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Heat Exchanger Laboratory Analysis

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1 Introduction

The following coursework will discuss the physical experiment conducted on a heat exchanger, an instrument adopted by many thermodynamic application and systems to transfer heat from one form or place to another. To do so, heat exchangers normally uses a circulating fluid that is heated or cooled by an air flow or vice versa.

Everyday examples of heat exchangers are the radiator of an engine, which is blown by fresh air while the vehicle is traveling and cools down the cooling fluid, or a distiller in which cold air is used to condense vapours of a heated fluid.

Three experiments were conducted to best highlight which parameter's variation has the biggest effect:

1. Variation of the fluid flow rate
2. Variation of the air flow rate
3. Variation of the fluid temperature and air flow rate

The aim of the coursework is to understand how a heat exchanger works and under which conditions it work best (efficiency), therefore learning the physical principles involved.

2 Heat exchanger understanding

The system used was a laboratory version of an everyday heat exchanger, to allow repeatable scenarios with different specific layouts or parameters.

Because heat exchangers can have various shapes and layouts, this coursework will only look at recuperative and cross flow systems: the first kind is when heat energy transfer happens through a dividing wall i.e. the tubes in which the hot water circulates; the latter, occurs when one fluid flow is perpendicular to the second one, i.e. the cooling air, flows at 90° to the hot water stream in the tubes.



Figure 1 Heat Exchanger

Heat exchanger are therefore, systems that, throughout convection and a negligible effect provided by conduction, by the flow of a fluid (air in the case of the experiment) forced through a duct by a fan, cool down a hotter fluid (water for this purpose) that circulates in a close circuit. The machine used for the experiment was equipped with thermocouple sensors to acquire temperature and pressure information for the purpose and then displayed on digital screens.

Moreover, it must be kept in mind that thermodynamically, heat transfer only occurs when there is a difference in temperature between the elements involved and it flows only from hot to cold, as the principle of conservation of energy; furthermore, there is no mix between the fluids. From the previous statements reasonably, it is easy to understand that heat exchangers obey to the first law of thermodynamics that specifies that energy can be

transformed from one form to another but cannot be destroyed.

The heat transfer rate can be calculated following:

$$\dot{Q} = \Delta T * A * U$$

Where:

- $\dot{Q}$ is the heat transfer in J/s or watts;
- ΔT is the temperature difference in °C (Celsius) or K (Kelvin);
- A is the heat transfer area in m^2 ;
- U is the overall heat transfer coefficient in W/m^2K .

3 Experiment one

3.1 Data acquisition

Experiment one is conducted to understand if the rate variation of a 60° C isothermal fluid, blown by a constant 250 Pa air flow, affects the heat exchanger performance.

Starting with a flow rate of 2.25 l/min, with a ± 0.01 l/min tolerance, it was allowed the heat exchanger to stabilize and then took the reading of the two circuits in and out temperatures; with decreasing steps of 0.5 l/min it was then repeated the data acquisition till a minimum water flow rate of 0.25l/min.

Flow	P_Drop	Tw1	Tw2	Ta1	Ta2	T_ambient
L/min	pa	°C	°C	°C	°C	°C
2,240	249	60,5	56,7	26,5	31,9	25,7
1,770	248	60,8	56,0	27,0	32,0	26,8
1,250	251	60,5	54,2	27,0	31,8	26,7
0,750	249	59,5	50,2	26,2	30,5	25,6
0,240	250	60,2	39,1	26,2	29,4	25,9

Table 1 Experiment 1 data

Where:

- P stand for pressure, in this case representing the cold flow stream;
- T stand for temperature;
- w stands for water;
- a stand for air
- 1 represents the inlet;
- 2 represents the outlet.

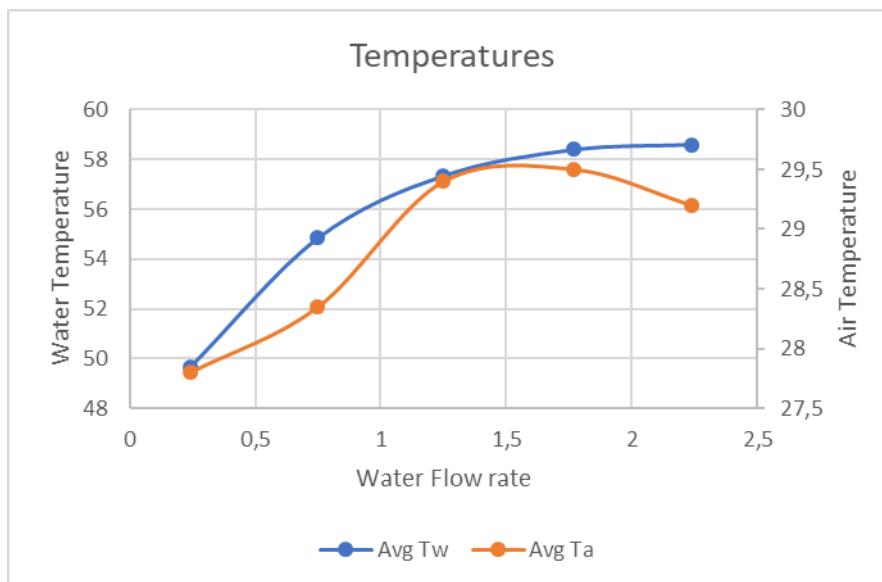
3.2 Results and analysis

It was calculated the change in temperature (ΔT) and the average temperature (AvgT) of both circuits as well water and air densities (ρ).

