

University of Wales Trinity Saint David

School of Engineering

# **Heat Exchanger Laboratory Analysis**

**Thermofluid Mechanics**

**M5X00406**

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# 1 Introduction

## 1.1 Aims

To carry out a set of experiments that show the thermodynamic properties during transfer of heat between fluids separated by a heat exchanger. The results of these experiments will be used to prove the theory of heat exchangers

## 1.2 Objectives

To carry out experiments varying the mass flow rate of air over or water through a heat exchanger at pre-determined temperatures of water. Calculations will be performed on these test results then graphs will be plotted to analyse the systems.

## 2 Background

### 2.1.1 Heat exchanger theory

Heat exchangers are devices that allow two fluid streams to exchange energy (heat) usually without mixing (Cengel, 2002). Although they are normally used to cool a fluid, they can be used to heat up a stream, condense a fluid or boil a fluid (Albanakis, et al., 2009).

### 2.1.2 Heat exchanger Design

The three basic types of heat exchanger are; Recuperators, in these the fluid streams are kept separate as they interact with each other. Regenerators, in these the fluids alternately occupy the same space. Direct contact heat exchangers, in these the hot and cold fluids are mixed e.g. a cooling tower (Kreith, 2011).

The two main types of recuperator heat exchanger are counter flow and parallel flow the advantage of parallel flow is that the initial temperature change is greater for a small area exchanger. The main disadvantage is the hot fluid can never reach the temperature of the hottest the cold fluid gets to at any point see figure 1. With counter flow heat exchangers, the final temperature of the cooling fluid can be higher than the outlet temperature of the hot stream as seen in figure 1 (Kreith, 2011). This makes them more efficient.

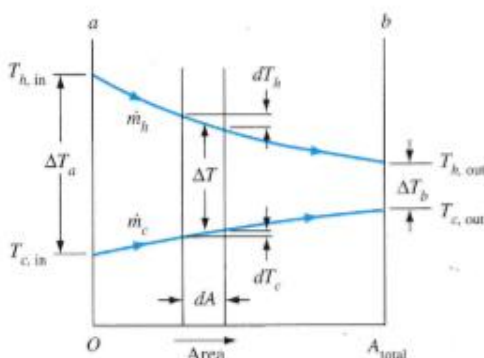


FIGURE 8.12 Temperature distribution in single-pass parallel-flow heat exchanger.

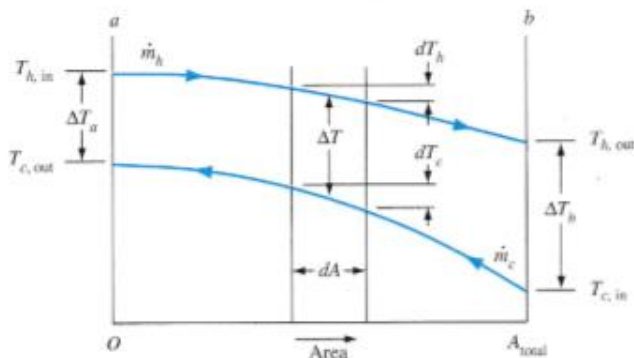


FIGURE 8.13 Temperature in single-pass counterflow heat exchanger.

*Figure 1 Stream Temp Changes Parallel and Cross Flow (Kreith, 2011)*

In automotive applications the design tends to favour cross flow, this has a similar temperature distribution to parallel though the hot stream is more linear (Emmenthal & Hucho, 1974).

## 2.2 Test Rig

### 2.2.1 General set up

To test the effectiveness of heat exchangers the Tecquipment TD1007 water to air exchanger will be used see figure 2. This has a fixed open inlet air orifice and a constant fan speed; it also has a fixed water pump speed. These dimensions are important for the calculations and can be seen in table 2 in the appendices 8.2.1.



Figure 2 TD1007 (TecEquipment Ltd, 2017)

Initial set up involves turning on, filling the tank with the allocated button and setting the hot water tank temperature with the arrows on the large red display.

### 2.2.2 Adjusting mass air flow

To adjust the mass air flow the red gate is lowered to restrict airflow, to monitor the amount of airflow the pressure difference is measured between the inlet and the room. See figure 3.

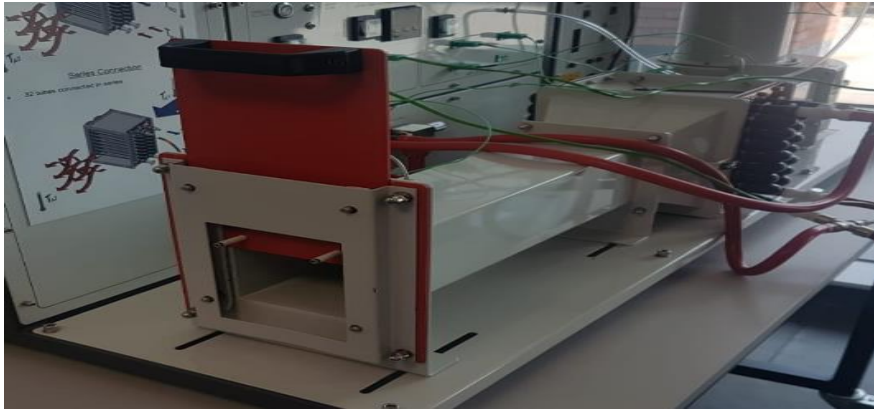


*Figure 3 Air Flow gate*

### 2.2.3 Adjusting mass water Flow

To adjust the water flow rate in the heat exchanger a knurled knob is screwed in clockwise to restrict water flow or anticlockwise to increase. The upper left display gives the result in liters per minute. See figure 4.



*Figure 4 Water Flow Control*

### 2.2.4 Results taking

The effect of air flow, water flow and tank temperature are read by 5 thermocouples;

1. TA1 inlet air temperature.
2. TA2 outlet air temperature.
3. TA3 ambient air temperature.
4. TW1 inlet water temperature.
5. TW2 outlet water temperature.

The order to run the experiment is;

- Set the hot water tank temperature
- Set the Air Pressure Difference
- Set the water flow rate

- Wait 6 mins (20 if the tank temperature has been adjusted) for experiment temperatures to stabilise.
- Record the water and air temperatures from thermocouples.

### 2.2.5 Calculations

The results are put into excel and using the given calculations (see appendices for equations) the following graphs are created.

### 3 Experiment 1 – The Effect of Varying Water Flow Rate

#### 3.1 Methodology

For this experiment the water tank was set to 60°C, the air pressure difference was set to 250pa and the first reading was taken at 2.25l/min water flow. The water flow was then reduced by 0.5 l/min stopping and taking a reading each time until 0.25 l/min was achieved.

#### 3.2 Results and Analysis

The power emitted is a negative as it is heat loss from the control volume of the heat exchanger piping but for analysis it has been converted to absolute. The results are placed in order of increasing flow rate on the x axis not the order in which they were taken. This approach of absolute values and increasing flow rate has been used to analyse all results within the report.

