

Cross Flow Heat Exchanger Laboratory Analysis

Thermofluid Mechanics ACMA5011

Tyler Powell 2318809

26/05/2025

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1. Introduction

This report is an assignment for Thermofluid Mechanics ACMA5011, the report details the results and analysis of 2 experiments conducted with a cross flow heat exchanger.

1.1. Background

Heat exchangers are devices designed to transfer thermal energy between two or more fluids at different temperatures without mixing them. They are widely used in industries such as power generation, refrigeration, chemical processing, and HVAC systems. Common types include shell-and-tube, plate, and finned-tube heat exchangers. In this experiment, a 32-tube parallel-flow heat exchanger is used to study how varying water and air flow rates affect its thermal performance.

1.2. Experiment Aims

The following are the key aims of the experimental study:

- To investigate how changes in water flow rate (while keeping air flow and inlet temperature constant) influence heat transfer efficiency, temperature differences, and the overall heat transfer coefficient.
- To analyse how different air flow rates (at a fixed water flow rate and temperature) impact the heat exchanger's performance, including heat absorption, temperature efficiencies, and the overall heat transfer coefficient.

The experiments aim to validate theoretical principles and provide practical insights into heat exchanger behaviour under varying operational conditions.

1.3. Theoretical Principles

Key concepts governing heat exchanger performance include:

- Heat Transfer Mechanisms – energy is transferred from the hot water to the cooler air via convection (fluid motion) and conduction (through tube walls). The rate depends on temperature gradients, flow rates, and surface area.
- Log Mean Temperature Difference (LMTD) – a critical parameter for calculating heat transfer in non-isothermal systems, defined as:

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

- Efficiency – measured as the ratio of actual heat transfer to the maximum possible. For fluids, it depends on specific heat capacities, mass flow rates, and temperature changes.

- Overall Heat Transfer Coefficient (U) – represents the heat exchanger's effectiveness, combining conductive and convective resistances. Higher U values indicate better performance and are calculated using:

$$U = \frac{Q}{A \cdot LMTD}$$

These principles will be applied to analyse experimental data and evaluate the heat exchanger's response to varying flow conditions.

2. Experimental Setup and Methodology

2.1. Apparatus and Materials

The experiment utilized a crossflow heat exchanger system with the following components:

2.1.1. Heat Exchanger Unit

- A 32-tube finned crossflow heat exchanger, where hot water flows through parallel tubes while air is forced perpendicularly over the tubes via an axial fan.
- Tubes arranged in a staggered/parallel configuration to maximize air-water contact.



Figure 1: Experiment Set Up

2.1.2. Heating and Flow System

- Electric water heater tank (set to 60°C) to supply hot water to the tubes.
- Centrifugal pump with a hand-operated flow control valve to regulate water flow rates (0.20–1.80 L/min).
- Digital flowmeter to measure water flow rate (± 0.01 L/min precision).

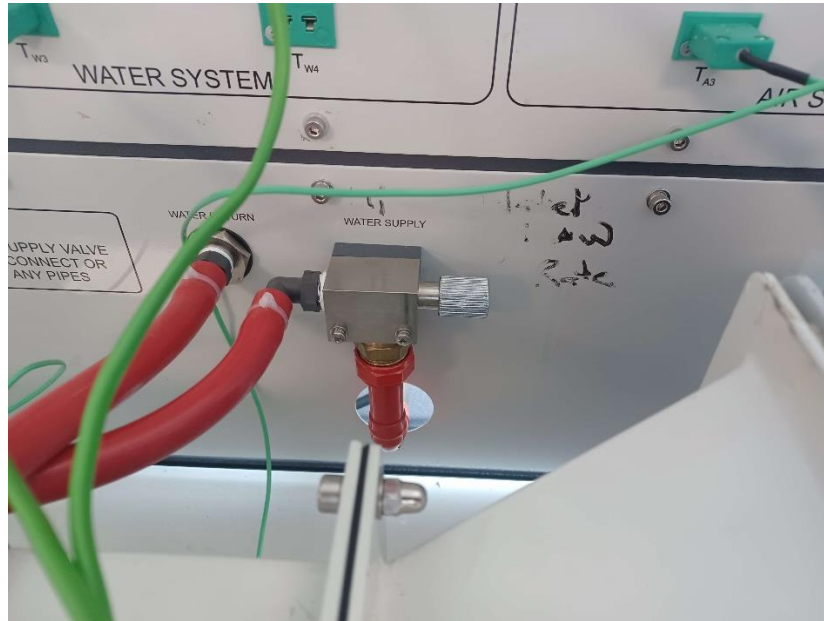


Figure 2: Water Flow Control Valve

2.1.3. Airflow System

- Variable-speed axial fan to generate airflow across the tubes.
- Orifice plate with 100.11 mm diameter to measure air pressure drop (50–250 Pa) via a manometer.
- Slide valve to adjust airflow rate by varying the orifice pressure drop.



