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Engineering

Heat Exchanger

Laboratory Analysis –

M5X00406

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2 Introduction

Three experiments were conducted on the 19th of February, the aim of determining how changing different parameters would effect a 32 tube cross-flow heat exchangers performance (see *Plate 1*). In a cross-flow heat exchanger ‘...both fluids flow normal to each other.’ (Thulukkanam, 2017)

The heat exchanger has 2 ‘tube bundles’ of 16 copper tubes. The 2 ‘tube bundles’ were connected in parallel, meaning at each bank of tubes the heated water was flowing from the bottom to the top (see *Plate 2*).

For the first experiment the water flow rate running through the heat exchanger was the independent variable, keeping the heater tank temperature and orifice pressure drop constant. For the second experiment the orifice pressure drop was the independent variable, keeping the heater tank temperature and water flow rate constant.

In the last experiment, the orifice pressure drop was the independent variable. It was a repeat of the second experiment, using a lower heater tank temperature.

In the experiments inlet and outlet temperatures for the air and water, heater tank temperature and orifice pressure drop were recorded. Using this data specific heat capacity, energy released/absorbed and temperature efficiency could be calculated. Water density was calculated at each temperature for more accurate results (see *Figure 10*, in *Appendix 9.1*) Then with this data mean temperature efficiency could be calculated, log mean temperature difference and the heat transfer coefficient for each experiment.

The first law of thermodynamics states ‘... energy cannot be created or destroyed, but only converted from one form to another ...’ (Dipl.-Ing. Karl-Heinz Dietsche, 2018)

Using the first law of thermodynamics, we can investigate the transfer of heat energy in the system, and therefore comment on the performance of the heat exchanger.

The Tecquipment TD1007 Water to Air Heat Exchanger Experimental Unit was used (see *Plate 3*), set up as seen in *Plate 4*.

3 Equipment / Apparatus

- Tecquipment TD1007 experimental unit
- Tecquipment 32 tube cross-flow heat exchanger
- Stopwatch
- Weather application (for atmospheric pressure)

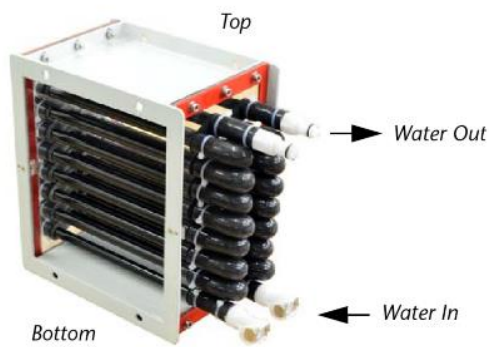


Plate 1 - 32 Tube cross flow heat exchanger used for the experiments

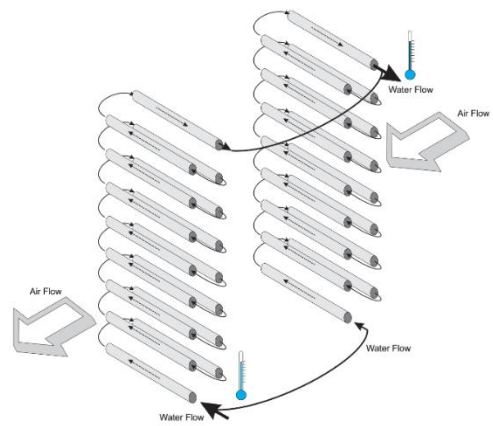


Plate 2 - Schematic of water flow through the heat exchanger connected in parallel flow

4 Methodology

For the first experiment the heater tank temperature was set to 60°C . The ambient air pressure and orifice diameter was recorded before collecting results. Using the slide valve (see *Plate 3*), the orifice pressure drop was set to 250Pa with a tolerance of $\pm 5\text{Pa}$, it remained constant throughout. Using the water supply valve, a flow rate of 2.25L/minute with a tolerance of $\pm 0.01\text{L/minute}$ was obtained. The results were recorded 4 minutes after changing the conditions, in order for the temperatures to stabilise, ensuring accurate results.

The procedure was repeated for flow rates of 1.75, 1.25, 0.75 and 0.25L/min .

For the second experiment, the heater tank temperature remained at 60°C throughout. The ambient air pressure and orifice diameter was recorded before collecting results. Using the slide valve, the orifice pressure drop was set to 250Pa ($\pm 5\text{Pa}$). Using the water supply valve, a flow rate of 0.25L/min ($\pm 0.01\text{L/minute}$) was obtained, and this remained constant.

The results were recorded 4 minutes after changing the conditions, in order for the temperatures to stabilise.

The procedure was repeated for airflow rates of 200, 150, 100, 50 and 25Pa pressure drops.

For the third experiment the heater tank temperature was set to 45°C , and the procedure for the second experiment was repeated.