##### 3.2.1 Chart 1 Power

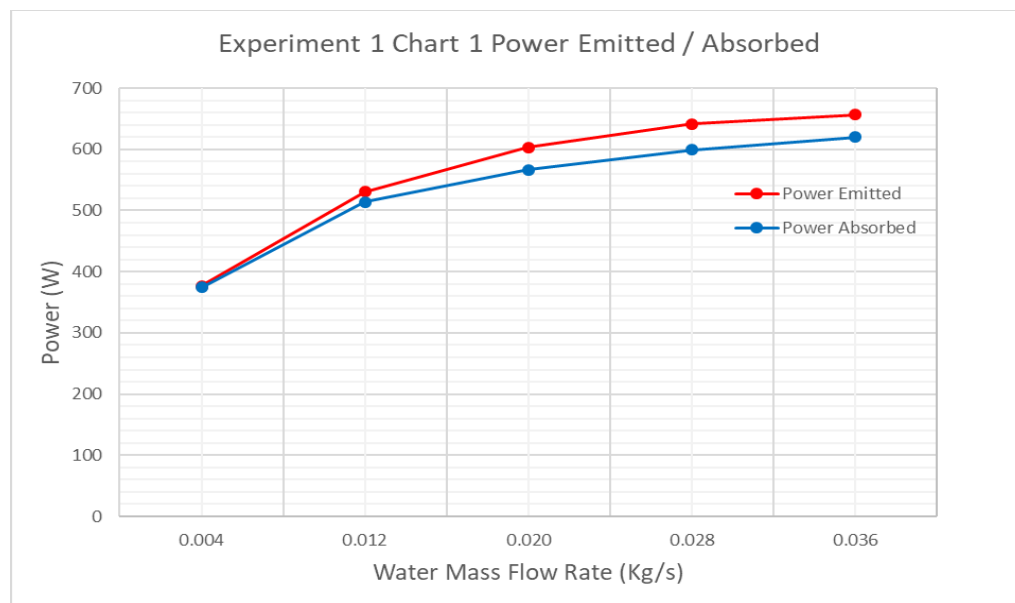


Figure 5 power emitted and absorbed experiment 1

Figure 5 shows that increasing the water flow rate increases the power absorbed and emitted from the system. The differences in absorbed by the air and emitted by the water may be due to losses to the surroundings or inaccuracies in the measurements. Throughout most of the tests the water into the heat exchanger was hotter than the hot water tank this may be due to inaccurate or badly placed thermocouples. You would expect the water to only cool once it has left the hot water tank not rise. Figure 5 also show that the energy transfer is not increasing linearly and is starting to level off. This

is thought to be because there will be a maximum energy transfer and increasing the water flow rate will have no further effect if anything it may decrease.

### 3.2.2 Chart 2 Efficiencies

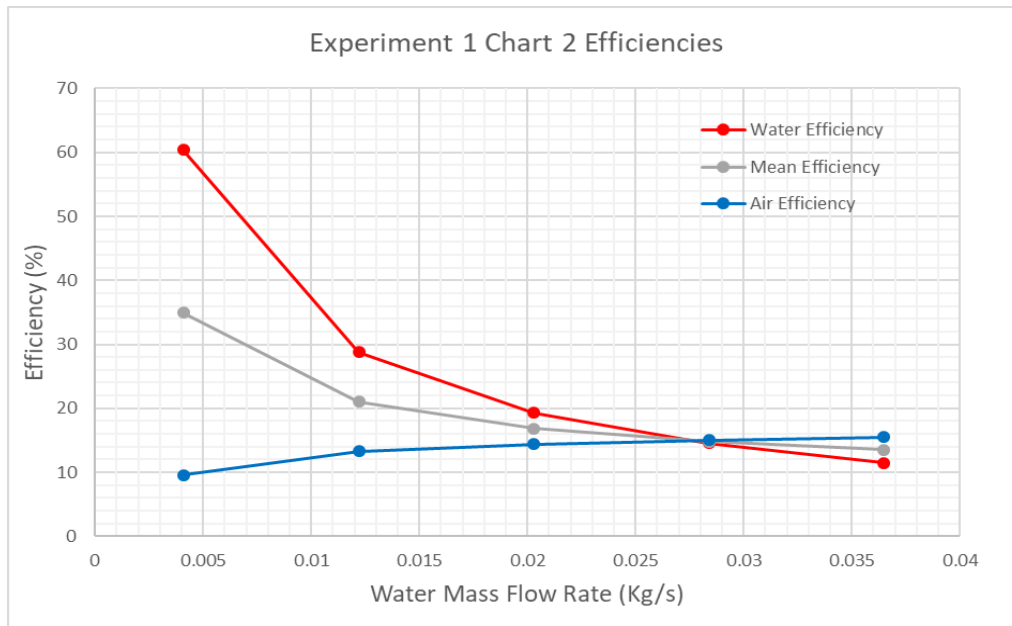


Figure 6 Experiment 1 efficiencies

Figure 6 shows that although more energy is transferred at a faster water flow rate (from fig 5) the water efficiency and therefore the mean efficiency drop (as the water efficiency has the largest effect on mean due to the larger temperature delta recorded in the water.) with increased water flow rates. The air efficiency increases with water flow rate as the power exchange increases as shown in figure 5 this is because of a smaller temperature delta in air for an increase in power.

### 3.2.3 Chart 3 Heat Transfer Coefficient

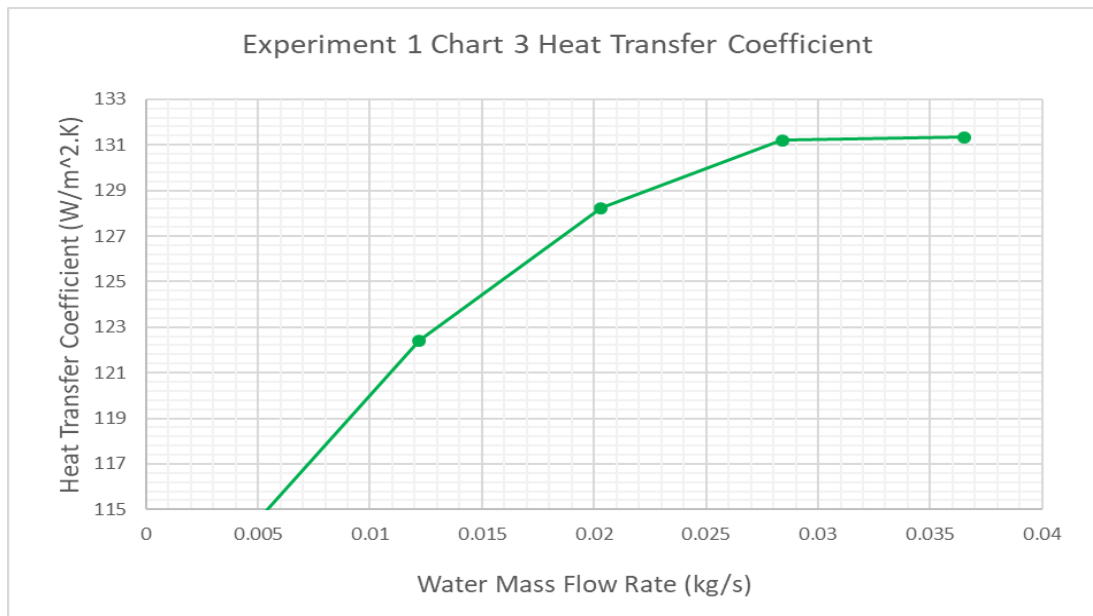


Figure 7 Experiment 1 Heat Transfer Coefficients

Figure 7 shows a similar trend to figure 5 for power increase with flowrate. It also shows that the maximum heat transfer is around 0.03  $\text{kg/s}$  of water flow as the graph is levelling off.

## 4 Experiment 2 – The Effect of Varying Air Flow Rate

### 4.1 Methodology

For this experiment the water tank was kept at 60°C, the water flow was kept at 0.25 l/min from end of previous experiment and the variable was air pressure difference starting at 250pa then reducing by 50pa until at 50pa difference then a further 25pa until at 25pa.

