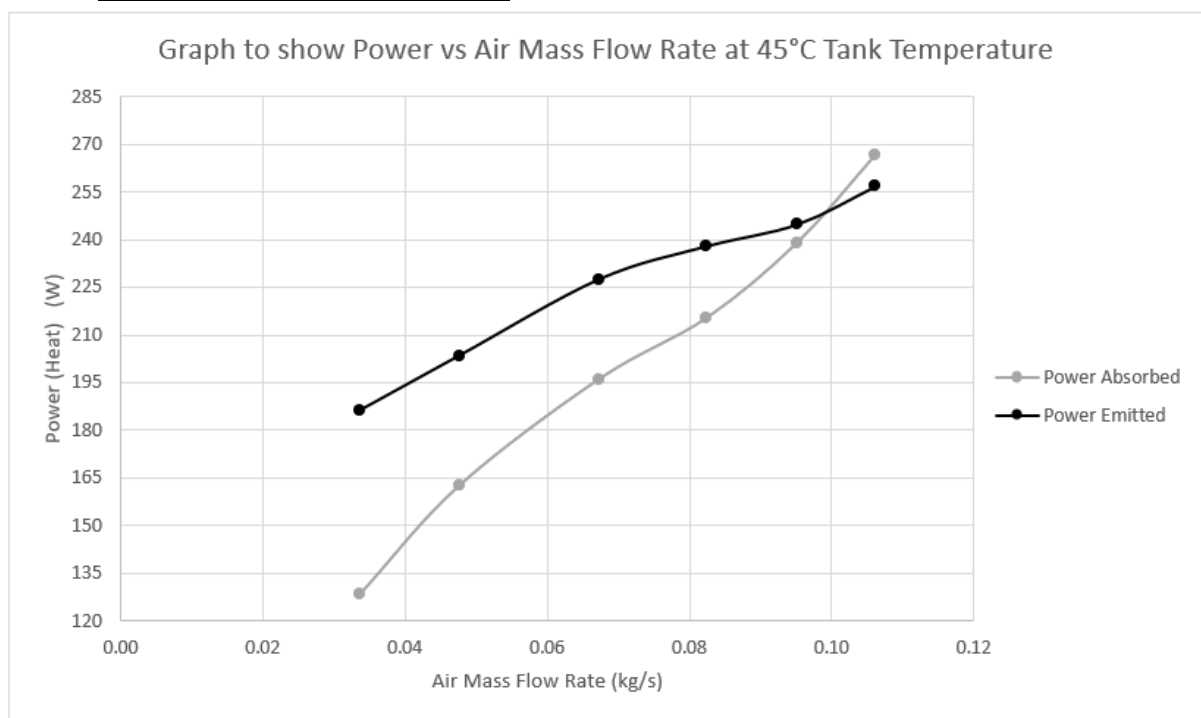


Figure 9 - Experiment 3 Power Graph

Figure 9 once more shows a clear correlation between air mass flow rate and power. It should again be noted that the values of power emitted are absolute values. This graph shows a very similar trend to figure 6, however there is no clear outlier in the dataset. This leads the author to believe even more that the outlier seen in figure 6 is just an anomaly.

This graph does however show untrustworthy data. Both lines converge early in the flow rate range and carry on overlapping, much like figure 6. By the final datapoint, the power absorbed is higher than the power emitted thus showing inaccuracy, as this once again disagrees with the law of conservation of energy and could show an anomaly, or that the system is absorbing energy from its surroundings; this should be re-tested for validation.