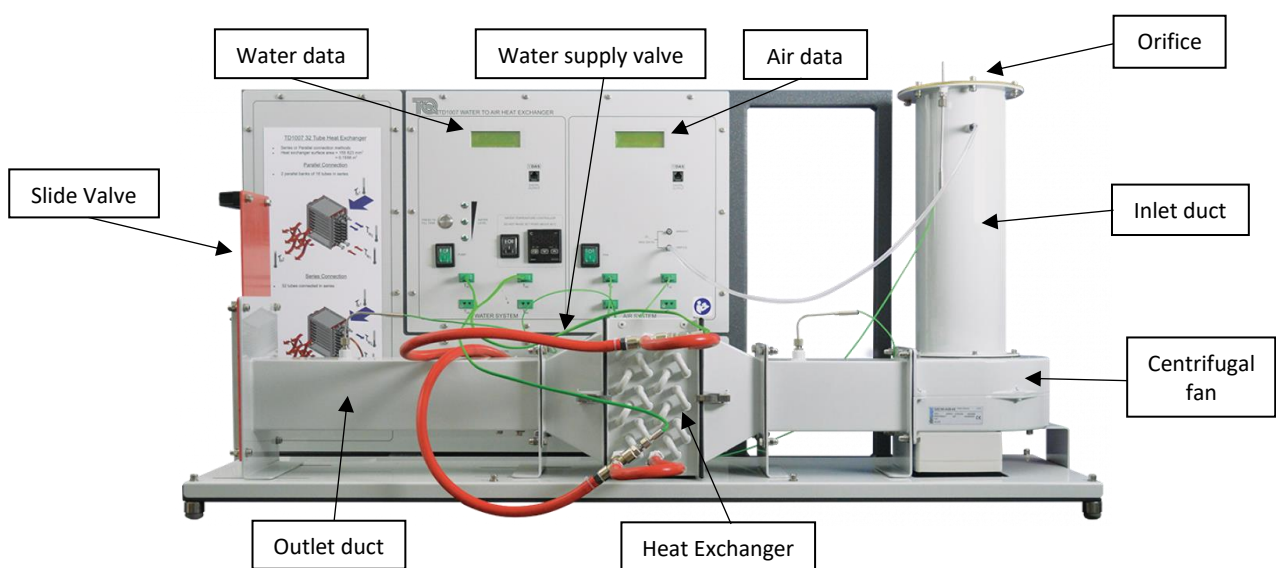


Plate 3 - Tecquipment TD1007 experiment apparatus

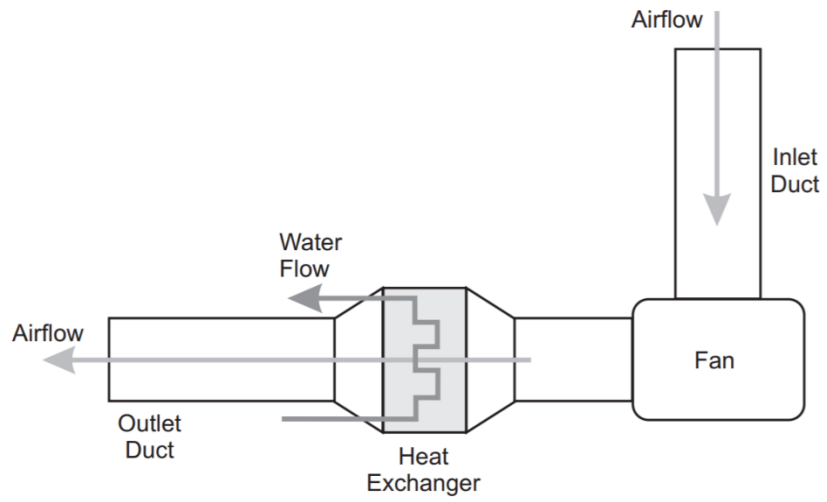


Plate 4 - Apparatus setup schematic

5 Experiment 1 – The effect of varying water flow rate

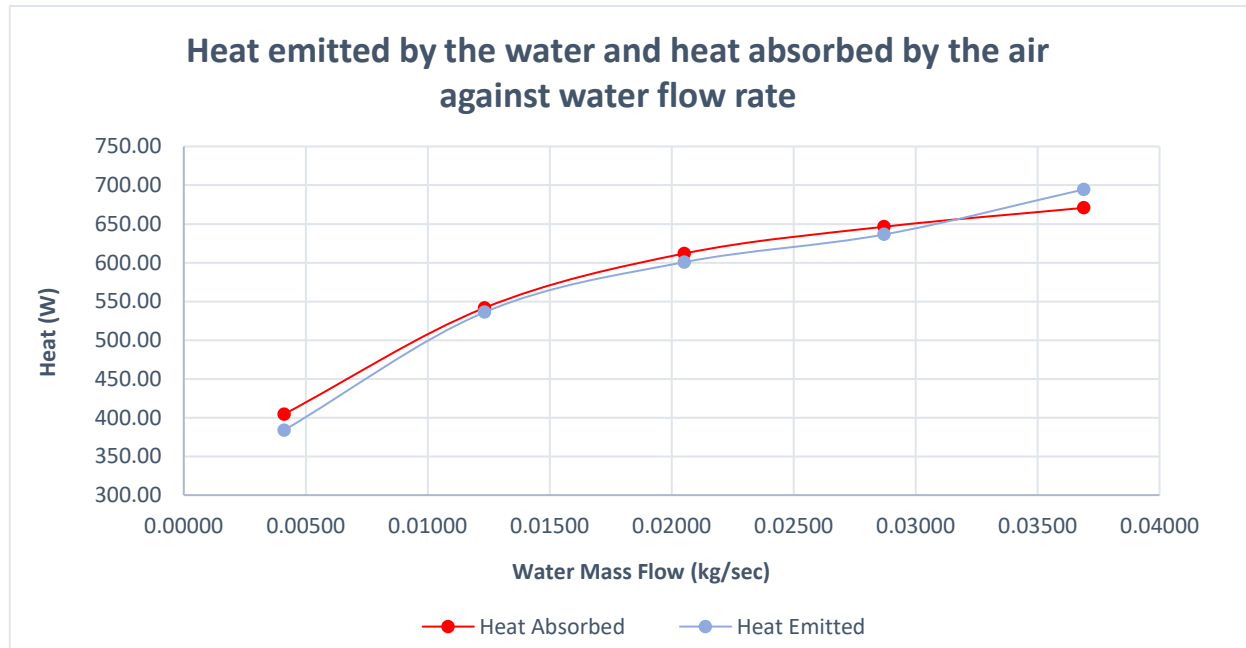


Figure 1 - EXPERIMENT 1 - Heat emitted by water and heat absorbed by air against change in water mass flow rate

Figure 1 shows the heat emitted by the water and heat absorbed by the air against water mass flow rate. The graph shows how the heat emitted by the water increases non-linearly, as flow rate increases. The change in heat emitted decreases as flow rate increases. The maximum value for heat emitted by the water is 694.5W at flow rate 0.0369kg/sec.

Knowing that the heat transfer rate of water, Q_w , is:

$$Q_w = \dot{m}_w \cdot c_{pw} \cdot (T_{iw} - T_{ow})$$

Where:

$\dot{m}_w$ [kg/sec] = Mass flow rate of the water

c_{pw} [J/kg.K] = Specific heat capacity of the water

T_{iw} [K] = Inlet water temperature of the heat exchanger

T_{ow} [K] = Outlet water temperature of the heat exchanger

(Edwards, 2008)

The equation shows how temperature is directly proportional to heat transfer rate. Therefore the higher the water temperature, the larger the rate of heat transfer. This means the heat exchangers performance is greater at higher water temperatures.