### 4.2 Results and Analysis

#### 4.2.1 Chart 1 Power

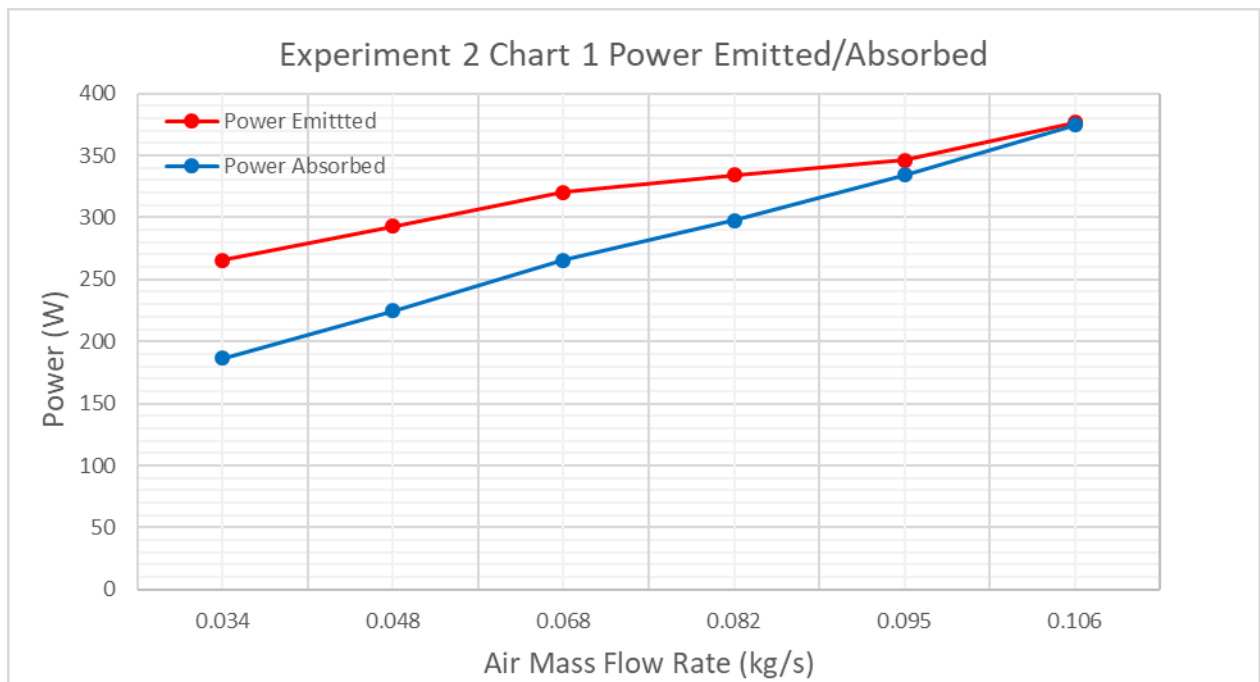


Figure 8 Experiment 2 Power absorbed/ emitted

Figure 8 shows the power absorbed increasing linearly this leads to believe that there is more scope to increase mass air flow rate before the power starts to level. The larger differences in powers at the restricted flow tends to suggest that more losses are in the system when the fan speed is restricted downstream.

## 4.2.2 Chart 2 Efficiencies

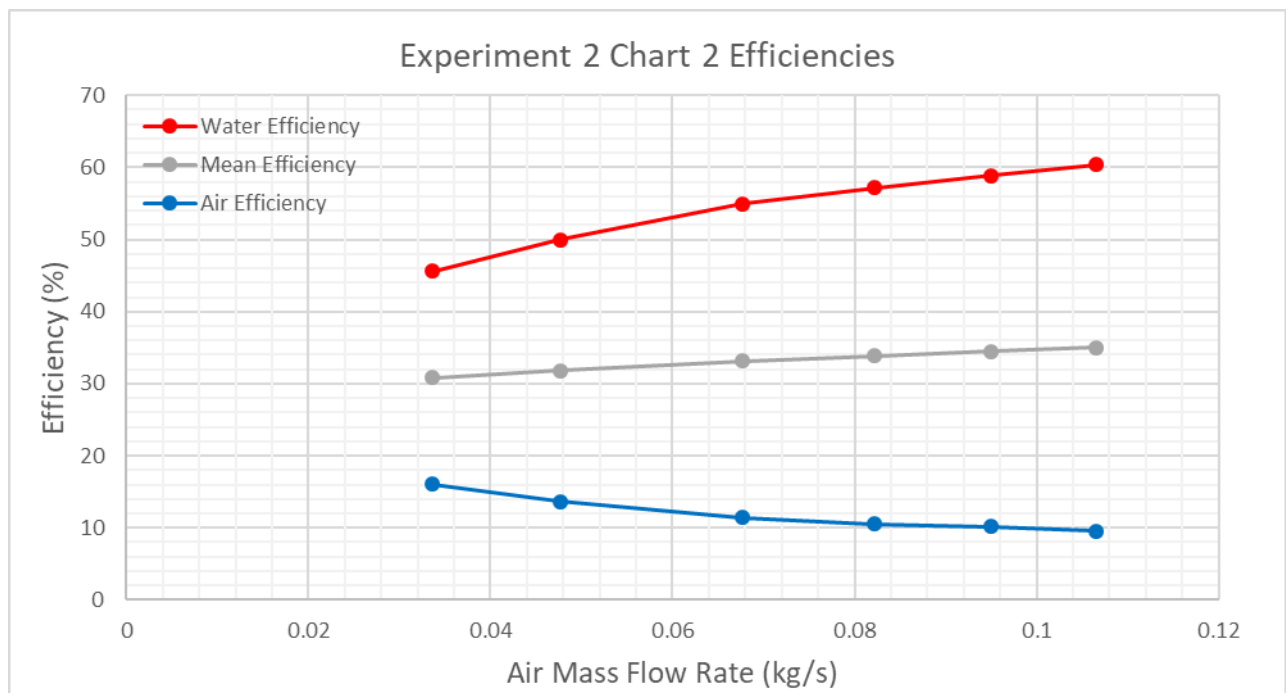
*Figure 9 Experiment 2 Efficiencies*

Figure 9 shows the mean efficiency increases with an increased air mass flow rate over the heat exchanger. This is the opposite mean trend to the increasing the water mass flow in experiment 1 (see figure 6). This is due to the larger water temperature change when the air flow rate is increased as the air efficiency decreases.

### 4.2.3 Chart 3 Heat Transfer Coefficient

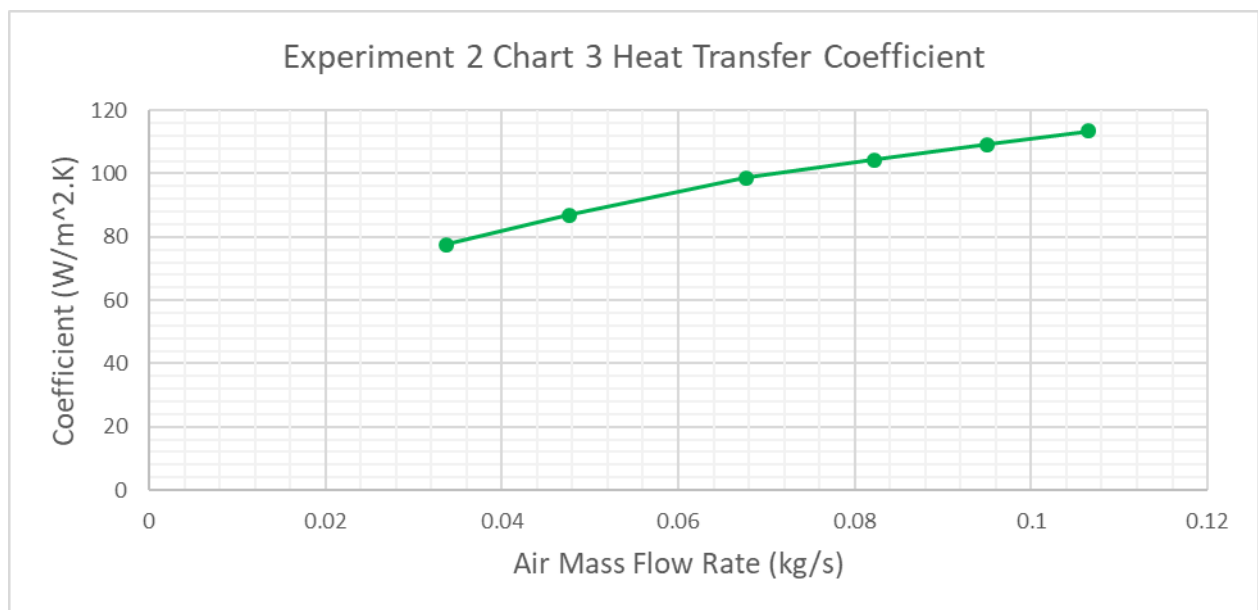


Figure 10 Experiment 2 Heat Transfer Coefficients

The linear increase in this shows that there is more scope to increase air flow to increase the temperature coefficient.