Flow	ΔT_w	ΔT_a	Avg Tw	Avg Ta	ρ_w	ρ_{air}	T_{amb}
L/min	°C	°C	°C	°C	Kg/m ³	Kg/m ³	°C
2,240	3,80	5,40	58,60	29,20	983,90	1,19	25,7
1,770	4,80	5,00	58,40	29,50	984,00	1,18	26,8
1,250	6,30	4,80	57,35	29,40	984,52	1,18	26,7
0,750	9,30	4,30	54,85	28,35	985,75	1,19	25,6
0,240	21,10	3,20	49,65	27,80	988,18	1,19	25,9

Table 2 Experiment 1 calculations

From the Graph it is possible understand that the more the water flow slows, the faster it cools since there is more time to allow heat transfer between the fluids. In fact, from the



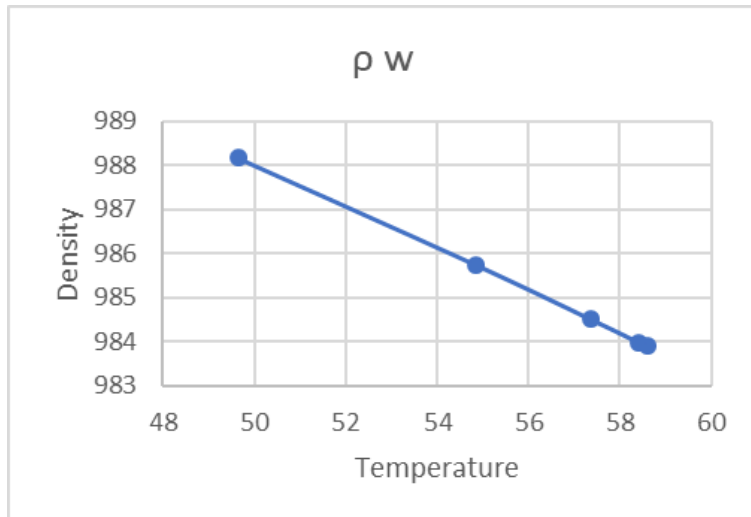
Graph 1 Experiment 1 Temperatures

table it is possible to notice how the slower the water flow is the less temperature difference there is between the air flow entering and the one exiting the system. Moreover, noticeable are the temperature difference steps that occurs between 1.25 l/min and 0.75 l/min

with a 2.5°C difference and the even bigger one between 0.75 and 0.24 l/min with a 5.2°C jump.

Water density is directly related to temperature: has maximum density at 4° C and it decreases as temperature rises or vice versa. Using the average temperature value, it was possible calculate water density from:

$$\rho_w = \frac{999.839 + 16.952T - 7.99 \cdot 10^{-3}T^2 - 46.241 \cdot 10^{-6}T^3 + 105.846 \cdot 10^{-9}T^4 - 281.03 \cdot 10^{-12}T^5}{1 + 16.887 \cdot 10^3T}$$



Graph 2 Experiment 1 water density

As the graph illustrates, as more the water gain heat as more the density tends to decrease.

Hypothetically, if it was possible to start from 0° C it would be possible to observe a peak density value around 4°C than following the same path.

Air density on the contrary has its maximum at absolute zero (0 K or -273°C) and it decreases as temperature rises. From:

$$\rho_a = \frac{P_{amb}}{R T_{avg}}$$

It is possible understand that air density is directly related to ambient pressure and on the experiment day, it was 1,031 bar; R is the gas constant with a value of 287,058 J/kgK.

In the experiment the air temperature did not vary a lot, therefore a graph is not helpful as the water one.

It was calculated the air flow rate through the duct (constant) from:

$$\dot{m}_{air} = C_d * A_o \sqrt{2 * \Delta P * \rho_a}$$

Where:

- C_d is the orifice discharge coefficient, a given value for the machine of 0.6;
- A_o is the orifice area calculated from its diameter stamped on the top (100,11 mm) achieving a surface of 0,00787127 m²;
- ρ_a air density;
- ΔP is the pressure drop through the duct;

It was converted the water flow rate into mas flow rate or SI units, from:

$$mass\ flow\ rate = \frac{volume\ flow\ rate}{6000} * water\ density;$$

$\dot{m}_{air}$	$\dot{m}_{water}$
kg/s	kg/s
0,115	0,037
0,114	0,029
0,115	0,021
0,115	0,012
0,115	0,004