‘...temperature is proportional to the average random kinetic energy of the molecules.’

(Tsokos, 2014)

These results cohere with the theory, because at lower water flow rates the particles will have less kinetic energy meaning the average temperature will be lower. At lower average temperatures the heat transfer rate will be lower, meaning a reduction in heat exchanger performance.

Figure 1 shows how the heat absorbed by the air also increases as flow rate increases. The heat absorbed by the air increases non-linearly with the largest increase at the lowest flow rate. These results are as expected as at higher flow rates, there is more heated water travelling through the heat exchangers tubes at a higher velocity, meaning the waters temperature will be higher at the exit, therefore the average water temperature will be higher.

Figure 1 shows how the heat absorbed is larger than the heat emitted from flow rate of 0.0041kg/sec to 0.0287kg/sec , meaning heat must have been absorbed from the surroundings. At approximately 0.0313kg/sec the heat emitted and heat released are equal, and the heat emitted is larger from this flow rate to 0.0369kg/sec .

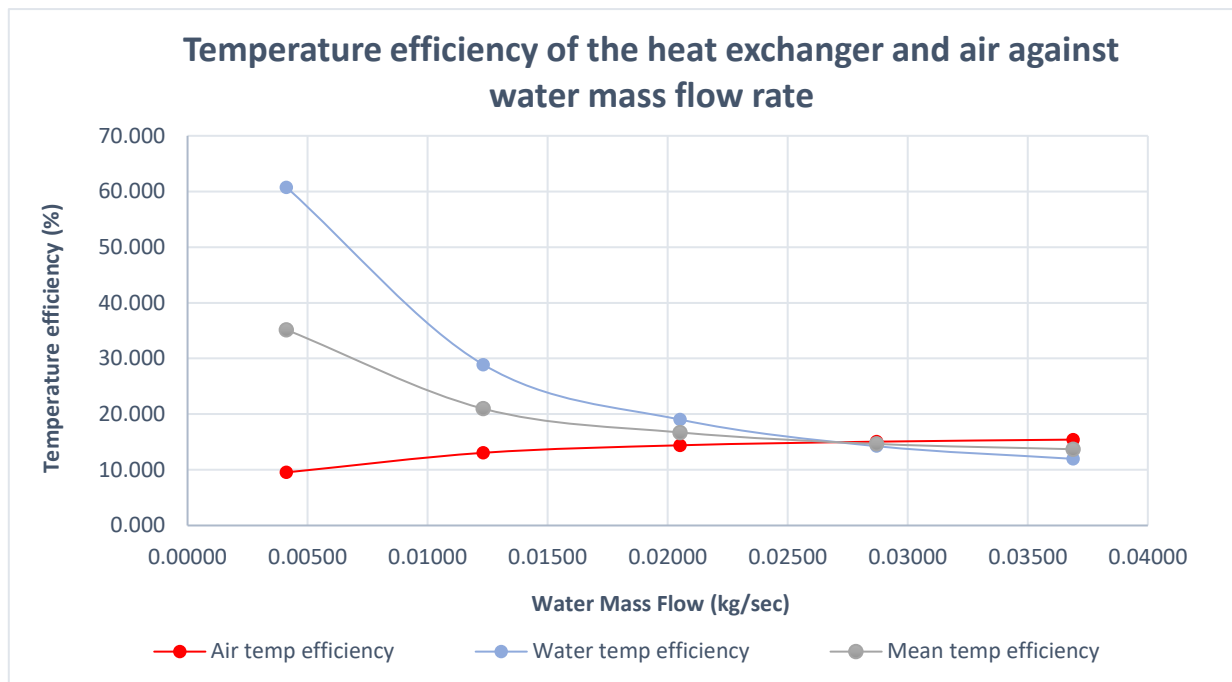


Figure 2 - EXPERIMENT 1 - Air, water and mean temperature efficiency against change in water mass flow rate

Figure 2 shows how air temperature efficiency increases as water mass flow rate increases. The air temperature efficiency increases from 9.54% at a flow rate of 0.0041kg/sec to 13.05% at flow rate 0.0123kg/sec. The trend is non-linear, with the change in air temperature efficiency decreasing as flow rate increases. From flow rate 0.0287kg/sec to 0.0369kg/sec, the air temperature efficiency rises from 15.05% to 15.43%. These results appear to be accurate, because according to the experiment guidance notes '*...temperature efficiency of the cooler air circuit of the heat exchanger is the ratio of the temperature change in the cold circuit, divided by the difference between the maximum and minimum temperatures of the hot and cold circuits.*' (See Appendix 9.2 and 9.3 for the notations and air temperature efficiency equation)

Since the air temperature outlet is decreasing very slightly the temperature efficiency will also decrease.

Figure 2 also shows how the water temperature efficiency decreases as flow rate increases. The decreases is most severe from 0.0041kg/sec to 0.0123kg/sec. As the flow rate increases, the change in heat exchanger temperature efficiency decreases. According to the experiment guidance notes '*...temperature efficiency of the hot water circuit of the heat exchanger is the ratio of the temperature change in the hot water, divided by the difference between the maximum and minimum temperatures of the hot and cold circuits.*' (See Appendix 9.2 and 9.3 for the notations and water temperature efficiency equation)

Since the water outlet temperature decreases with flow rate, so will the temperature change.

Therefore the water temperature efficiency will also decrease as flow rate increases.

The mean temperature efficiency decreases as flow rate increases with its maximum value of 35.15% occurring at a flow rate of 0.0041kg/sec . Its minimum value of 13.70% occurs at flow rate 0.0369kg/sec .