## 5 Experiment 3 – The Effect of Varying Temperature (Driving Force)

### 5.1 Methodology

This was a repeat of experiment 2 with the flow rate at 0.25 l/min and decreasing the pressure difference from 250pa to 25pa with the same steps except the hot water tank Temperature (Driving Force) was at 45°C for this experiment.

### 5.2 Results and Analysis

#### 5.2.1 Chart 1 Power

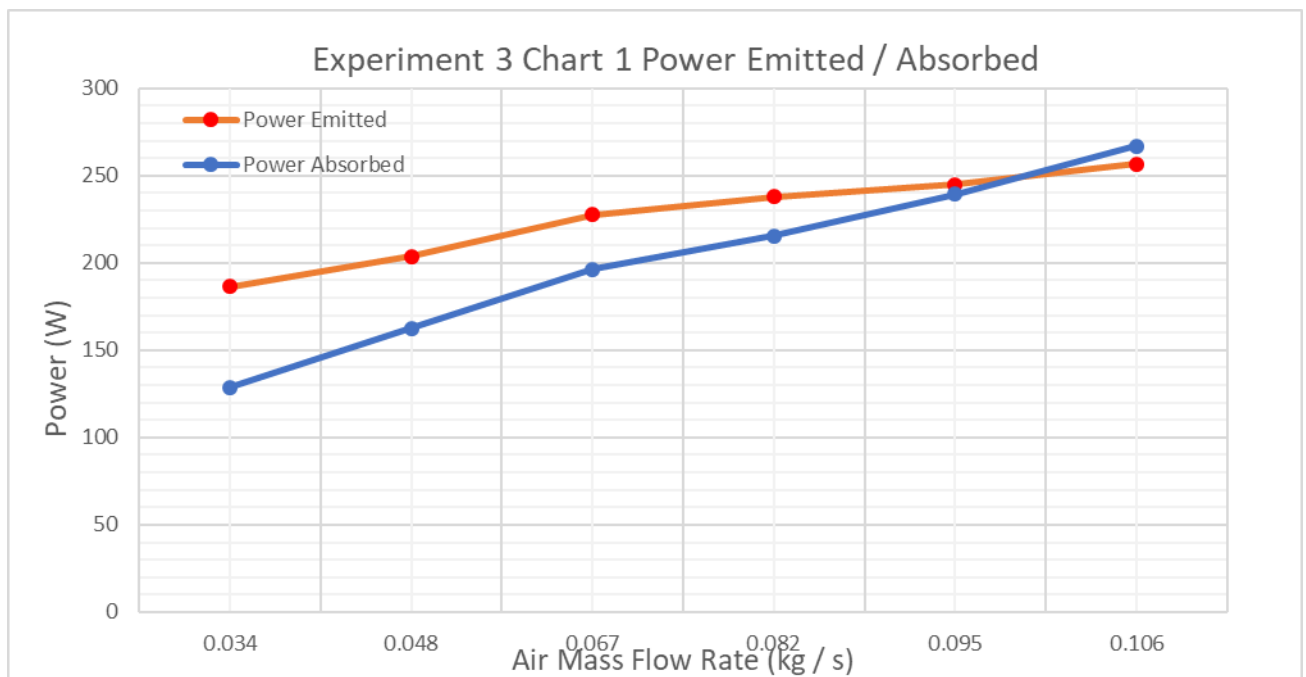


Figure 11 Experiment 3 Power Emitted/ Absorbed

Figure 11 shows the power absorbed and emitted at 45°C does not raise as steeply with air mass flow increase as in figure 8 when at 60°C. this shows that when the driving force is lowered (water temp entering heat exchanger) the system gets closer to peak power as it is levelling.

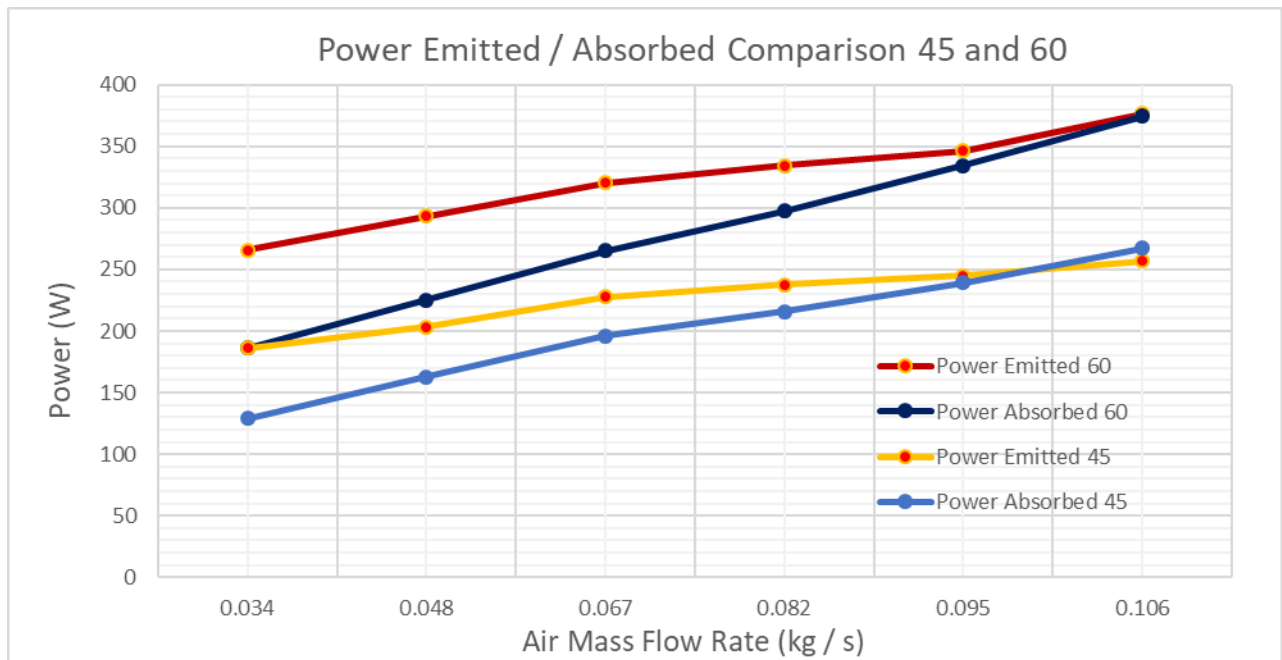


Figure 12 Experiment 3 compared 45 with 60

Figure 12 shows the shallower gradient as explained previously at lower temperatures. The overall power is lower at 45 this is to be expected as the initial temperature difference is lower between the two streams.