Figure 3: Airflow Control Hatch

2.1.4. Measurement Instruments

- Thermocouples (RTDs or K-type) to record inlet/outlet temperatures of water and air.
- Pressure transducer to monitor orifice pressure drop (± 5 Pa tolerance).
- Data Acquisition System (VDAS) for recording measurements.

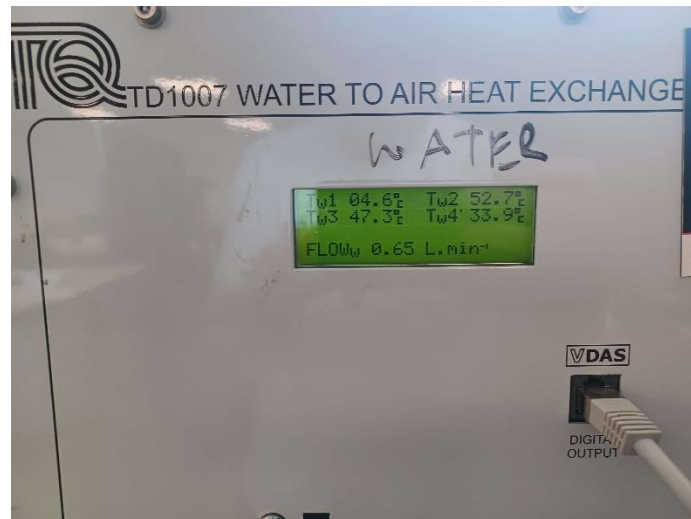


Figure 4: Water Measurement Readings

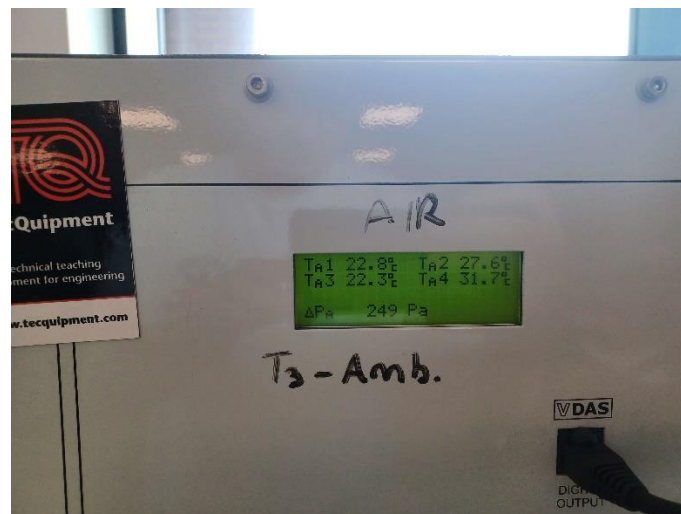


Figure 5: Air Measurement Readings

2.2. Experimental Procedure

2.2.1. Experiment 1: Effect of Varying Water Flow Rate

Operation:

- Ensure the system is maintaining a constant airflow orifice pressure of 250Pa.
- Set the heater tank to 60°C and allow for the system to stabilize.
- Adjust the water flow valve to 1.45 L/min (± 0.01 L/min) using the flowmeter.

Data Collection:

- Wait a minimum of 5 minutes for thermal equilibrium.
- Then record the following:
 - Water inlet/outlet temperatures (T_{w2} , T_{w3}).
 - Air inlet/outlet temperature (T_{a1} , T_{a2}).
 - Orifice pressure (ensuring $250 \pm 5\text{Pa}$).
- Repeat for water flow rates of 1.25, 1.05, 0.85, 0.65 L/min, readjusting airflow if needed.

2.2.2. Experiment 2: Effect of Varying Air Flow Rate

Operation:

- Adjust the airflow pressure to 250Pa with slider.
- Set the heater tank to 60°C and allow for the system to stabilize.
- Fix the water flow rate to 0.2 L/min (± 0.01 L/min) using the flowmeter.

Data Collection:

- Wait a minimum of 5 minutes for thermal equilibrium.
- Then record the following:
 - Water inlet/outlet temperatures (T_{w2} , T_{w3}).
 - Air inlet/outlet temperature (T_{a1} , T_{a2}).
 - Orifice pressure (ensuring $250 \pm 5\text{Pa}$).
- Repeat for airflow pressure drops of 200, 150, 100 and 50Pa, regularly verifying water flow rates are fixed.

3. Experiment 1: Effect of Varying Water Flow Rate

This experiment investigated how changing the water flow rate (1.45 to 0.65 L/min) affected the heat exchanger's performance while maintaining a constant air flow rate (250Pa orifice pressure drop) and fixed water inlet temperature (60°C).