Table 3 Experiment 1 mass flow rate

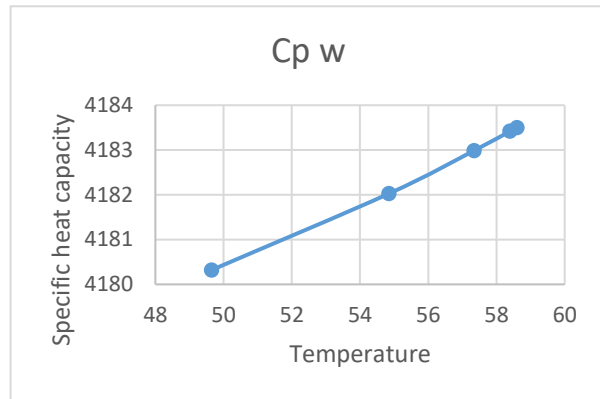
Then it was calculated the specific heat capacity of the water at each flow rate and temperature. This parameter is the amount of energy needed to increase 1kg of material by 1°C and for water can be calculated from:

$$c_{p\ w}(at\ T\ [^{\circ}C]) = 0.996185 + 28.74 * 10^5 \left(\frac{T+100}{100} \right)^{5.26} + 0.01116 * 10^{-0.036T} * 4185.5$$

Where 4185.5 J/kgK is the specific heat capacity of water at 15°C.

Flow	Avg Tw	Cp w
L/min	°C	J/KgK
2,240	58,60	4183,50
1,770	58,40	4183,42
1,250	57,35	4182,99
0,750	54,85	4182,03
0,240	49,65	4180,32

Table 4 Experiment 1 Average Temperature and specific heat capacity



Graph 3 Experiment 1 water's specific heat capacity

Reasonably, the lower the temperature less energy will be required to heat the fluid by 1 degree Celsius, as the table and the graph highlights.

Additionally, the heat transfer rate $\dot{Q}$ can also be considered as power, because energy per unit time. Consequently, it was possible calculate the heat emitted and absorbed.

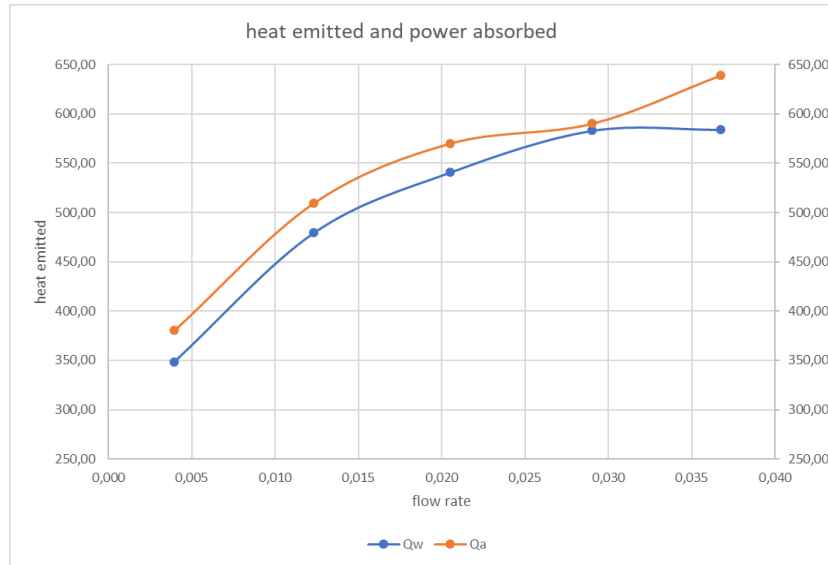
The heat emitted by the water was calculated from:

$$Q_{emitted/absorbed} = \dot{m} * c_p * \Delta T$$

And similarly, was calculated the heat absorbed by the air. Theoretically, in an ideal heat exchanger system, the two values calculated are equal, due to no loss or absorption by the surroundings, hence the cooler air flow absorbs entirely the heat from the hotter water; in reality, some heat crosses the system's boundary thus, as the following table and graph highlights, the two values are different.

Flow	Qemit w	Air Cv	Qabs a	η_w	η_a	Mean η	LMTD	U
L/min	watts	J/KgK	watts	%	%	%		W/m ² .K
2,240	583,94	1031,00	638,90	11,18	15,88	13,53	29,16	128,54
1,770	582,89	1031,00	590,10	14,20	14,79	14,50	28,62	130,72
1,250	540,52	1031,00	570,00	18,81	14,33	16,57	27,58	125,80
0,750	479,23	1031,00	509,47	27,93	12,91	20,42	25,91	118,73
0,240	348,65	1031,00	380,25	62,06	9,41	35,74	19,37	115,50

Table 5 Experiment 1 energy, efficiency and LMTD



Graph 4 Experiment 1 heat emitted and power absorbed

The graph therefore, highlights that energy absorbed and emitted improves with water flow. The lines show is not a linear behavior and that there is a maximum value after which it will start to decrease.