4.3.2 Power vs Water Mass Flow Rate for Each Temperature

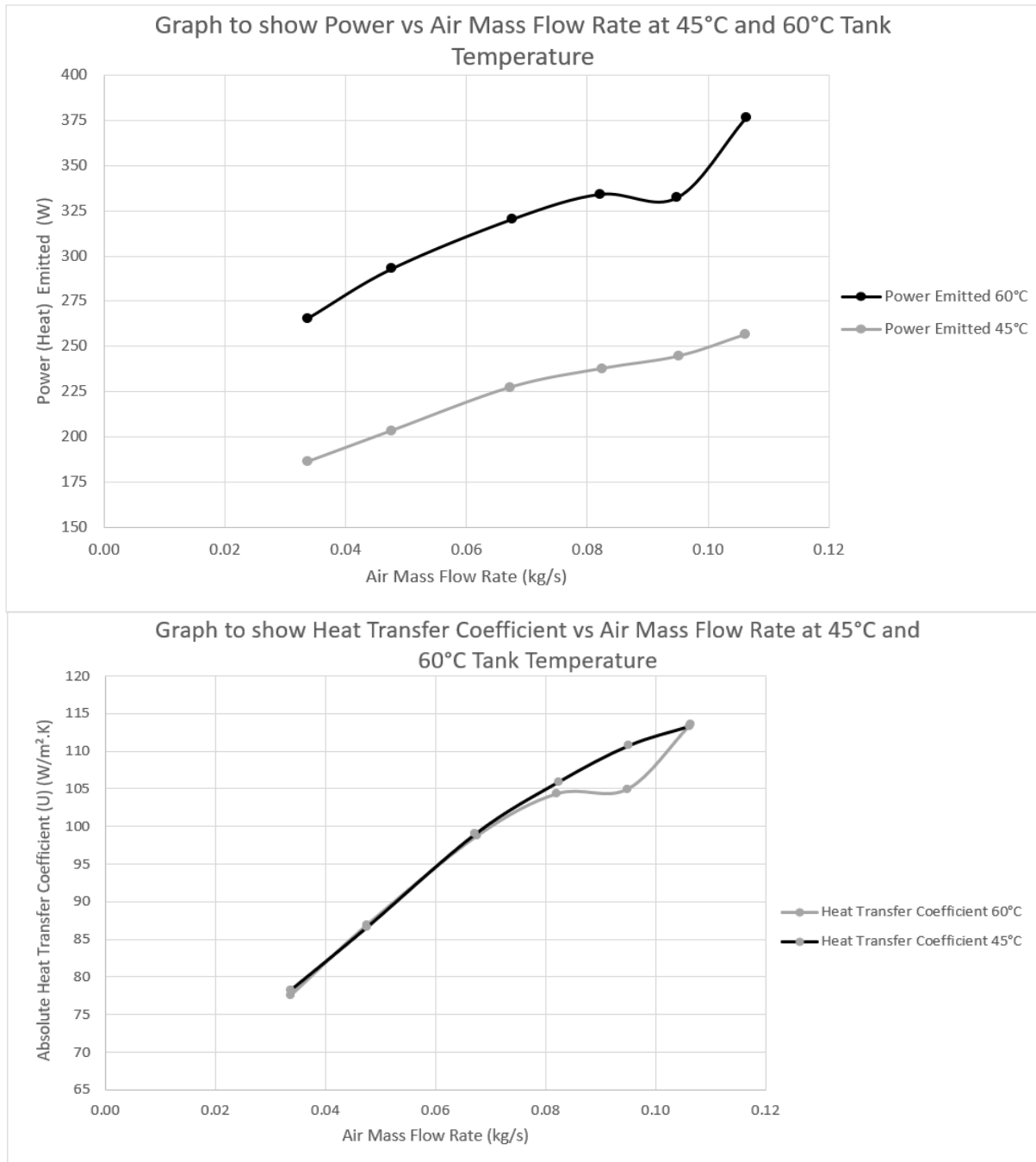


Figure 10 - Experiment 2 and 3 Power and Heat Transfer Coefficient Comparison

Figure 10 shows less power is emitted when the water supply temperature is lower. This is the trend expected as cooler water contains less heat energy. This is because specific heat capacity decreases with temperatures between 0°C and 35°C then climbs again, thus meaning the specific heat capacity of water at 45°C is below that of 60°C and this is used to calculate power (TecQuipment, 2017).

$$\text{Power Emitted} = \text{Mass flow rate water} \times \text{spec. heat cap. water} \times \Delta T_{\text{water}}$$

It is also clear that the heat transfer coefficient is largely unchanged between the two temperatures. This is because of how the value is calculated:

$$\frac{\text{Heat emitted from water}}{\text{Surface area} \times \text{LMTD}}$$

Factoring in the LMTD value ensures the starting temperature is considered, thus changing the calculation to suit the changed temperature (figure 2). It also shows the heat transfer effectiveness of the system is not dependant on water supply temperature (Andrews, 2016).