### 5.2.2 Chart 2 Efficiencies

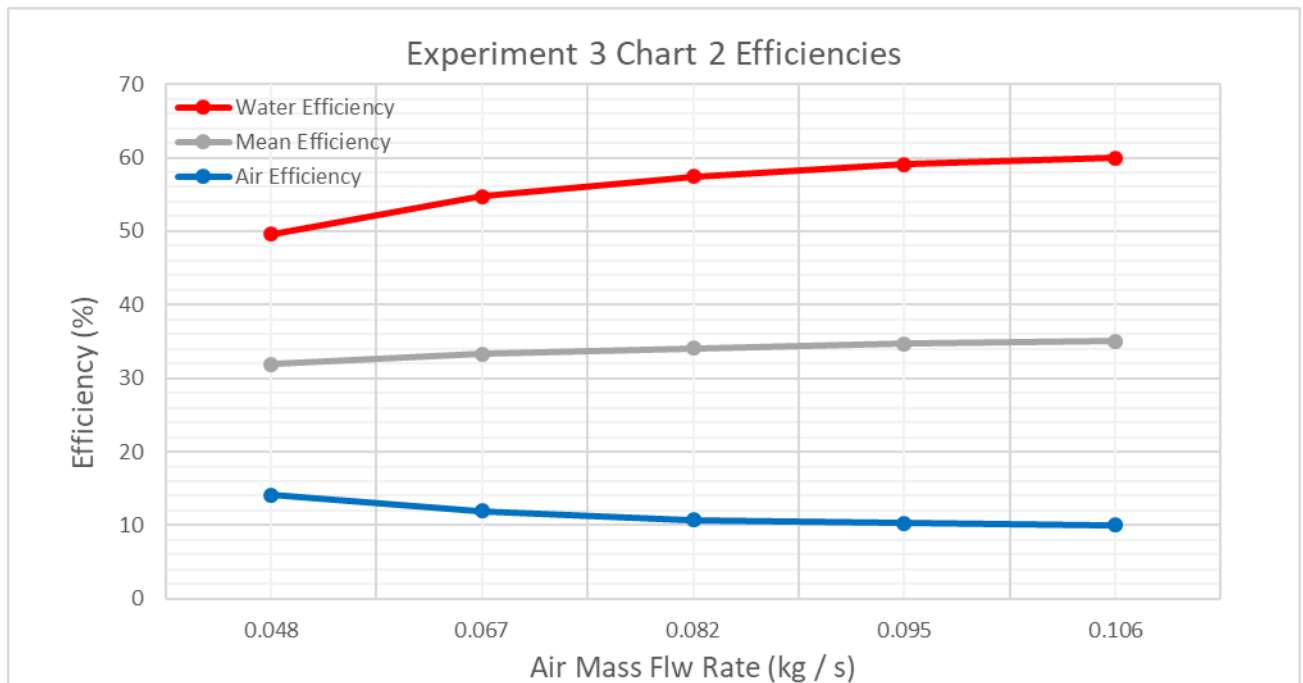


Figure 13 Experiment 3 efficiencies

Figure 13 has the same trend as experiment 2 although the water efficiency is slightly lower. This is due to the lower water temperature and therefore the lower water to air temperature delta.

## 5.2.3 Chart 3 Heat Transfer Coefficient

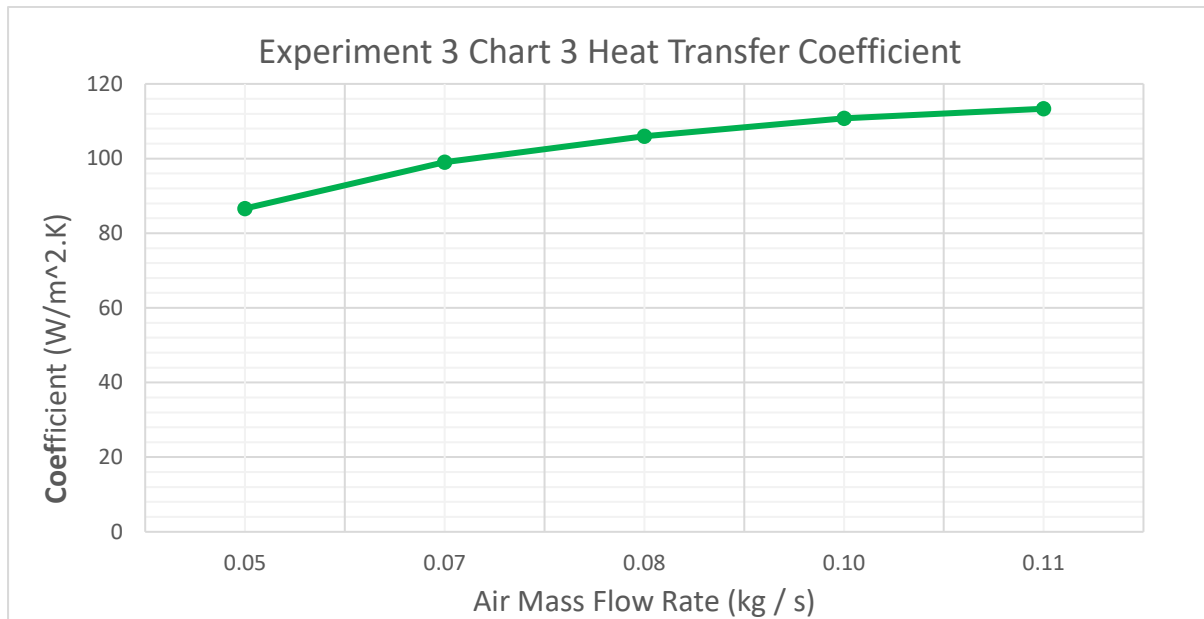


Figure 14 Experiment 3 Coefficients

Figure 14 shows what was described for the power at 45 that the peak heat transfer is levelling off and the line is less linear than the coefficient for experiment 2. This is similar because the heat transfer coefficient and the power are directly proportional to each other.

## 6 Conclusions

### 6.1 Effects of flow rates air and water

During experiments 1 it could be seen that at the highest water flow it was near peak energy transfer for that air flow and heat exchanger set up at that tank water temperature. Experiment 2 showed that the air mass rate over the heat exchanger could be increased more to improve energy transfer, when testing at that slower water flow rate. Essentially increasing the flow rate of either stream increases the heat energy transfer although this does not necessarily increase efficiency.

At lower stream mass flow rates the heat transfer may be lower due to the fact the boundary layers build up in laminar flow conditions providing insulation to water deeper in the pipes but efficiently cooling the edges at the boundary causing the higher water efficiency (Bergman, Lavine, Incropera, & Dewitt, 2011).

As the coldest the hot stream gets on exit is never colder than the entry of the cold stream this proves the theory researched about parallel heat exchangers see figure 1.

### 6.2 Other variables

#### 6.2.1 Different Piping arrangements

A Counter flow heat exchanger could be tested to see if the performance would increase for all the previously discussed reasons to do with the ability to have lower hot stream exit temperatures.

#### 6.2.2 Different Heat Exchangers

Research showed that heat exchanger area is a major factor in the power output of a system as can be seen from figure 1. The effective area can be increased with fins which act like heat sinks on the piping or by just inserting a heat exchanger with larger pipe surface area (Cengel, 2002). The formula:

$$\dot{Q} = UAF\Delta T_{LM}$$

Shows that the area is directly proportional to the total energy exchange.

The material the heat exchanger is made from would affect the Heat transfer coefficient (U) this would then effect the overall heat energy transfer.

## 6.3 Validity of results

### 6.3.1 Energy balance coefficient (CED)

This is the relationship between the energy absorbed and the energy emitted.

$$C_{EB} = \frac{\dot{Q}_A}{\dot{Q}_E}$$

From this it can be seen that this ratio is sometimes greater than 1 which in reality is impossible as the second law of thermodynamics states that energy cannot be created (Cengel, 2002). The reason for this is that it is not a perfect system and there are losses which are not accounted for in the experiments measurements.