3.1. Data Presentation

Experiment 1				
Water Flowrate	Water Inlet	Water Outlet	Air Inflow	Air Outflow
1.45	56.8	53.7	22.4	28.0
1.25	56.1	52.6	22.5	28.0
1.05	55.0	51.1	22.7	27.9
0.85	54.0	49.4	22.6	27.7
0.65	52.3	47.0	22.6	27.4

3.1.1. VDAS Calculations

Due to using the VDAS system, all calculated values for the experiment were all automatically calculated by the system.

Calculated Parameters – Water						
ΔT_w	Average T_w	Specific Heat, C_{p_w}	Density	Mass Flow Rate	Power Emitted, Q	η_w
-3.4	58.5	4183.46	984.0	0.0239	-340	9.0
-4.1	58.2	4183.34	984.1	0.0203	-348	10.9
-26.8	68.4	4188.35	978.7	0.0170	-1908	45.3
-35.9	72.0	4190.50	976.6	0.0138	-2076	53.3
-47.7	76.2	4193.29	974.1	0.0104	-2080	61.6

Calculated Parameters – Air						
ΔT_a	Average T_a	Specific Heat, C_{p_a}	Density	Mass Flow Rate	Power Absorbed, Q	η_a
5.6	25.2	1004.8	1.17	0.1138	640	14.8
5.5	25.3	1004.8	1.17	0.1140	630	14.6
5.2	25.3	1004.8	1.17	0.1140	596	8.8
5.1	25.2	1004.8	1.17	0.1142	585	7.6
4.8	25.0	1004.8	1.17	0.1142	551	6.2

VDAS Calculated Parameters - System			
Heat Transfer Coefficient, U	Mean Temperature Efficiency	Log Mean Temperature Difference	Energy Balance Coefficient
-65.9	11.9	33.096	-1.88
-68.4	12.8	32.665	-1.81
-298.4	27.1	41.042	-0.31
-305.4	30.5	43.636	-0.28
-288.4	33.9	46.291	-0.26

There are some discrepancies in the calculated parameters that might suggest the system is inaccurate:

- Negative U values – Physically impossible (likely sign error in VDAS).
- Inconsistencies – U should increase with water flow rate (higher turbulence), but some data points deviate (e.g., Data Series 3 shows erratic jumps).

Possible causes:

- Incorrect LMTD calculation due to temperature measurement errors.
- Heat losses to surroundings not factored in.

3.1.2. Result verification

To verify if these calculated results are correct, the following calculations were made to validate the VDAS system.

Heat Transfer Rate (Q):

$$Q = m_w \cdot c_{pw} \cdot (T_{w2} - T_{w3})$$

- m_w = Water mass flow rate
- c_{pw} = Specific heat of water = 4186 J/kg·K

$$Q = 0.0242 \cdot 4186 \cdot (56.8 - 53.7) = 313.5W$$

Log Mean Temperature Difference (LMTD):

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln \left(\frac{\Delta T_1}{\Delta T_2} \right)}$$

- $\Delta T_1 = T_{w2} - T_{a2}$
- $\Delta T_2 = T_{w3} - T_{a1}$

$$\Delta T_1 = 56.8 - 28 = 28.8^\circ\text{C}, \quad \Delta T_2 = 53.7 - 22.4 = 31.3^\circ\text{C}$$

$$LMTD = \frac{28.8 - 31.3}{\ln\left(\frac{301.95}{304.45}\right)} = 30.0 \text{ K}$$

Compared to the VDAS calculation it appears that it may have made an error, it most likely used the boiler temperature as the inlet temperature and the input temperature as the output temperature.

It is a safe assumption to disregard the VDAS calculated results, and it would be appropriate to recalculate all the values.

3.1.3. Hand Calculations

Calculated Parameters - System			
Heat Transfer Coefficient, U	Mean Temperature Efficiency	Log Mean Temperature Difference	Energy Balance Coefficient
67.48	9.01	30.03	2.08
66.81	10.41	29.08	2.14
65.46	12.07	27.74	2.16
65.94	14.64	26.54	2.20
61.62	17.84	24.64	2.39

These hand calculated results look more reliable to use to graph the changes in the system when flowrates in the system change. The energy balance coefficient being over 2 is problematic however after hours, no solution can be found to correct it, the possible causes that haven't been checked are the orifice plate calibration, heat exchanger insulation. Most heat exchangers typically range from 0.09 – 0.17, so it will cause the graphs representing the system to be either inaccurate or unexpected.