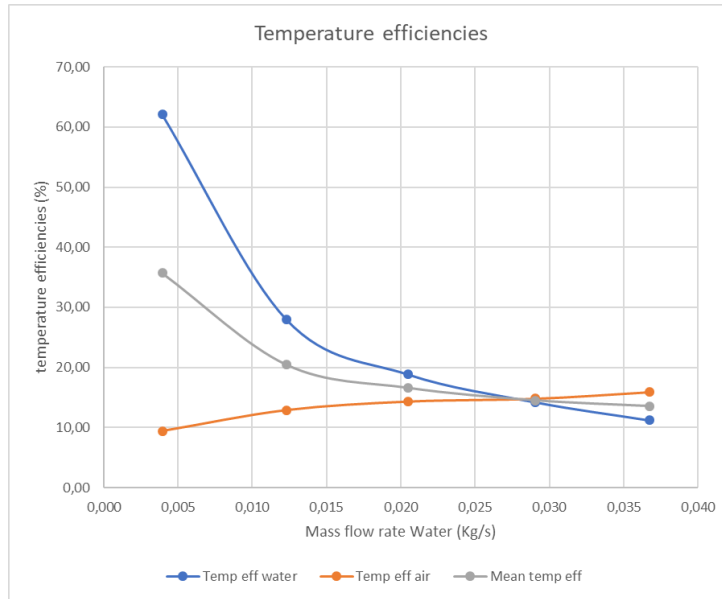
Therefore, to compare the performance of different heat exchangers useful results are given by mean temperature efficiency and the heat transfer coefficient.

The mean temperature efficiency is a percentage value, average of the individual efficiencies.

$$\eta_x = \frac{T_{x2} - T_{x1}}{T_{x1} - T_{Y1}} * 100;$$

$$\bar{\eta} = \frac{\eta_x + \eta_y}{2};$$

Where x and y are respectively the two fluids involved.



Graph 5 Experiment 1 temperature efficiencies

The graph highlights the concept already expressed: the slower the hot fluid flows the more efficient the heat transfer process of the entire system is, i.e. 13.53% of efficiency when the hot flow runs at 2.24 l/min and 35.74% for 0.24 l/min.

The graph shows how the two circuits act differently: water temperature efficiency decreases with the increase of the flow rate, contrarily to air temperature efficiency. However, water's change temperature efficiency is greater than air's, due to the bigger temperature change throughout the process, i.e. see ΔT in the table. Moreover, the graph highlights an intersection point at 0.021 kg/s, where all three temperature efficiencies intersect. It can be considered the optimal point for the system for maximum efficiency.

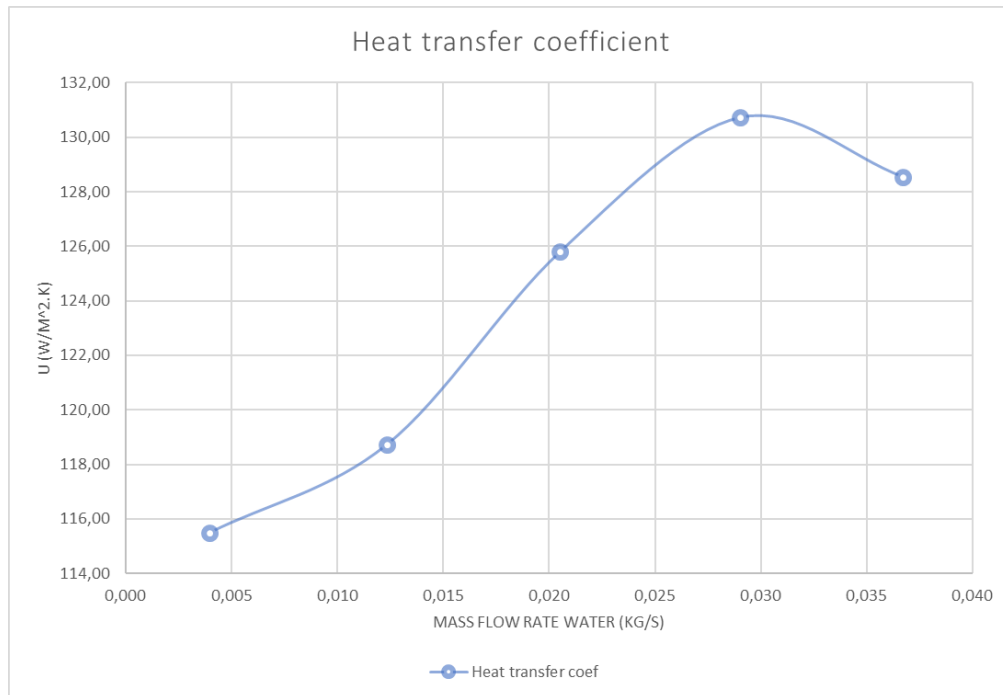
The second parameter that can be used to compare different heat exchangers systems is the heat transfer coefficient U , which indicates how well the system performs, the bigger the value the best it performs:

$$U = \frac{\dot{Q}_w}{A * LMTD};$$

Where:

- A is the heat transfer area, given by the heat exchanger manual guide, of 0,1558 m²;
- $\dot{Q}_w$ is the energy rate emitted;
- $LMTD$ is the logarithmic mean temperature difference, i.e. the force that creates the heat transfer, achieved from:

$$LMTD = \frac{(T_{w2}-T_{a2})-(T_{w1}-T_{a1})}{\ln\left(\frac{T_{w2}-T_{a2}}{T_{w1}-T_{a1}}\right)};$$



Graph 6 Experiment 1 heat transfer coefficient

The graph highlights the optimal flow regime at which the system is working best: the heat transfer coefficient grows with the increase of water flow, reaches a peak and then starts to decrease, suggesting that once the optimum flow regime is reached, the further increase of the flow does not improve the performance. Moreover, peculiar is to notice how this peak is not the same as for the mean temperature efficiency. Even though it might be foreseen to be the same, this difference is related to the system it-self (features, materials used, shape, dimensions etc) while the temperature efficiencies take into account the property of the singular fluid.

Therefore, taking into consideration these two factors it can be assumed that the optimal regime for the system with this configuration is the one between the 0.021 and 0.03 kg/s.

4 Experiment two

4.1 Data acquisition

Experiment 2 is conducted to show the differences in performance caused by the variation of the cold air flow, keeping the hot stream flow at constant temperature (60°C) and flow rate (0.25 l/min). By steps of 50 Pa, the air flow is reduced from 250 Pa to 50 Pa.

P	Flow	Tw1	Tw2	Ta1	Ta2	T_ambient
pa	l/min	°C	°C	°C	°C	°C
250,5	0,240	60,2	39,1	26,2	29,4	25,9
200,0	0,240	58,1	38,6	26,1	29,3	25,6
147,5	0,240	58,1	39,0	26,2	29,5	25,7
102,5	0,240	58,0	40,1	26,0	29,7	25,2
48,0	0,240	58,3	41,9	26,2	30,6	25,4

Table 6 Experiment 2 data

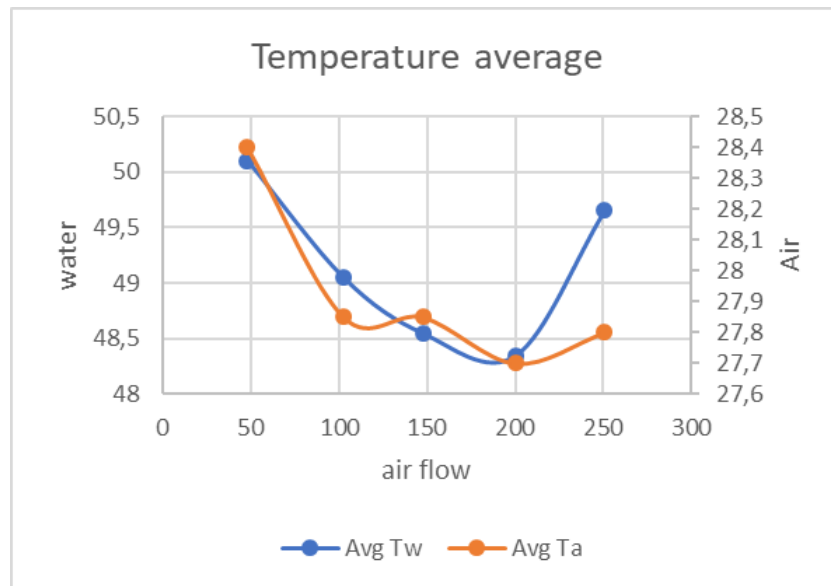
4.2 Results and analysis

As for the previous experiment, were calculated the change in temperature and the average temperature per each circuit.

P	ΔT_w	ΔT_a	Avg Tw	Avg Ta	ρ_w	ρ_a
pa	°C	°C	°C	°C	Kg/m ³	Kg/m ³
250,5	21,1	3,2	49,65	27,80	988,18	1,191
200,0	19,5	3,2	48,35	27,70	988,76	1,192
147,5	19,1	3,3	48,55	27,85	988,67	1,192
102,5	17,9	3,7	49,05	27,85	988,45	1,193
48,0	16,4	4,4	50,10	28,40	987,98	1,191

Table 7 Experiment 2 calculations

It is immediately clear that contrarily to the first experiment, by slowing the cold stream the effects are opposite, as the tables and the following graph highlights



Graph 7 Experiment 2 temperatures

From the graph it is noticeable that only when the cold flow is at 200 Pa, both streams are at their minimum temperature value; for slower cold streams the heat transfer is less, hence the temperature turn to raise again. The densities on the contrary, are not affect by the variation of the cold stream.