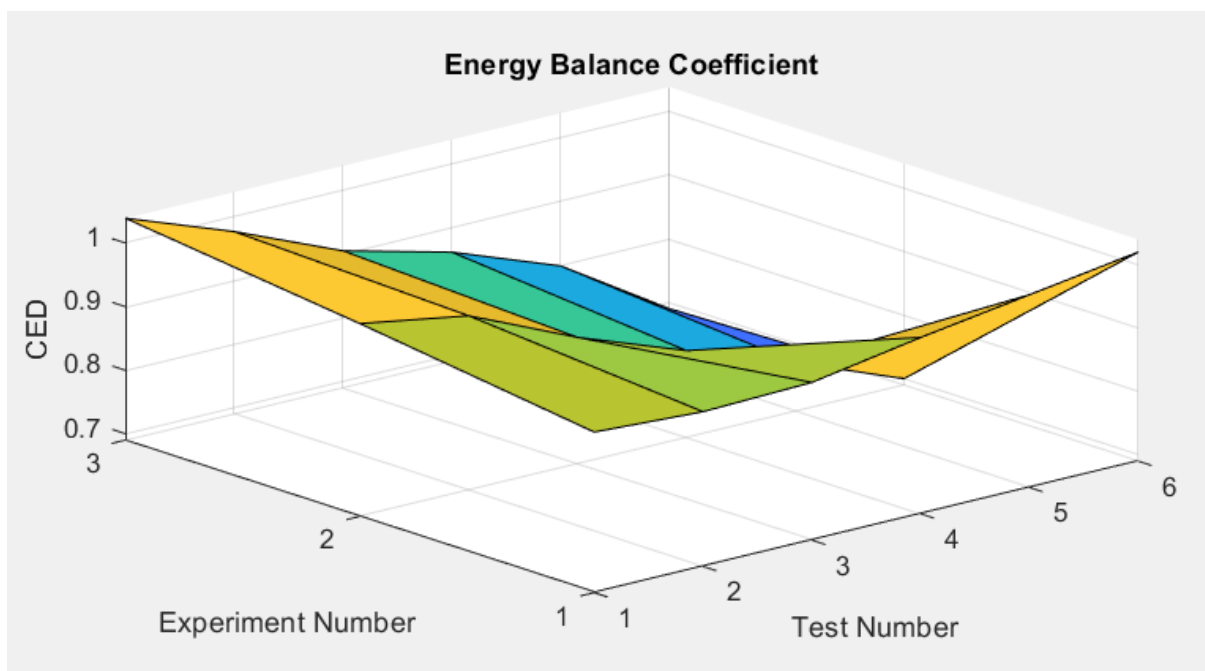


Figure 15 3D Energy Balance Coefficient

In figure 15 the 'test number' axis has the results in the order they were taken therefore test 1 is the fastest air or water flow rate test 6 is the slowest.

Figure 15 shows that for each experiment when the air or water is at max flow rate (test1) the energy balance is closest to 1. In experiment 1 when the water flow rate is decreased throughout the tests the CED has little change. In experiments 2 and 3 when the air flow is decreased throughout the tests the CED drops to below 0.7 this is because of the losses in the energy absorbed in the air stream as this has considerably lower wattage than the heat emitted from the water side for the same test.

To create Figure 15 the result for experiment 1, test 6 was interpolated using MATLAB's Fill missing linear function. That point is only representative as is reality the water flow rate could not get low enough to carry out that test.

### 6.3.2 Thermocouples

The other reason for a CED of over 1 may be due to inaccurate thermocouple as previously said before the largest increase in temperature outside the tank is  $3.6^{\circ}\text{C}$  that is seen in Experiment 3 at 249pa. when these reading were taken the in/out temperature delta for the water was only  $-15^{\circ}\text{C}$  this means that a perceived inaccuracy of 3.6 degrees is 24% of that total delta.

### 6.3.3 Barometer

The ambient pressure on the day was taken off the internet not from a weather station within the room as local pressures and the buildings HVAC system could affect this.

### 6.3.4 Repeatability

A good indication of the validity of the results is to repeat the experiment and see if the same results can be obtained. Before any additional tests it would be wise to remove the known inaccuracies by calibrating the thermocouples for their positions and obtaining a barometer.

## 7 References

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## 8 Appendices

### 8.1 Equations

#### 8.1.1 Nomenclature

Table 1 Nomenclature Table (TecQuipment Ltd, 2014)

| Symbol                            | Definition                                                                                   | Units                           |
|-----------------------------------|----------------------------------------------------------------------------------------------|---------------------------------|
| $A$                               | Heat Transfer Area                                                                           | $\text{m}^2$                    |
| $A_O$                             | Orifice Area                                                                                 | $\text{m}^2$                    |
| $C$                               | Heat capacity                                                                                | $\text{J.K}^{-1}$               |
| $C_d$                             | Coefficient of discharge (orifice)                                                           | -                               |
| $c_p$ and $c_{pA}$ and $c_{pW}$   | Specific Heat Capacity, of air and water at Constant Pressure (atmospheric pressure for air) | $\text{J.kg}^{-1}\text{K}^{-1}$ |
| $LMTD$                            | Logarithmic Mean Temperature Difference                                                      | K or °C where shown             |
| $\rho$ and $\rho_A$ and $\rho_W$  | Density, of air and water                                                                    | $\text{kg.m}^{-3}$              |
| $\eta_o$                          | Overall Efficiency                                                                           | %                               |
| $C_{EB}$                          | Energy Balance Coefficient                                                                   | -                               |
| $\bar{\eta}_A$ and $\bar{\eta}_W$ | Mean Temperature Efficiencies                                                                | %                               |
| $\Delta p$                        | Orifice pressure drop                                                                        | Pa                              |
| $\underline{Q}$                   | Heat energy transferred for a unit mass                                                      | $\text{J.kg}^{-1}$              |
| $\dot{Q}$                         | Heat energy transferred for a unit time (heat transfer rate - or power)                      | W                               |
| $\dot{Q}_A$ and $\dot{Q}_W$       | Heat energy (power) absorbed by the air and emitted by the water in a unit time              | W                               |
| $R$                               | Specific gas constant for dry air                                                            | $287 \text{ J/kg.K}$            |
| $T, T_W, T_A$                     | Temperature, of water and air                                                                | K or °C where shown             |
| $\Delta T$                        | Change in Temperature                                                                        | K or °C where shown             |
| $\bar{T}$                         | Mean Temperature                                                                             | K or °C where shown             |
| $U$                               | Heat Transfer Coefficient                                                                    | $\text{W.m}^{-2}\text{K}^{-1}$  |
| $\dot{m}_W$ and $\dot{m}_A$       | Mass Flow Rate (hot water circuit and air circuit)                                           | $\text{kg.s}^{-1}$              |

#### 8.1.2 Specific Heat Capacity of water

$$c_{pW} = 0.996185 + 0.0002874 \left( \frac{T + 100}{100} \right)^{5.26} + (0.011160 \times 10^{-0.036T}) \times c_{pW@15^\circ}$$

Equation 1 - Specific Heat Capacity (TecQuipment Ltd, 2014)

## 8.1.3 Air Density

$$\rho_a = \frac{P}{RT} \quad \text{Equation 2 - Air Density}$$

## 8.1.4 Water Density

$$\rho_w = \frac{(999.839 + 16.952T - 7.990 \times 10^{-3}T^2 - 46.241 \times 10^{-6}T^3 + 105.846 \times 10^{-9}T^4 - 281.030 \times 10^{12}T^5)}{(1 + 16.887 \times 10^{-3}T)} \quad \text{Equation 3 Water Density}$$

## 8.1.5 Mass Flow Rate

$$\dot{m}_w = \frac{\text{Vol Flow (Lmin)}}{60000} \times \rho \quad \text{Equation 4 Water Mass Flow Rate}$$

$$\dot{m}_a = C_d \times A_o \sqrt{\Delta P \times 2 \times \rho_a} \quad \text{Equation 5 Mass Flow Rate Air}$$

## 8.1.6 Power Emitted/Absorbed

$$Q = \dot{m} \times C_p \times \Delta T \quad \text{Equation 6 Power Emitted/Absorbed}$$

## 8.1.7 Efficiencies

$$\eta_w = \frac{T_{w1} - T_{w2}}{T_{w1} - T_{a1}} \times 100 \quad \text{Equation 7 Water Side Efficiency}$$

$$\eta_a = \frac{T_{a2} - T_{a1}}{T_{w1} - T_{a1}} \times 100 \quad \text{Equation 8 Air Side Efficiency}$$

## 8.1.8 Heat Transfer Coefficient

$$LMTD = \frac{(T_{w2} - T_{a2}) - (T_{w1} - T_{a1})}{\ln\left(\frac{T_{w2} - T_{a2}}{T_{w1} - T_{a1}}\right)} \quad \text{Equation 9 Log Mean Temperature Difference}$$

$$U = \frac{\dot{Q}_w}{A \times LMTD} \quad \text{Equation 10 Heat Transfer Coefficient}$$