3.2. Graphical Analysis

3.2.1. Heat Emitted vs Heat Absorbed vs Mass Water Flowrate

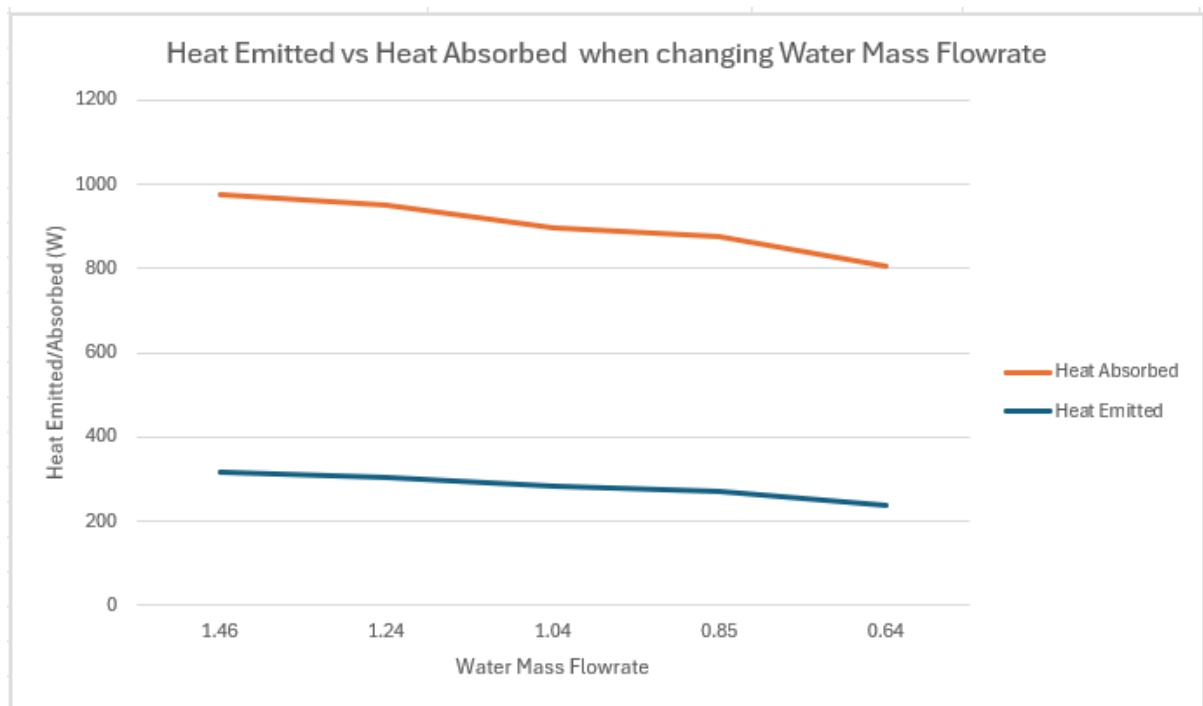


Figure 6: Heat Emitted vs Heat Absorbed vs Water Mass Flowrate

3.2.2. Mean Temperature Efficiency vs Mass Water Flowrate

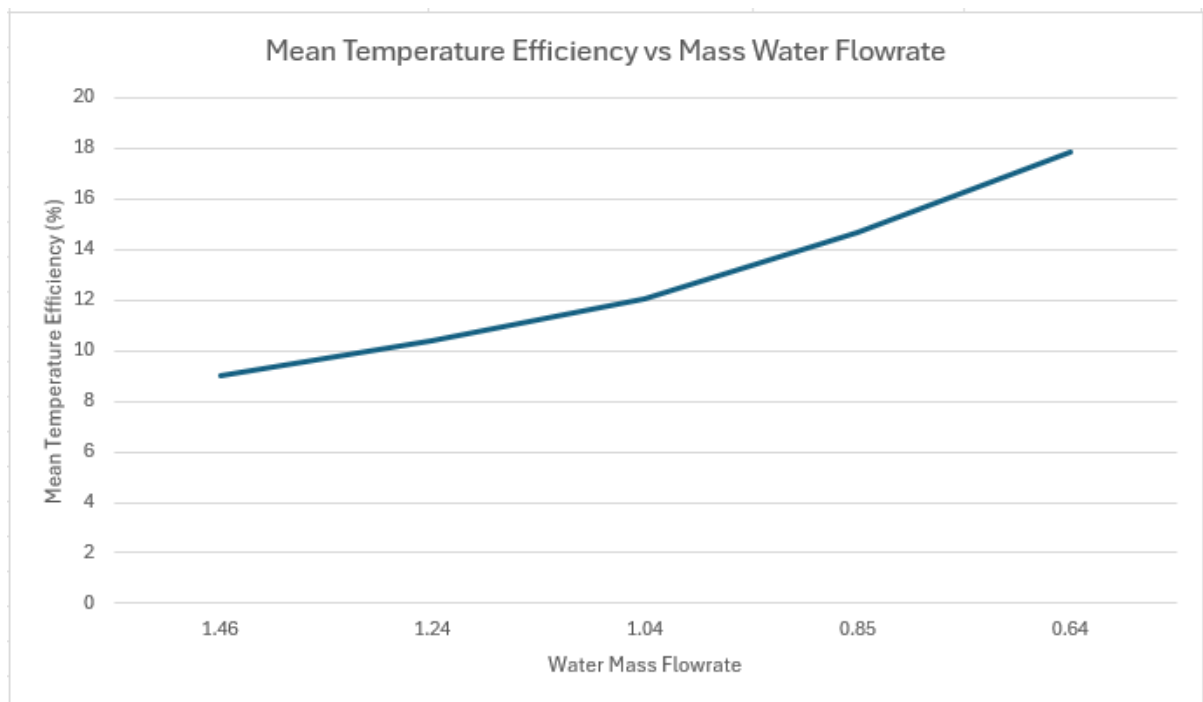


Figure 7: Mean Temperature Efficiency vs Mass Water Flowrate

3.2.3. Overall Heat Transfer Coefficient vs Mass Water Flowrate

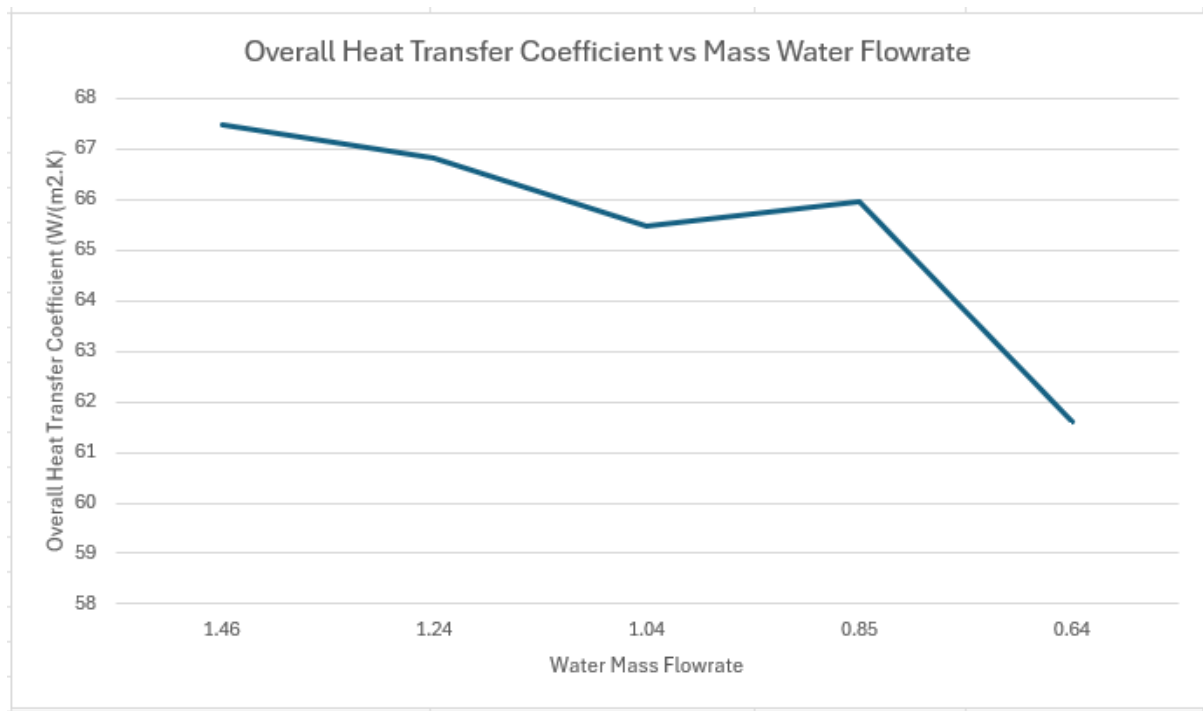


Figure 8: Overall Heat Transfer Coefficient vs Mass Water Flowrate

3.3. Discussion

3.3.1. Heat Transfer Coefficient

As the water flow rate decreased from approximately 1.45-0.65 L/min, the heat transfer coefficient slightly decreased from 67.5-61.6 W/m²K, which is as expected because higher flow rates should increase turbulence and improve the heat transfer coefficient. Literature reports for the heat transfer coefficient for similar systems suggest it should be within the range of 100-300 W/m²K, the lower values in this experiment suggest fouling or poor contact between the air/water. The rise on the fourth data point suggests insufficient stabilization time or measurement errors but without reconducting the experiment to compare, the cause will be difficult to determine.

3.3.2. Mean Temperature Efficiency

The temperature efficiency rose from 9-17.8% as the water flow decreased which also aligns with what was expected as lower flowrates allow more time for heat exchange. For cross flow, max efficiency is approximately 30-40%, experiment 1 results are lower due to losses.

3.3.3. Log Mean Temperature Difference

The log mean temperature difference also decreased with flow rates, decreasing from 30-24.6 K, this was expected and aligns with theory, smaller change in temperature at reduced flows.