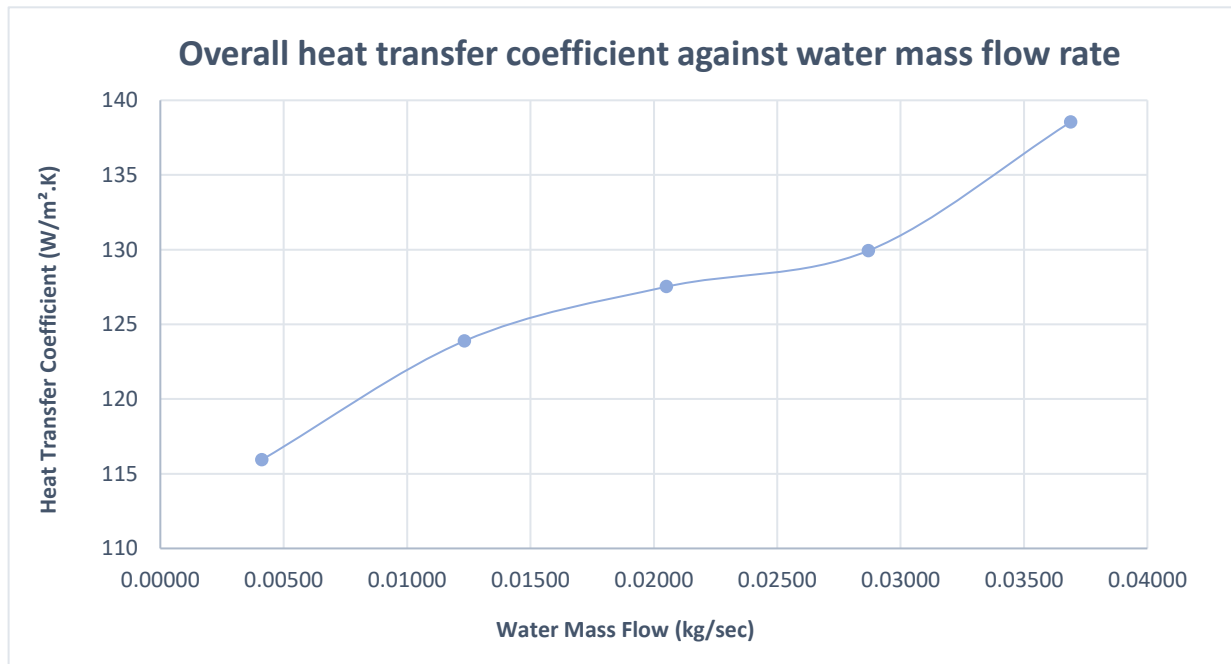


Figure 3 - EXPERIMENT 1 - Overall heat transfer coefficient against change in water mass flow rate

Figure 3 shows how as the water mass flow rate increases, the overall heat transfer coefficient also increases. The rate of change of heat transfer coefficient decreases from flow rate 0.0041kg/sec to 0.0205kg/sec . The rate of change of heat transfer coefficient then increases from 0.0205kg/sec to 0.0369kg/sec . The maximum value for heat transfer coefficient, $138.55\text{W/m}^2.\text{K}$, occurs at maximum flow rate. The heat exchanger's performance is greatest at the highest heat transfer coefficient, thus the performance is greatest at maximum water mass flow rate.

Figure 3 shows the performance of the heat exchanger increases as the water flow increases. 'When atoms are in motion, the more heat the system contains...'
(Feynman, 2011)

Therefore as the water gains motion the difference in water and air temperature will be greater. Since the rate of heat transfer is directly proportional to the difference in temperature, the rate of heat transfer will increase.

6 Experiment 2 – The effect of varying air flow rate

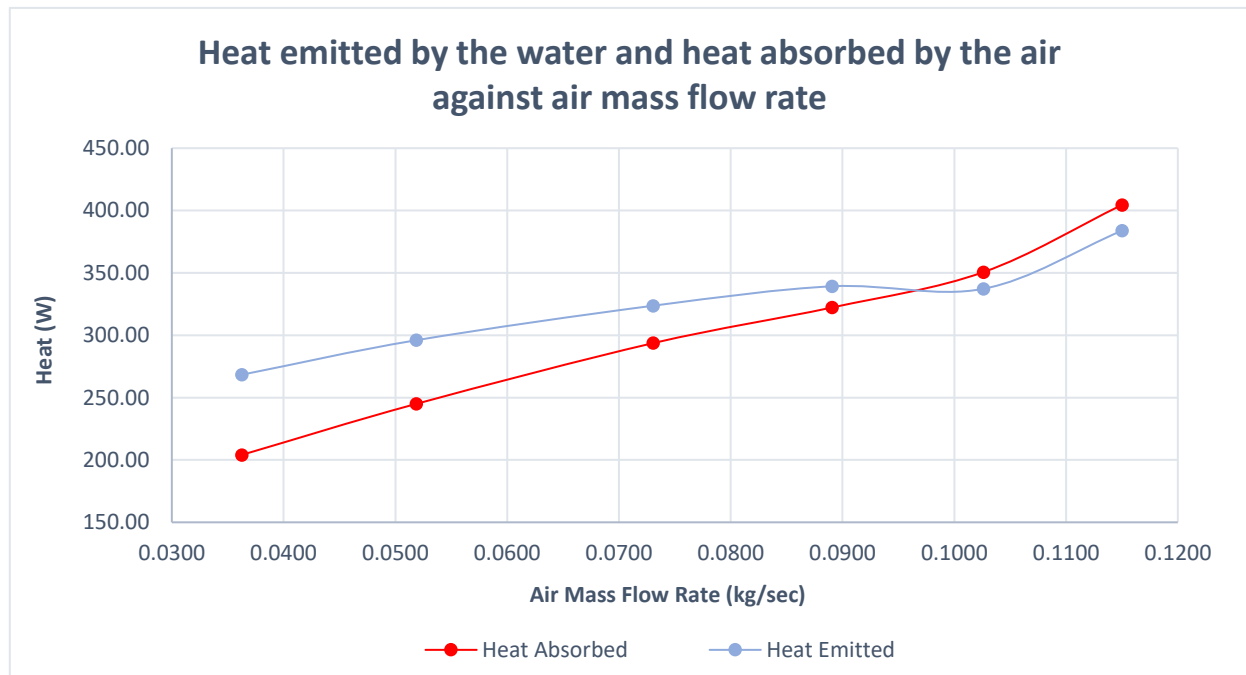


Figure 4 - EXPERIMENT 2 - Heat emitted by water and heat absorbed by air against change in air mass flow rate

Figure 4 shows overall the heat emitted by the water increases as air mass flow rate increases. There is an anomaly in the results at flow rate of 0.1026 kg/sec , where the heat emitted by the water is less than the previous result. Despite leaving 4 minutes after changing the orifice pressure drop and recording the results, this result is likely because the water had not reached thermal equilibrium. A value of approximately 350 W would be expected at flow rate 0.1026 kg/sec , as the heat released by the water should increase relatively linearly.