## 8.2 Results Tables (Test Variables in Red Characters)

### 8.2.1 Test Rig and room for all Experiments

*Table 2 Test Rig and room for all Experiments*

| TEST RIG             |                                |                                |                        |
|----------------------|--------------------------------|--------------------------------|------------------------|
| Orifice Diameter (m) | Orifice Area (m <sup>2</sup> ) | Surface Area (m <sup>2</sup> ) | Ambient Pressure (Bar) |
| 0.10011              | 0.0079                         | 0.1558                         | 1.017                  |

### 8.2.2 Air Results Experiment 1

*Table 3 Air Results Experiment 1*

| Air Data |                          |                  |             |              |
|----------|--------------------------|------------------|-------------|--------------|
| Test     | Pressure Difference (Pa) | TA3 ambient (°C) | TA1 in (°C) | TA2 out (°C) |
| 1        | 249                      | 23.3             | 23.5        | 29.3         |
| 2        | 250                      | 23.2             | 23.6        | 29.2         |
| 3        | 249                      | 23.1             | 23.6        | 28.9         |
| 4        | 250                      | 23.3             | 23.6        | 28.4         |
| 5        | 250                      | 23.4             | 23.8        | 27.3         |

### 8.2.3 Water Results Experiment 1

*Table 4 Water Results Experiment 1*

| Water Data |                    |                |             |              |
|------------|--------------------|----------------|-------------|--------------|
| Test       | Water Flow (L/min) | Tank Temp (°C) | TW1 in (°C) | TW2 out (°C) |
| 1          | 2.25               | 59.9           | 60.9        | 56.6         |
| 2          | 1.75               | 59.9           | 60.8        | 55.4         |
| 3          | 1.25               | 60.2           | 60.4        | 53.3         |
| 4          | 0.75               | 60.1           | 59.7        | 49.3         |
| 5          | 0.25               | 60.1           | 60.4        | 38.3         |

## 8.2.4 Calculated Air Results Experiment 1

Table 5 Calculated Air Results Experiment 1

| Calculated Air Results |                    |                   |                                     |                      |                              |                   |                            |
|------------------------|--------------------|-------------------|-------------------------------------|----------------------|------------------------------|-------------------|----------------------------|
| Test                   | $\Delta$ Temp (°C) | Average Temp (°C) | Density of Air (kg/m <sup>3</sup> ) | Mass Flowrate (kg/s) | Spec. Heat Capacity (J/Kg/K) | Heat Absorbed (W) | Temperature Efficiency (%) |
| 1                      | 5.8                | 26.4              | 1.195088                            | 0.1062               | 1005                         | 618.853           | 15.5080214                 |
| 2                      | 5.6                | 26.4              | 1.195491                            | 0.1064               | 1005                         | 598.712           | 15.0537634                 |
| 3                      | 5.3                | 26.25             | 1.195895                            | 0.1062               | 1005                         | 565.504           | 14.4021739                 |
| 4                      | 4.8                | 26                | 1.195088                            | 0.1064               | 1005                         | 513.182           | 13.2963989                 |
| 5                      | 3.5                | 25.55             | 1.194685                            | 0.1064               | 1005                         | 374.195           | 9.56284153                 |

## 8.2.5 Calculated water Results Experiment 1

Table 6 Calculated water Results Experiment 1

| Calculated Water Results |                    |                   |                                       |                      |                              |                  |                            |
|--------------------------|--------------------|-------------------|---------------------------------------|----------------------|------------------------------|------------------|----------------------------|
| Test                     | $\Delta$ Temp (°C) | Average Temp (°C) | Density of Water (kg/m <sup>3</sup> ) | Mass Flowrate (kg/s) | Spec. Heat Capacity (J/Kg/K) | Heat Emitted (W) | Temperature Efficiency (%) |
| 1                        | -4.3               | 58.75             | 973.203                               | 0.0365               | 4183.6                       | -656.52          | 11.4973262                 |
| 2                        | -5.4               | 58.1              | 973.5906                              | 0.0284               | 4183.3                       | -641.47          | 14.516129                  |
| 3                        | -7.1               | 56.85             | 974.3309                              | 0.0203               | 4182.8                       | -602.82          | 19.2934783                 |
| 4                        | -10.4              | 54.5              | 975.7035                              | 0.0122               | 4181.9                       | -530.44          | 28.8088643                 |
| 5                        | -22.1              | 49.35             | 978.6239                              | 0.0041               | 4180.2                       | -376.7           | 60.3825137                 |

## 8.2.6 Overall Results Analysis Experiment 1

Table 7 Overall Results Analysis Experiment 1

| Overall Flow Results Analysis |                                         |                               |                                 |        |
|-------------------------------|-----------------------------------------|-------------------------------|---------------------------------|--------|
| Test                          | Logarithmic Mean $\Delta T$ (LMTD) (°C) | Heat Transfer Coefficient (U) | Mean Temperature Efficiency (%) | CED    |
| 1                             | 32.08549                                | 131.314                       | 13.50267                        | 0.9426 |
| 2                             | 31.37932                                | 131.19                        | 14.78495                        | 0.9333 |
| 3                             | 30.17658                                | 128.2                         | 16.84783                        | 0.9381 |
| 4                             | 27.81113                                | 122.401                       | 21.05263                        | 0.9675 |
| 5                             | 21.29513                                | 113.523                       | 34.97268                        | 0.9933 |

## 8.2.7 Air Results Experiment 2

Table 8 Air Results Experiment 2

| Air Data |                          |                  |             |              |
|----------|--------------------------|------------------|-------------|--------------|
| Test     | Pressure Difference (Pa) | TA3 ambient (°C) | TA1 in (°C) | TA2 out (°C) |
| 1        | 250                      | 23.4             | 23.8        | 27.3         |
| 2        | 199                      | 23.7             | 23.8        | 27.3         |
| 3        | 149                      | 23.6             | 23.8        | 27.4         |
| 4        | 101                      | 23.2             | 24          | 27.9         |
| 5        | 50                       | 23.3             | 24.2        | 28.9         |
| 6        | 25                       | 23.3             | 24.7        | 30.2         |

## 8.2.8 Water Results Experiment 2

Table 9 Water Results Experiment 2

| Water Data |                    |                |             |              |
|------------|--------------------|----------------|-------------|--------------|
| Test       | Water Flow (L/min) | Tank Temp (°C) | TW1 in (°C) | TW2 out (°C) |
| 1          | 0.25               | 60.1           | 60.4        | 38.3         |
| 2          | 0.25               | 60.1           | 58.3        | 38           |
| 3          | 0.25               | 60             | 58.1        | 38.5         |
| 4          | 0.25               | 60.1           | 58.2        | 39.4         |
| 5          | 0.25               | 60             | 58.6        | 41.4         |
| 6          | 0.25               | 60.1           | 58.9        | 43.3         |

## 8.2.9 Calculated Air Results Experiment 2

Table 10 Calculated Air Results Experiment 2

| Calculated Air Results |                    |                   |                                     |                      |                              |                   |                            |
|------------------------|--------------------|-------------------|-------------------------------------|----------------------|------------------------------|-------------------|----------------------------|
| Test                   | $\Delta$ Temp (°C) | Average Temp (°C) | Density of Air (kg/m <sup>3</sup> ) | Mass Flowrate (kg/s) | Spec. Heat Capacity (J/Kg/K) | Heat Absorbed (W) | Temperature Efficiency (%) |
| 1                      | 3.5                | 25.55             | 1.194685                            | 0.1064               | 1005                         | 374.195           | 9.56284153                 |
| 2                      | 3.5                | 25.55             | 1.193478                            | 0.0949               | 1005                         | 333.853           | 10.1449275                 |
| 3                      | 3.6                | 25.6              | 1.19388                             | 0.0821               | 1005                         | 297.136           | 10.4956268                 |
| 4                      | 3.9                | 25.95             | 1.195491                            | 0.0676               | 1005                         | 265.024           | 11.4035088                 |
| 5                      | 4.7                | 26.55             | 1.195088                            | 0.0476               | 1005                         | 224.721           | 13.6627907                 |
| 6                      | 5.5                | 27.45             | 1.195088                            | 0.0336               | 1005                         | 185.949           | 16.0818713                 |