$\dot{m}$ air	$\dot{m}$ water	Cv air	Cv w
kg/s	kg/s		J/Kg.K
0,115	0,004	1031	4180,321
0,103	0,004	1031	4179,958
0,089	0,004	1031	4180,012
0,074	0,004	1031	4180,150
0,051	0,004	1031	4180,452

Table 8 Experiment 2 calculations

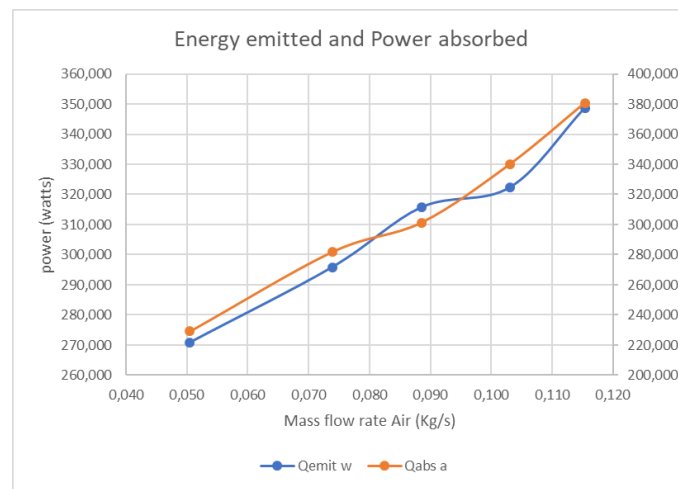
It was calculated, as previously, the mass flow rate of both circuits and the specific heat capacity. Even though the air flow rate is changed through the experiment, its value is not dependent to the variation in time and remains constant at normal atmospheric pressure, as the formula also highlights:

$$c_p = \frac{Q}{\Delta T}$$

As for the previous experiment, were calculated the energy emitted by the water, the power absorbed by the air flow, the mean temperature efficiencies and the heat transfer coefficient.

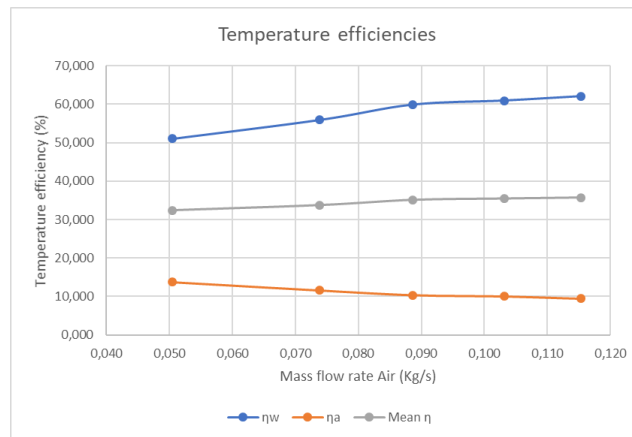
P	Q _{emit} w	Q _{abs a}	η_w	η_a	Mean η	LMTD	U
p _a	watts	watts	%	%	%		W/m ² .K
250,5	348,649	380,628	62,059	9,412	35,735	19,374	115,503
200,0	322,372	340,244	60,938	10,000	35,469	18,370	112,638
147,5	315,735	301,327	59,875	10,345	35,110	18,492	109,588
102,5	295,841	281,700	55,938	11,563	33,750	19,218	98,805
48,0	270,940	229,095	51,090	13,707	32,399	19,922	87,290

Table 9 Experiment 2 energies, efficiencies and LMTD



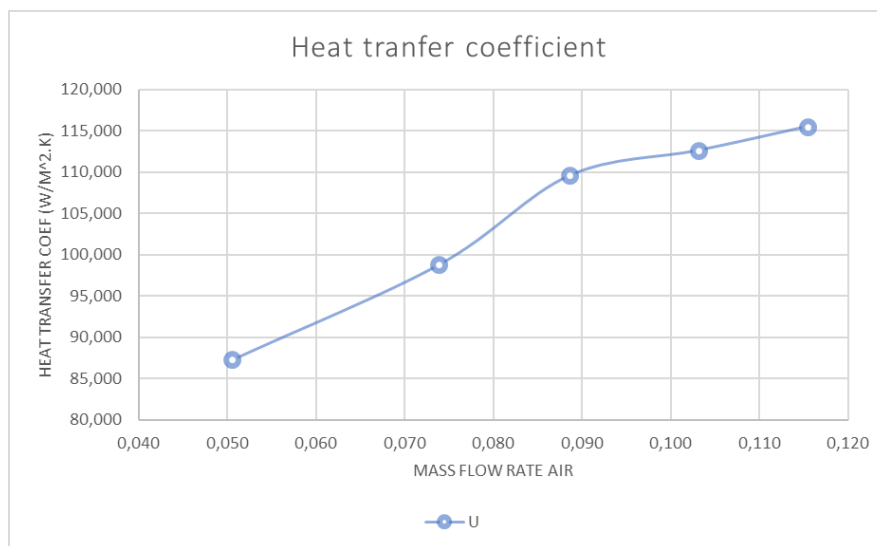
Graph 8 Experiment 2 energy emitted and power absorbed

From the table and the graph, it is easy to see how the difference between the two energies is very small throughout the experiment: the energy increases with the air flow. At low air flow rates, even though the difference is very small, air's energy is slightly bigger suggesting a higher energy loss than at higher flow rates. As the flow increases this difference fluctuates but then the two lines start to converge suggesting that for higher air flow rates the heat transfer would be bigger.