Figure 4 shows how the heat absorbed by the air increases as flow rate increases. The increase is almost linear, with the gradient increasing from 0.0891 kg/sec to 0.1150 kg/sec .

These results correlate to the theory, as when the air has a higher mass flow rate its kinetic energy is greater. This means its particles will collide more vigorously with the walls of the heat exchangers tubes resulting in more heat being transferred from the walls of the tubes to the air primarily by convection. Due to the centrifugal fan, the heat transfer is forced convection. Conductive heat transfer also happens through the heat exchangers copper tube walls.

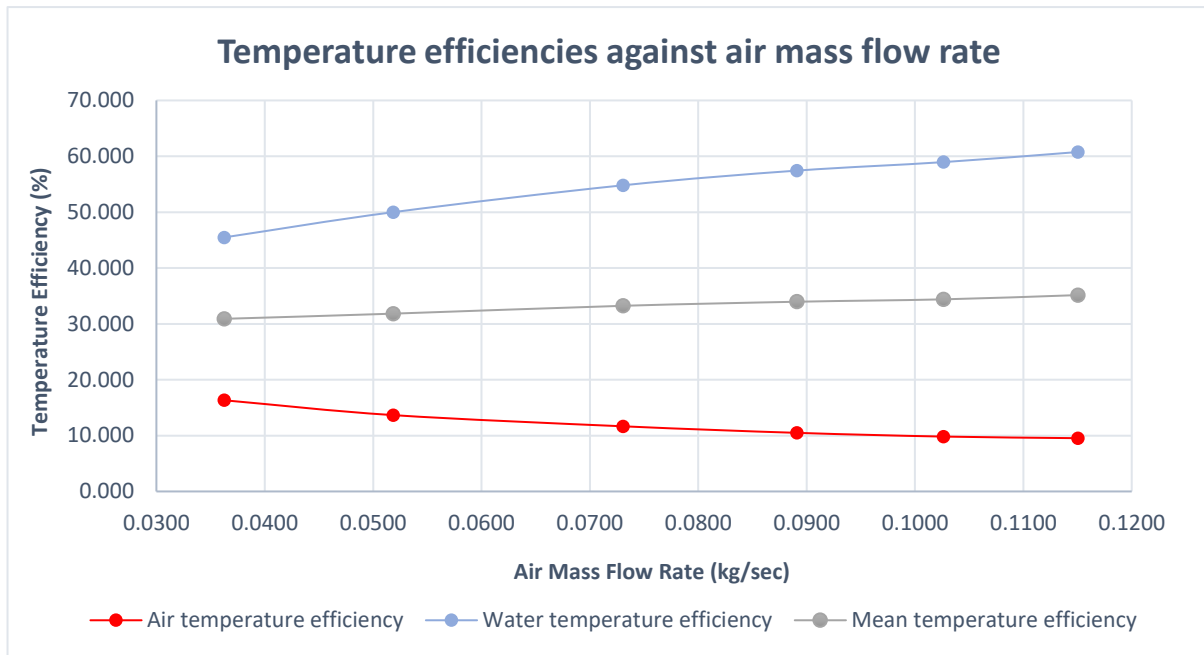


Figure 5 - EXPERIMENT 2 - Air, water and mean temperature efficiency against change in air mass flow rate

Figure 5 shows how air temperature efficiency decreases as the air mass flow rate increases. The trend is non-linear, and the rate of change of air temperature efficiency decreases as the flow rate increases. As the flow rate increases the air velocity also increases, meaning there is less time for the heat to be transferred from the water to the air.

The water temperature efficiency increases as flow rate increases, in an almost linear fashion. This is because the change in air temperature increases as air mass flow rate decreases.

The mean temperature efficiency increases as flow rate increases. The rate of change of mean temperature efficiency decreases as flow rate increases. The minimum value of mean temperature efficiency, 30.9% occurs at the minimum flow rate of 0.0363kg/sec. The maximum value of mean temperature efficiency, 35.2% occurs at the maximum flow rate of 0.1150kg/sec.