## 8.2.10 Calculated water Results Experiment 2

Table 11 Calculated water Results Experiment 2

| Calculated Water Results |                    |                   |                                       |                      |                              |                  |                            |
|--------------------------|--------------------|-------------------|---------------------------------------|----------------------|------------------------------|------------------|----------------------------|
| Test                     | $\Delta$ Temp (°C) | Average Temp (°C) | Density of Water (kg/m <sup>3</sup> ) | Mass Flowrate (kg/s) | Spec. Heat Capacity (J/Kg/K) | Heat Emitted (W) | Temperature Efficiency (%) |
| 1                        | -22.1              | 49.35             | 978.6239                              | 0.0041               | 4180.2                       | -376.7           | 60.3825137                 |
| 2                        | -20.3              | 48.15             | 979.2868                              | 0.0041               | 4179.9                       | -346.23          | 58.8405797                 |
| 3                        | -19.6              | 48.3              | 979.2043                              | 0.0041               | 4179.9                       | -334.26          | 57.1428571                 |
| 4                        | -18.8              | 48.8              | 978.9286                              | 0.0041               | 4180.1                       | -320.54          | 54.9707602                 |
| 5                        | -17.2              | 50                | 978.262                               | 0.0041               | 4180.4                       | -293.08          | 50                         |
| 6                        | -15.6              | 51.1              | 977.6452                              | 0.0041               | 4180.8                       | -265.67          | 45.6140351                 |

## 8.2.11 Overall Results Analysis Experiment 2

Table 12 Overall Results Analysis Experiment 2

| Overall Flow Results Analysis |                                         |                               |                                 |        |
|-------------------------------|-----------------------------------------|-------------------------------|---------------------------------|--------|
| Test                          | Logarithmic Mean $\Delta T$ (LMTD) (°C) | Heat Transfer Coefficient (U) | Mean Temperature Efficiency (%) | CED    |
| 1                             | 21.29513                                | 113.523                       | 34.97268                        | 0.9933 |
| 2                             | 20.32945                                | 109.296                       | 34.49275                        | 0.9643 |
| 3                             | 20.56373                                | 104.317                       | 33.81924                        | 0.8889 |
| 4                             | 20.82801                                | 98.765                        | 33.18713                        | 0.8268 |
| 5                             | 21.63331                                | 86.9437                       | 31.8314                         | 0.7667 |
| 6                             | 21.98802                                | 77.5411                       | 30.84795                        | 0.6999 |

## 8.2.12 Air Results Experiment 3

Table 13 Air Results Experiment 3

| Air Data |                          |                  |             |              |
|----------|--------------------------|------------------|-------------|--------------|
| Test     | Pressure Difference (Pa) | TA3 ambient (°C) | TA1 in (°C) | TA2 out (°C) |
| 1        | 249                      | 23.1             | 23.6        | 26.1         |
| 2        | 200                      | 23.4             | 23.9        | 26.4         |
| 3        | 150                      | 23.2             | 23.9        | 26.5         |
| 4        | 100                      | 23.1             | 23.9        | 26.8         |
| 5        | 50                       | 23.2             | 24.3        | 27.7         |
| 6        | 25                       | 23.2             | 24.7        | 28.5         |

## 8.2.13 Water Results Experiment 3

Table 14 Water Results Experiment 3

| Water Data |                    |                |             |              |
|------------|--------------------|----------------|-------------|--------------|
| Test       | Water Flow (L/min) | Tank Temp (°C) | TW1 in (°C) | TW2 out (°C) |
| 1          | 0.25               | 45             | 48.6        | 33.6         |
| 2          | 0.25               | 45.2           | 48.1        | 33.8         |
| 3          | 0.25               | 44.7           | 48.1        | 34.2         |
| 4          | 0.25               | 44.7           | 48.2        | 34.9         |
| 5          | 0.25               | 45.1           | 48.3        | 36.4         |
| 6          | 0.25               | 45.5           | 48.5        | 37.6         |

## 8.2.14 Calculated Air Results Experiment 3

Table 15 Calculated Air Results Experiment 3

| Calculated Air Results |                    |                   |                                     |                      |                              |                   |                            |
|------------------------|--------------------|-------------------|-------------------------------------|----------------------|------------------------------|-------------------|----------------------------|
| Test                   | $\Delta$ Temp (°C) | Average Temp (°C) | Density of Air (kg/m <sup>3</sup> ) | Mass Flowrate (kg/s) | Spec. Heat Capacity (J/Kg/K) | Heat Absorbed (W) | Temperature Efficiency (%) |
| 1                      | 2.5                | 24.85             | 1.195895                            | 0.1062               | 1005                         | 266.747           | 10                         |
| 2                      | 2.5                | 25.15             | 1.194685                            | 0.0952               | 1005                         | 239.064           | 10.3305785                 |
| 3                      | 2.6                | 25.2              | 1.195491                            | 0.0824               | 1005                         | 215.317           | 10.7438017                 |
| 4                      | 2.9                | 25.35             | 1.195895                            | 0.0673               | 1005                         | 196.091           | 11.9341564                 |
| 5                      | 3.4                | 26                | 1.195491                            | 0.0476               | 1005                         | 162.564           | 14.1666667                 |
| 6                      | 3.8                | 26.6              | 1.195491                            | 0.0336               | 1006                         | 128.601           | 15.9663866                 |

## 8.2.15 Calculated water Results Experiment 3

Table 16 Calculated water Results Experiment 3

| Calculated Water Results |                    |                   |                                       |                      |                              |                  |                            |
|--------------------------|--------------------|-------------------|---------------------------------------|----------------------|------------------------------|------------------|----------------------------|
| Test                     | $\Delta$ Temp (°C) | Average Temp (°C) | Density of Water (kg/m <sup>3</sup> ) | Mass Flowrate (kg/s) | Spec. Heat Capacity (J/Kg/K) | Heat Emitted (W) | Temperature Efficiency (%) |
| 1                        | -15                | 41.1              | 983.0445                              | 0.0041               | 4178.4                       | -256.72          | 60                         |
| 2                        | -14.3              | 40.95             | 983.1219                              | 0.0041               | 4178.4                       | -244.76          | 59.0909091                 |
| 3                        | -13.9              | 41.15             | 983.0187                              | 0.0041               | 4178.4                       | -237.89          | 57.4380165                 |
| 4                        | -13.3              | 41.55             | 982.8117                              | 0.0041               | 4178.5                       | -227.58          | 54.7325103                 |
| 5                        | -11.9              | 42.35             | 982.3955                              | 0.0041               | 4178.6                       | -203.54          | 49.5833333                 |
| 6                        | -10.9              | 43.05             | 982.0288                              | 0.0041               | 4178.8                       | -186.37          | 45.7983193                 |

## 8.2.16 Overall Results Analysis Experiment 3

*Table 17 Overall Results Analysis Experiment 3*

| Overall Flow Results Analysis |                                                           |                               |                                 |        |
|-------------------------------|-----------------------------------------------------------|-------------------------------|---------------------------------|--------|
| Test                          | Logarithmic Mean $\Delta T$ (LMTD) ( $^{\circ}\text{C}$ ) | Heat Transfer Coefficient (U) | Mean Temperature Efficiency (%) | CED    |
| 1                             | 14.53521                                                  | 113.348                       | 35                              | 1.039  |
| 2                             | 14.17874                                                  | 110.783                       | 34.71074                        | 0.9767 |
| 3                             | 14.40882                                                  | 105.955                       | 34.09091                        | 0.9051 |
| 4                             | 14.74588                                                  | 99.0443                       | 33.33333                        | 0.8616 |
| 5                             | 15.07789                                                  | 86.6332                       | 31.875                          | 0.7987 |
| 6                             | 15.29002                                                  | 78.2253                       | 30.88235                        | 0.69   |