Graph 9 Experiment 2 temperature efficiencies

The mean temperature efficiencies figures highlight a better performance throughout the entire variation. The 35% efficiency has its peak at maximum flow rate and almost constant for the next two steps, opposite to what happens in experiment 1 where the same figure is reached at minimum hot stream flow. Peculiar is how each temperature efficiency line does not have an intersection point and remains linear: in fact, opposite of what happened in experiment, air efficiency decreases with the increase of air flow while water efficiency tends to increase.



Graph 10 Experiment 2 heat transfer coefficient

The heat transfer coefficient graph and table highlight how almost linearly the performance of the system increases the faster the cold air stream flows. The trend of the graph suggests that for higher flow rates there could be a further heat transfer increase.

5 Experiment 3

5.1 Data acquisition

Experiment 3 is intended to highlight the variation in performance of the heat exchanger by varying the cold air stream, as the previous experiment, but with a constant lower temperature of the hot stream fixed at 45°C.

P	P_Drop	Tw1	Tw2	Ta1	Ta2	T_ambient
pa	l/min	°C	°C	°C	°C	°C
251	0,250	49,40	34,20	24,90	27,30	24,4
201	0,240	48,30	33,80	24,60	27,00	24,1
149	0,250	47,90	34,20	25,00	27,40	24,6
98	0,250	47,80	35,40	25,70	28,20	25,0
47	0,250	47,90	36,80	25,30	28,50	24,2
25	0,250	48,20	37,70	25,50	29,10	24,2

Table 10 Experiment 3 data

5.2 Results and Analysis

P	ΔTw	ΔTa	Avg Tw	Avg Ta	ρ w	ρ a
pa	°C	°C	°C	°C	Kg/m ³	Kg/m ³
251	15,20	2,40	41,80	26,10	991,503	1,198
201	14,50	2,40	41,05	25,80	991,798	1,200
149	13,70	2,40	41,05	26,20	991,798	1,199
98	12,40	2,50	41,60	26,95	991,582	1,196
47	11,10	3,20	42,35	26,90	991,284	1,197

Table 11 Experiment 3 calculations

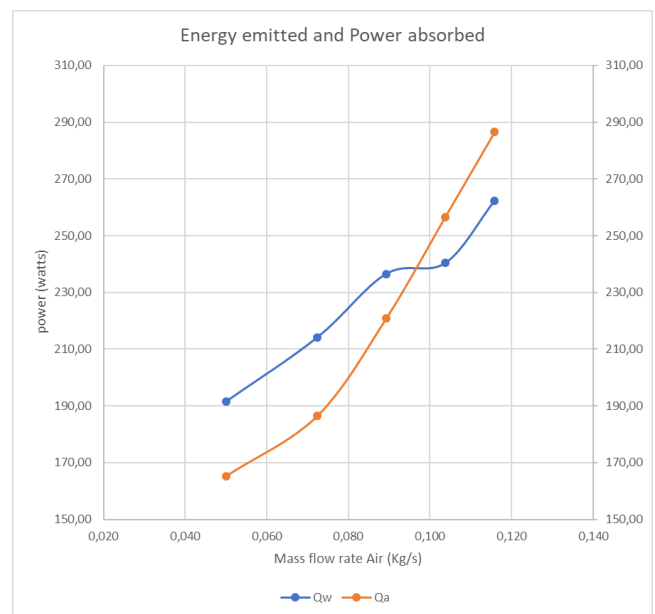
As for the previous experiment there is no remarkable variation for the densities, on the contrary due to an initial lower hot stream temperature, the differences between the inlet and outlet stream temperature are smaller. The average temperature are directly influenced and the overall difference between the temperature extremes (251Pa and 47Pa) are just above 1°C for both streams.

P	Qemit w	Qabs a	η_w	η_a	Mean η	LMTD	U
pa	watts	watts	%	%	%		W/m ² .K
251	262,39	286,57	62,04	9,80	35,92	13,89	121,26
201	240,36	256,63	61,18	10,13	35,65	13,54	113,98
149	236,56	220,86	59,83	10,48	35,15	13,26	114,51
98	214,07	186,40	56,11	11,31	33,71	13,29	103,42
47	191,58	165,28	49,12	14,16	31,64	14,28	86,13

Table 12 Experiment 3 energies, efficiencies and LMTD

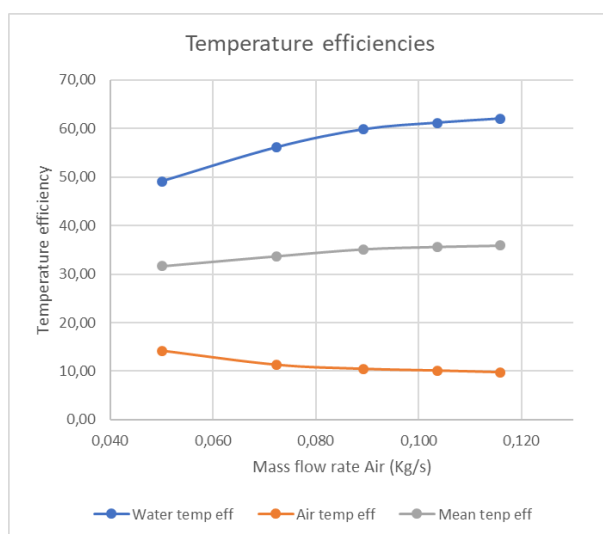
P	Δ Energy 60°C	Δ Energy 45°C
pa	Watts	watts
250,5	31,980	24,17
200,0	17,873	16,27
147,5	14,408	15,70
102,5	14,141	27,68
48,0	41,846	26,30