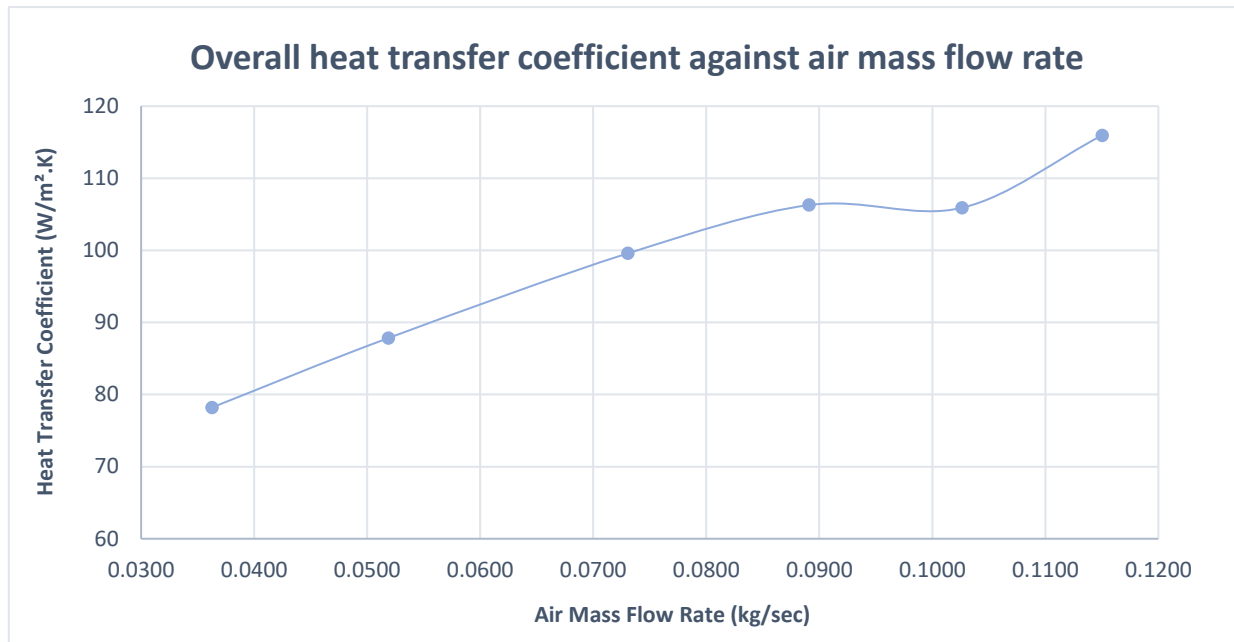


Figure 6 - EXPERIMENT 2 - Overall heat transfer coefficient against change in air mass flow rate

Figure 6 shows how the heat transfer coefficient increases as air mass flow rate increases. The results appear to be increasing linearly, therefore the value for the heat transfer coefficient at flow rate 0.1026 kg/sec must be incorrect. A value of approximately 110 W/m².K would be expected. The higher the overall heat transfer coefficient, the easier it is for heat to be transferred from the water to the air.

The graph shows how the heat exchangers performance is greatest at the highest air mass flow rate. The equation for heat transfer coefficient is inversely proportional to Log Mean Temperature Difference (LMTD) proving the results are correct. As the flow rate increases, the air's average temperature will decrease, meaning a smaller LMTD resulting in an increase in heat transfer coefficient.

The maximum value of heat transfer coefficient is 115.94 W/m².K at maximum flow rate. Comparing this to the maximum for experiment 1 we find that the heat exchangers performance was superior in Experiment 1 with a maximum heat transfer coefficient of 138.55 W/m².K. The heat exchanger in Experiment 1 will yield a 16.9% increase in heat transfer coefficient.

7 Experiment 3 – Effect of varying water temperature (driving force)

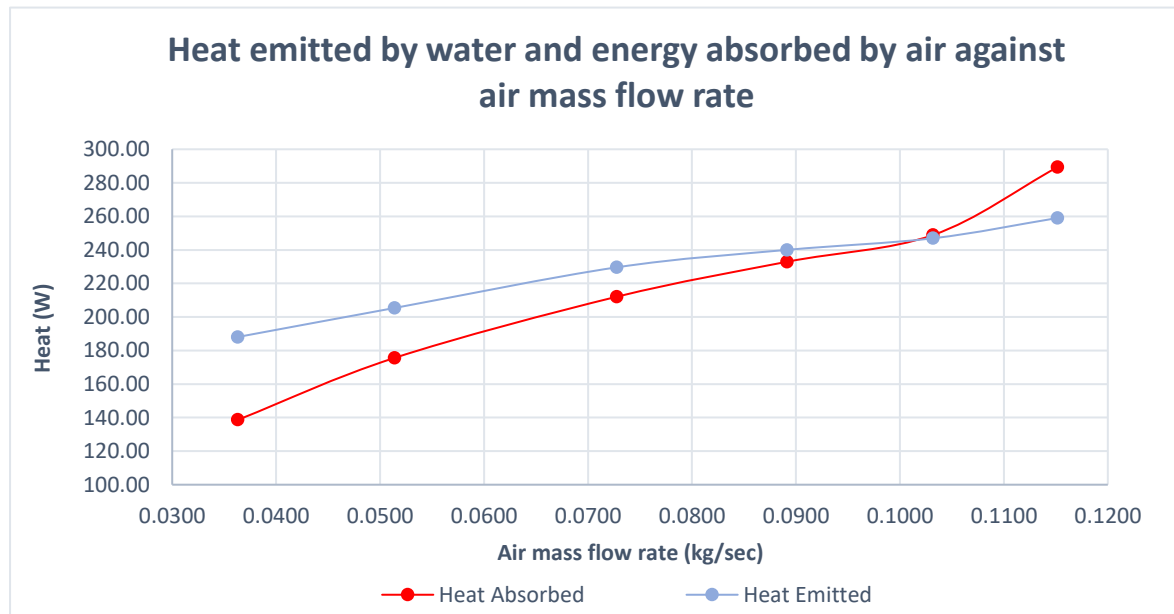


Figure 7 - EXPERIMENT 3 - Heat emitted by water and heat absorbed by air against change in air mass flow rate

Figure 7 shows the heat emitted by the water increases as air mass flow rate increases. The trend is almost linear. The maximum heat emitted is 259.01W. Compared to Experiment 2, the heat emitted is considerably lower, with a maximum heat emitted of 383.87W for Experiment 2. Both Experiment 2 and 3 followed the same method, the only difference being the heat exchangers water inlet temperature being decreased from 60°C in Experiment 2 to 45°C in Experiment 3. By decreasing the water inlet temperature by 25%, the maximum heat emitted by the water decreased by 32.5%.

The heat absorbed by the air also increases as air mass flow rate increases. The gradient of the heat absorbed increases sharply from flow rate 0.1032kg/sec to 0.1151kg/sec.

The results show that at the minimum flow rate 49.43W of heat is lost to the surroundings.

Comparing to Experiment 1, where 20.69W is lost to the surroundings.