3.3.4. Energy Balance Coefficient

The energy balance coefficient values consistently being above 2 suggests some discrepancies, implying heat losses potentially from poorly insulated components or ambient drafts which are unlikely. It may have also been caused by airflow overestimation, orifice plate calibration issues such as incorrect pressure readings, but again this cause seems unlikely as the equipment was very recently recalibrated. The only realistic cause that seems appropriate are temperature errors from not allowing thermocouples to reach steady state, which also shouldn't be the case since the VDAS system took data recordings every 10 seconds over the course of the 5 minutes for each data reading to allow for steady state conditions and the VDAS data suggests it was at steady state conditions. The impact of this is that the heat absorbed is greater than the heat emitted, which violates energy conservation.

4. Experiment 2: Effect of Varying Air Flow Rate

4.1. Data Presentation

Experiment 2				
Air Pressure	Water Inlet	Water Outlet	Air Inflow	Air Outflow
250	52.1	46.7	22.6	27.4
200	52.5	47.3	22.7	27.6
150	53.1	47.9	22.9	28.1
100	54.0	49.2	23.1	28.8
49	55.1	50.8	23.5	30.1

4.1.1. VDAS Calculations

Due to using the VDAS system, all calculated values for the experiment were all automatically calculated by the system.

VDAS Calculated Parameters – Water						
ΔT_w	Average T_w	Specific Heat, C_{p_w}	Density	Mass Flow Rate	Power Emitted, Q	η_w
-84.3	94.3	4209.04	962.4	0.0103	-3655	74.1
-60.1	82.6	4198.14	970.1	0.0103	-2599	66.9
-26.7	66.5	4187.24	979.8	0.0103	-1152	46.9
-16.1	62.1	4185.02	982.2	0.0106	-714	34.3
-4.8	57.5	4183.05	984.5	0.0107	-215	13.2

VDAS Calculated Parameters – Air						
ΔT_a	Average T_a	Specific Heat, C_{p_a}	Density	Mass Flow Rate	Power Absorbed, Q	η_a
4.8	25.0	1004.8	1.17	0.1142	551	4.2
4.9	25.2	1004.8	1.17	0.1022	503	5.5
5.2	25.5	1004.8	1.17	0.0885	462	9.1
5.7	26.0	1004.8	1.16	0.0719	412	12.1
6.6	26.8	1004.8	1.16	0.0504	334	18.1

VDAS Calculated Parameters - System			
Heat Transfer Coefficient, U	Mean Temperature Efficiency	Log Mean Temperature Difference	Energy Balance Coefficient
-402.2	39.2	58.325	-0.15
-329.5	36.2	50.630	-0.19
-190.6	28.0	38.788	-0.40
-131.0	23.2	34.975	-0.58
-45.5	15.7	30.344	-1.55

Again, for the same reasons as in experiment 1, the VDAS calculations will be disregarded and will be replaced with hand calculations.

4.1.2. Hand Calculations

Calculated Parameters - System			
Heat Transfer Coefficient, U	Mean Temperature Efficiency	Log Mean Temperature Difference	Energy Balance Coefficient
63.7	16.4	24.4	2.28
62.1	15.7	24.1	2.16
63.5	15.4	23.6	1.98
72.7	16.3	23.2	1.58
69.4	14.6	22.3	1.38

Like experiment 1, the same issues have arisen which will be further in the report.