Table 13 Experiment 2 and 3 energy comparison



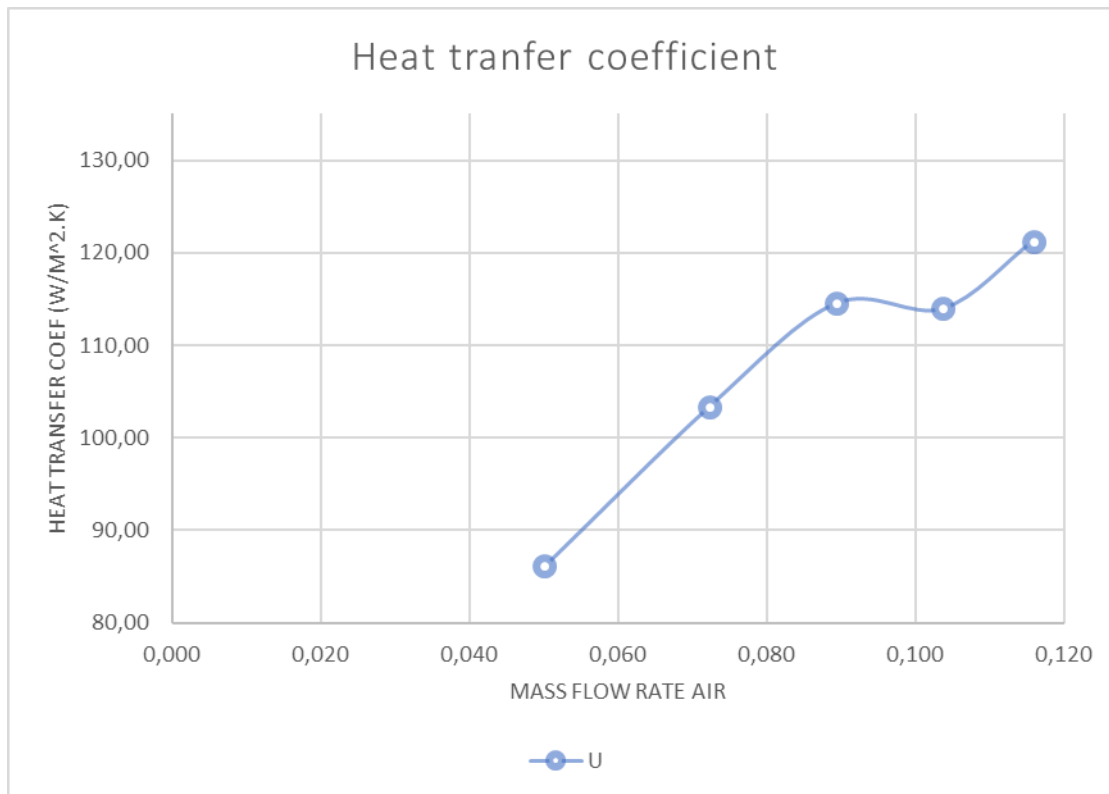
Graph 11 Experiment 3 energy emitted and power absorbed

From the energy point of view, the two systems share the same graphs but from a magnitude point of view, experiment 3 highlights the more balance between energy absorbed and emitted, making this layout more like a perfect scenario with no energy losses.



Graph 12 Experiment 3 temperature efficiencies

The temperature efficiencies highlight the very close similarity to the previous experiment, sharing almost the exact same values.



Graph 13 Experiment 3 heat transfer coefficient

The heat transfer coefficient shows higher values for every step comparing it to the previous experiment. However, while the previous one tends to grow almost constantly, the third experiment shows a big negative deflection in the gradient at the same point.

6 Recommend Further Work

- For experiment 1, smaller steps in the flow rate would better highlight at which point the flow rate influences the most the heat transfer between the circuits;
- For experiment 2, smaller air flow rates steps would help to find where is reached almost the energy equilibrium;
- For experiment 2, would be ideal to increase by steps the cold streams to find the optimal for best performance of the heat exchanger.

7 Conclusion

Experiment 1 and 2 suggest that a maximization of the efficiency of a heat exchanger can be reached by the combination of various types and layouts of heat exchangers. For instance, the configuration adopted, helped the performance of the heat exchanger: the two fluids pass each other multiple times (multi pass heat exchanger), therefore a further optimization can be reached by adding other hot stream lines to increase the heat transfer area.

8 Bibliography

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