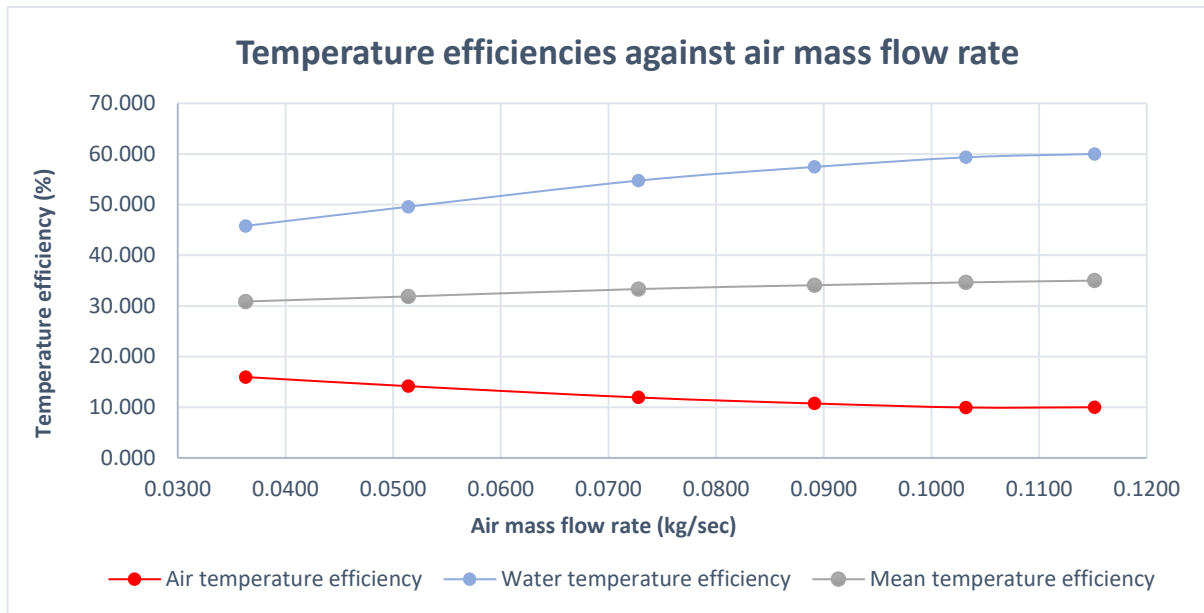


Figure 8 - EXPERIMENT 3 - Air, water and mean temperature efficiency against change in air mass flow rate

Figure 8 shows as the air mass flow rate increases air temperature efficiency decreases non-linearly. The rate of change of air temperature efficiency decreases as flow rate increases, to a minimum value of 10% efficiency at airflow 0.1151kg/sec.

The water temperature efficiency increases as flow rate increases, from a minimum efficiency of 45.8% to a maximum of 60.0%. The water temperature efficiency is considerably higher than that of the air.

Figure 8 shows how the mean temperature efficiency increases as flow rate increases. Therefore, the heat exchanger works best at a larger air mass flow rate. The minimum value of 30.9% for mean temperature efficiency occurs at flow rate 0.0363kg/sec, with a maximum efficiency of 35.0% occurring at flow rate 0.1151kg/sec. The increase in mean temperature efficiency is almost linear.

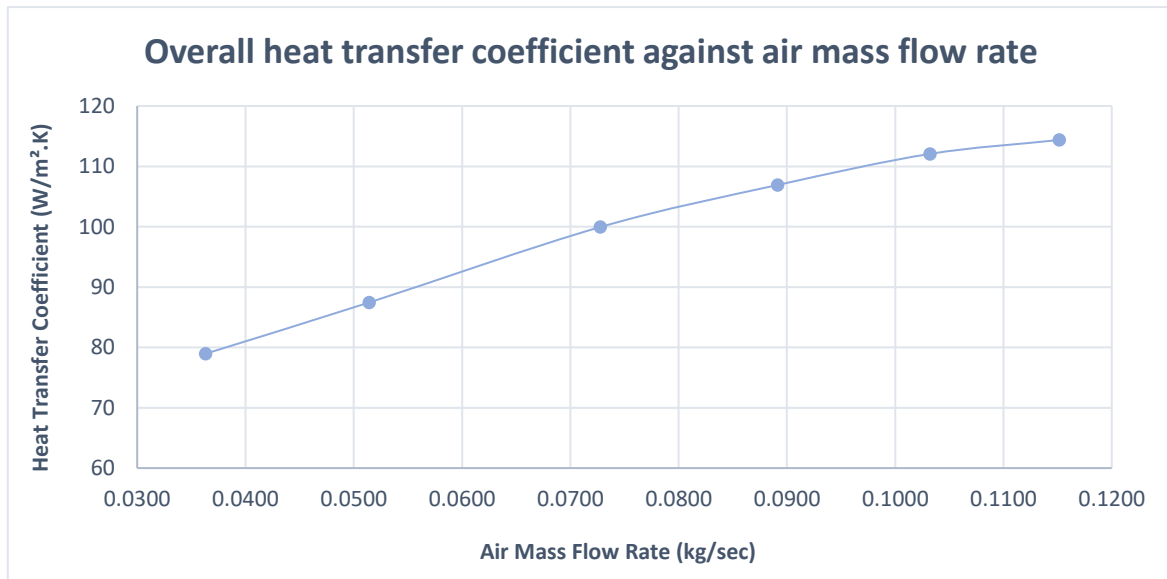


Figure 9 - EXPERIMENT 3 - Overall heat transfer coefficient against change in air mass flow rate

Figure 9 shows how the overall heat transfer coefficient increases as air mass flow rate increases. The heat transfer coefficient increases linearly from flow rate 0.0363kg/sec to 0.0728kg/sec. The gradient then decreases from flow rate 0.0728kg/sec to 0.1151kg/sec. The minimum heat transfer coefficient of 78.95 W/m².K occurs at the minimum flow rate with the maximum of 114.37 W/m².K occurring at maximum flow rate. The heat exchanger in Experiment 2 has a 21.1% larger heat transfer coefficient than that of Experiment 3, therefore better performance.

8 Conclusion

To conclude, I believe the results obtained were relatively accurate, and showed the right trends. However, had multiple heat exchangers been compared, different types of heat exchangers performance could have been discussed. The graphs would show data from multiple heat exchangers, and these trends could have been compared.

In order to collect more accurate results the fouling factor of the heat exchanger would also need to be considered. According to HRS heat exchangers '*...fouling factor represents the theoretical resistance to heat flow due to a build-up of a layer of dirt or other fouling substance on the tube surfaces of the heat exchanger...*' (HRS Heat Exchangers, 2016)

The heat exchanger used in this experiment likely had some form of chemical fouling. Despite copper being very resistant to oxidation, over time it will occur in the form of a patina building on the inner surface of the pipe.