4.2. Graphical Analysis

4.2.1. Heat Emitted vs Heat Absorbed vs Air Pressure

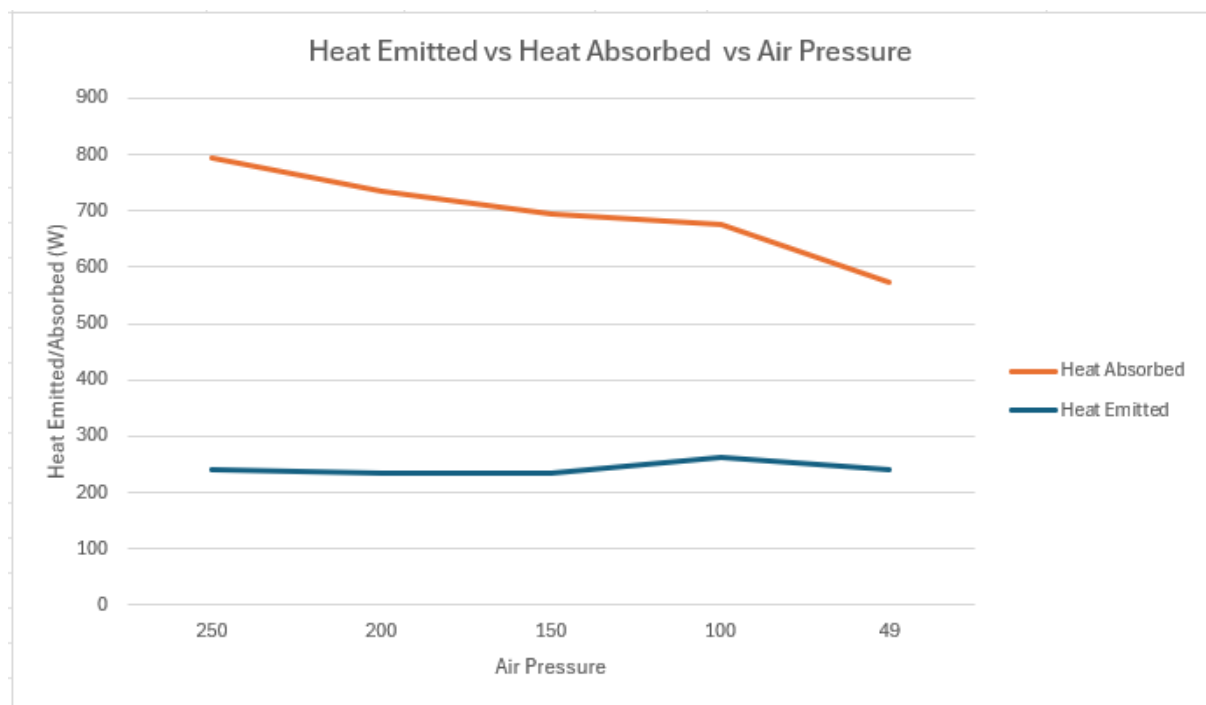


Figure 9: Heat Emitted vs Heat Absorbed vs Air Pressure

4.2.2. Temperature Efficiency vs Air Pressure

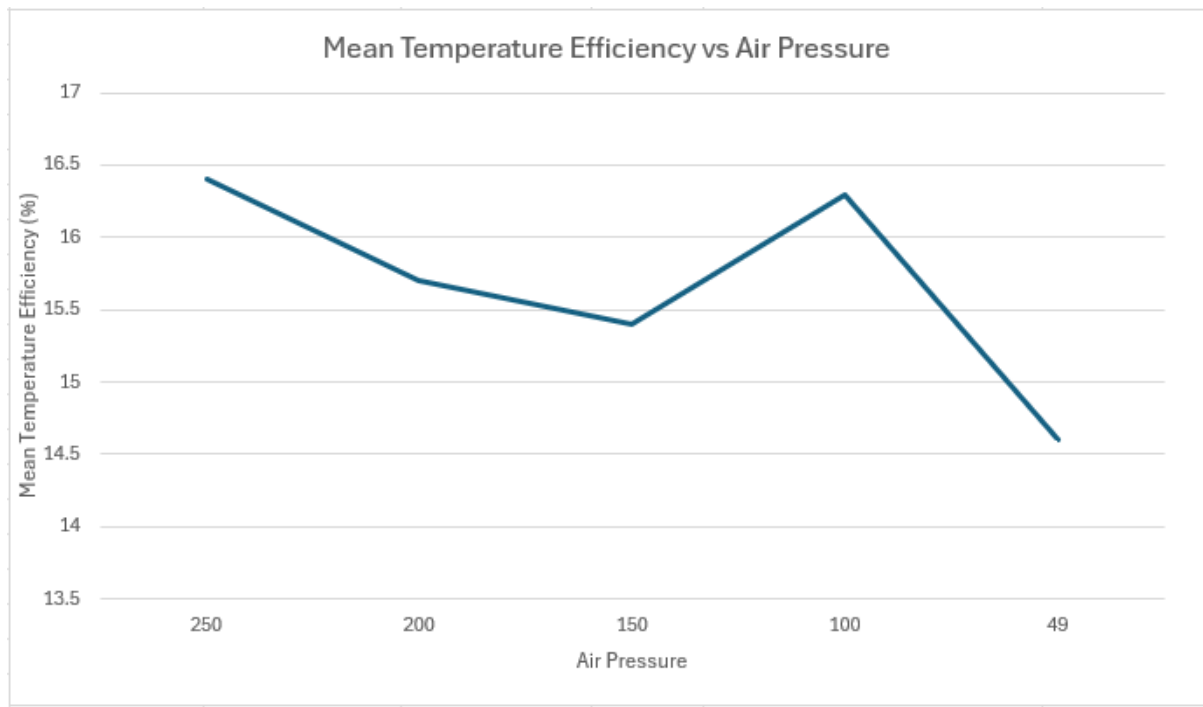


Figure 10: Temperature Efficiency vs Air Pressure

4.2.3. Overall Heat Transfer Coefficient vs Air Pressure

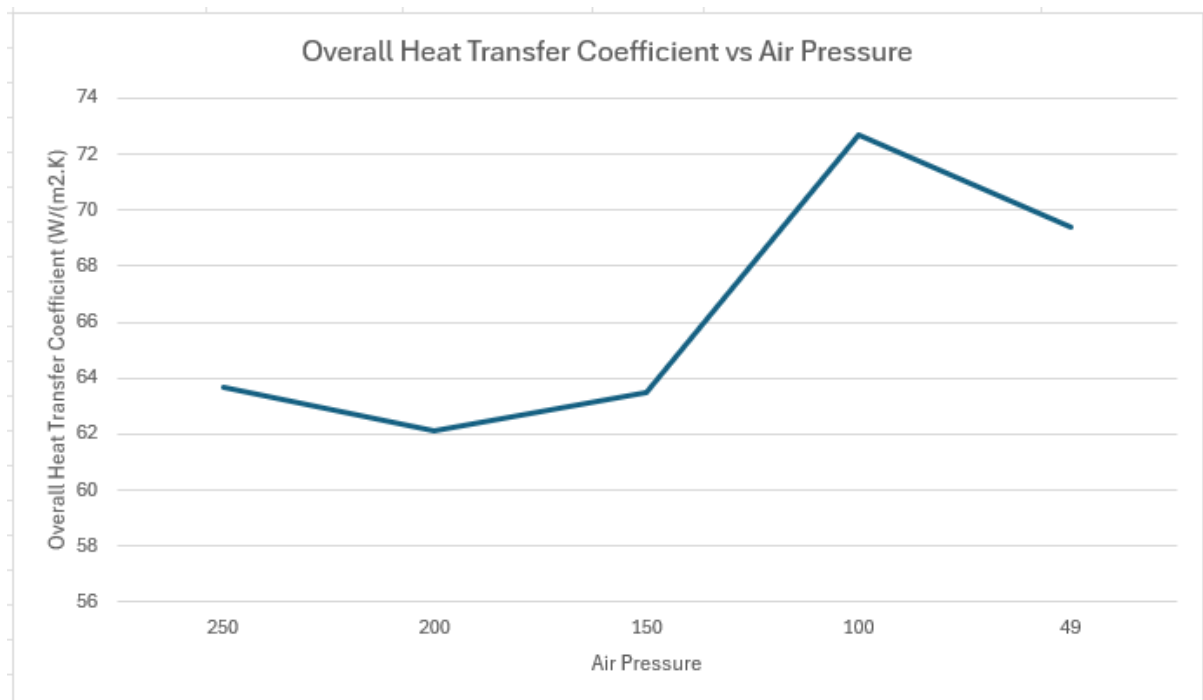


Figure 11: Overall Heat Transfer Coefficient vs Air Pressure

4.3. Discussion

4.3.1. Heat Transfer Coefficient

Heat transfer coefficient peaked at $72.7 \text{ W/m}^2\text{K}$ at 100 Pa and then dropped slightly at 49 Pa likely due to laminar flow dominance at very low pressure. Similar to experiment 1, the heat transfer coefficient did not follow a perfect trend due to experimental errors, however the peak does suggest optimal turbulence at mid-range flow. This may indicate that air flow has a more complex impact on turbulence and heat transfer than water flow rate.

4.3.2. Mean Temperature Efficiency

Efficiency remained stable ranging between 15-16%, but it was slowly decreasing, with its lowest being 14.6% at the lowest recorded airflow, indicating reduced heat transfer effectiveness with very low airflow. In contrast to experiment 1, lower water flowrates increased efficiency whilst in experiment 2, efficiency was less sensitive to airflow changes.

4.3.3. Log Mean Temperature Difference

The log Mean Temperature Difference dropped as airflow decreased, consistent with theory because at lower airflows, there is a smaller change in temperature. However, the change in temperature remained similar across varying air pressures, suggesting that air pressure has very little impact on heat transfer as the temperature difference remained similar throughout.

4.3.4. Energy Balance Coefficient