4.3.3 System Efficiencies vs Water Mass Flow Rate

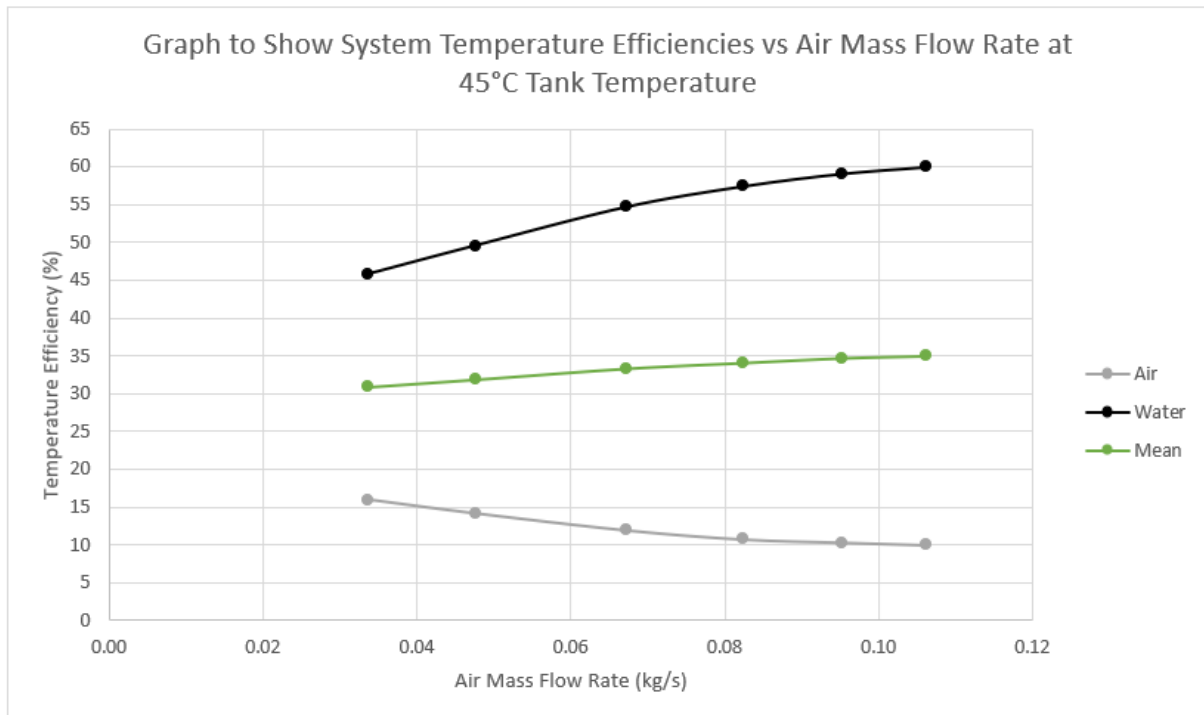


Figure 11 - Experiment 3 Efficiencies Graph

Figure 10 shows similar results to those of experiment 2, with an overall slight increase in water efficiency and slight decrease in air efficiency. The increase in water efficiency is at a slightly larger rate than that of the air, thus meaning a small increase in overall efficiency of 11.7%, almost exactly the same as with setup three. This shows the water supply temperature has very little effect on efficiency.