According to Alfa Laval Heat Exchangers fouling allowances can be expressed as '*...an additional percentage of heat transfer area, or as a fouling factor (R_f) expressed in the units $W/m^2 \cdot ^\circ C$* '

(Alfa Laval Heat Exchangers, n.d.)

Fouling factor can be represented as an additional function of overall heat transfer coefficient, k . Had fouling factor been taken into consideration, more accurate results could have been produced.

Thermocouple cable and connector accuracy would also need to be taken into consideration. The conductors used for air and water temperature were Nickel Chromium/Nickel Aluminium (conductor type K), and the cable type was KX. According to RS Components, the thermocouple wire type KX had an accuracy of $\pm 2.5^\circ C$. (RS Components, n.d.)

Lastly the atmospheric pressure used was taken off a weather app on a phone. To gain more accurate results, we could have used a barometer, recording the atmospheric pressure each time temperature was recorded.

9 Appendix

9.1 Change in water density with temperature

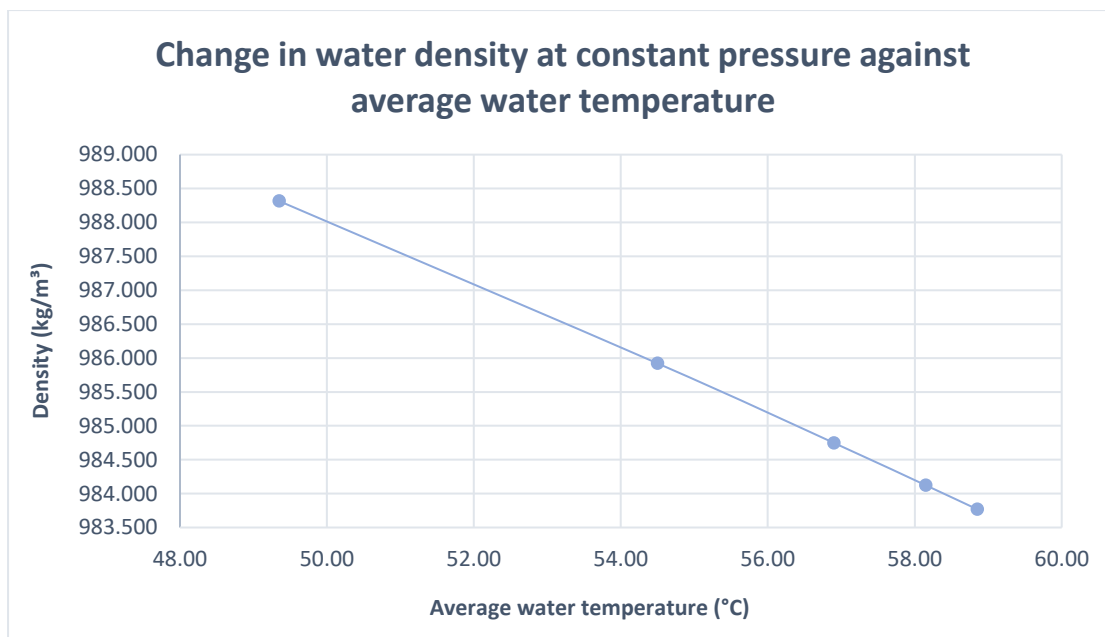


Figure 10 - Change in water density at constant pressure as water temperature increases

Figure 10 shows how water's density changes with temperature (from Experiment 1). Water is often labelled as an incompressible fluid, but in reality pressure and temperature can change its density very slightly. For a 19% increase in temperature, density changes by 1%.

9.2 Notation

Symbol	Definition	Units
A	Heat Transfer Area	m^2
A_O	Orifice Area	m^2
C	Heat capacity	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 $^{\circ}\text{C}$ where shown
ρ and ρ_A and ρ_W	Density, of air and water	kg.m^{-3}
η_o	Overall Efficiency	%
C_{EB}	Energy Balance Coefficient	-
$\bar{\eta}_A$ and $\bar{\eta}_W$	Mean Temperature Efficiencies	%
Δp	Orifice pressure drop	Pa
Q	Heat energy transferred for a unit mass	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 J/kg.K
T, T_W, T_A	Temperature, of water and air	K or $^{\circ}\text{C}$ where shown
ΔT	Change in Temperature	K or $^{\circ}\text{C}$ where shown
$\bar{T}$	Mean Temperature	K or $^{\circ}\text{C}$ 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)	kg.s^{-1}

Plate 1 - Notation from the experimental guidance notes

9.3 Equations used from the guidance notes:

$$\dot{m}_A = C_d \times A_o \sqrt{\Delta p \times 2 \times \rho_A}$$

$$\rho_A = \frac{p}{RT}$$

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

From tests, the specific heat capacity of water at 15°C is 4185.5 J.kg⁻¹.K⁻¹

$$\rho_W = \frac{\left(999.839 + 16.952T - 7.990 \times 10^{-3}T^2 - 46.241 \times 10^{-6}T^3 + 105.846 \times 10^{-9}T^4 - 281.030 \times 10^{-12}T^5 \right)}{\left(1 + 16.887 \times 10^{-3}T \right)}$$

$$\dot{Q}_W = \dot{m}_W \times c_{pW} \times \Delta T_W$$

$$\dot{Q}_A = \dot{m}_A \times c_{pA} \times \Delta T_A$$

$$\eta_W = \frac{T_{W1} - T_{W2}}{T_{W1} - T_{A1}} \times 100$$

$$\eta_A = \frac{T_{A2} - T_{A1}}{T_{W1} - T_{A1}} \times 100$$

$$LMTD = \frac{(T_{W2} - T_{A2}) - (T_{W1} - T_{A1})}{\ln \left(\frac{T_{W2} - T_{A2}}{T_{W1} - T_{A1}} \right)}$$

$$U = \frac{\dot{Q}_W}{A \times LMTD}$$

10 References

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