Energy Balance Coefficient improved with airflow, decreasing from 2.28-1.38, however, the value remained above 1, confirming systematic heat losses. Like in experiment 1, this contrasts the conservation of energy, this same causes highlighted in the discussion for experiment 1 can be applied here also.

5. Conclusion

The experiment 1 results showed that reducing the water flow rate from 1.45 to 0.65 L/min increased temperature efficiency from 9.0% to 17.6%, consistent with theory due to longer residence time. However, the heat transfer coefficient remained low compared to literature values, likely due to unaccounted heat losses or airflow measurement errors. The energy balance coefficient indicated significant heat loss, possibly from uninsulated components. To improve accuracy, future experiments should further insulate the system, calibrate the orifice plate, and allow longer stabilization times. Despite discrepancies, the trends confirm that lower flow rates improve efficiency but highlight the need for better control of experimental conditions.

Experiment 2 demonstrated that reducing airflow caused LMTD to decline as expected, while the heat transfer coefficient peaked at $72.7 \text{ W/m}^2\text{K}$ at $\Delta P = 100 \text{ Pa}$ before dropping. This contrasts with Experiment 1, where U decreased monotonically with water flow rate, suggesting airflow has a more complex impact on turbulence. Efficiency remained stable until the lowest airflow, unlike Exp. 1 where η rose consistently at lower flows. Both experiments shared high EBC values (>1.0), indicating systemic heat losses. To improve accuracy, future work should insulate the system and calibrate airflow measurements. The results highlight that mid-range airflow optimizes performance, a valuable insight for industrial applications.

6. Bibliography

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