4.3.4 Heat Transfer Coefficient vs Mass Flow Rate

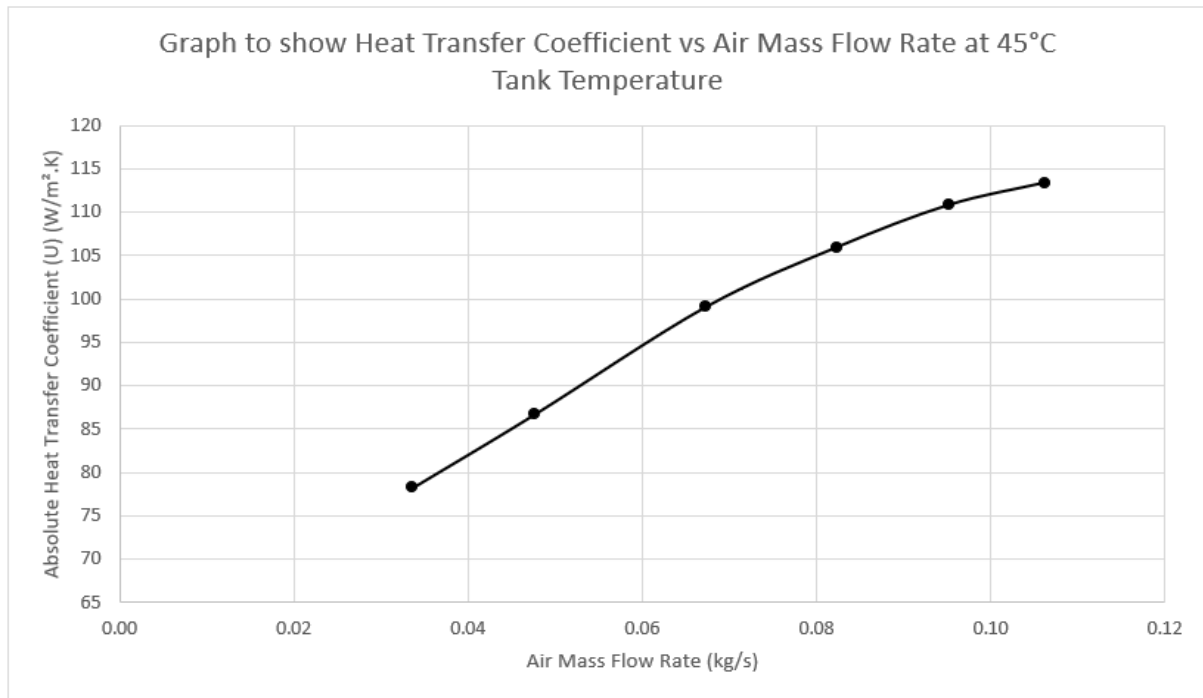


Figure 12 - Experiment 3 Heat Transfer Coefficient Graph

Figure 11 shows a very similar positive correlation to that of experiment two. The third experiment however does not see an anomaly and is a much smoother curve. The values of each datapoint, aside from figure 8's anomaly, are all within 2% difference hence showing that varying the water supply temperature has little effect on the effectiveness of the heat exchanger.

5 Conclusion

5.1 Experiment Limitations

It was clear that the data showed anomalies within the power graphs for experiments two and three, and the heat transfer coefficient graphs for experiments one and two. The anomalies here seem to be random, thus it is unlikely systematic error to blame. As detailed in section 4.1.3 it appears that the datapoints are close together, showing a likely error in reading the screen, and the possibility of the group not letting the system settle for enough time between readings.

It is seen on experiments 1 and 3 that the water temperature into the tank is warmer than inside the tank. This is unlikely to be true as the tank is where the water gets heated. The water may experience friction through the pipe, but not enough to heat it to this degree. It can be assumed there is inaccuracy within the calibration of the sensors because of this, potentially explaining some of the author's anomalies.

The data tables seen in section 3 include the Energy Balance Coefficient for each experiment. As a ratio between emitted and absorbed power, this should always be less than one. However tables 4 and 6 each show one value over 1. This correlates to figures 6 and 9, as they both show absorbed energy to be higher than emitted energy at some points. This shows either inaccuracy within the results, or that the system is absorbing energy from its surroundings (TecQuipment, 2017; Holman, 2010).

Another limitation is the possibility that at low water mass flow rate, because of the low velocity of the water, it is experiencing laminar flow. When laminar flow occurs a boundary layer forms along the surfaces of the heat exchanger tubes. This means the system becomes less effective and thus may show a reduced value for heat transfer coefficient and efficiency (University of Oslo, 2013).

5.2 Summary

As detailed in section 4.1, increasing the rate of water entering the system decreases efficiency, due to its crossflow nature, but increases the amount of heat transfer possible until its maximum value where no more water can be used for heat exchange.

As detailed in section 4.2, increasing the rate of air entering the system increases efficiency and increases the amount of heat transfer possible. These increases did not level out, showing that there was capacity to increase efficiency and effectiveness more with further increased air mass flow.

As detailed in section 4.3, reducing the water supply temperature reduces the power absorbed, but has little to no change on the efficiency or heat transfer coefficient.

For the most efficient performance from this system, and to achieve the most effective heat transfer, the data leads the author to believe the air mass flow rate should be increased as much as possible, the graphs in experiment 2 and 3 did not level out, showing no maximum point of correlation. Moreover, the system should be run with the water mass flow rate at the highest point before the graphs level off, this was around 0.202kg/s according to figure five. For efficiency, the temperature of the tank did not make a noticeable difference.

It must be noted that the author did not test any higher air mass flow rates and did not test the combination of higher water and air flow rates. Because of this, the above is only a hypothesis of how to make the system more efficient, applying knowledge from extrapolating the data. These conditions should be tested to fully support this statement.

The data from these experiments show that the cooling fluid exits the system warmer than it enters, and visa versa for the pre-heated fluid. This supports the second law of thermodynamics as heat is only transferred from a warm to a cold fluid. Moreover, the graphs always show entry temperatures of the two fluids are very dissimilar, and these temperatures converge when exiting the system. This supports the basic theory of a heat exchanger and proves thermal energy is being transferred inside the system.

6 Referenced Work

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