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Optimal Design of Heat Exchangers to Enhance Thermal Performance

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Abstract

Heat transfer is a key aspect of devices and industrial processes for maintaining their functionality and achieving better product quality. Heat exchangers of different types and sizes are used to transfer heat between a source and a working fluid to maintain the desirable working temperatures. Due to the space requirements of devices, there is a need for efficient heat exchangers with **less size** and **less weight**. Gyroid structure is a type of Triply Periodic Minimal Surface structures that define an internal volume that maximizes surface area and strength while minimizing mass. The hypothesis is that gyroid structures are useful in heat exchanger design, as they can optimize heat transfer to be **more efficient**, compared to traditional heat exchanger designs. A gyroid structured heat exchanger was designed, 3D printed, and compared to a commercial plate heat exchanger. Using different water flow rates, temperatures at the hot and cold inlets/outlets were measured using thermocouples and PicoLog until they reached steady state and calculated heat transfer rate and efficiency. It is found that heat transfer rate linearly increases with flow rate and that the heat transfer rate for the commercial heat exchanger is about twice the heat transfer rate for the gyroid one. A gyroid heat exchanger with the same surface area as the commercial one is likely to have a much larger heat transfer rate. Additional measurements, such as pressure drop and internal volume, should be taken to properly compare different heat exchangers, while minimizing heat loss and uncertainty in data.

Introduction

Heat transfer is a key aspect of devices and industrial processes for maintaining their functionality and achieving better product quality. Heat exchangers of different types and sizes are used to transfer heat between a source and a working fluid without mixing them to maintain the desirable working temperatures [1]. Heat exchangers which transfer thermal energy between fluids are used in systems including refrigeration, fuel cells and the types of internal combustion engines used in cars and aircrafts [2]. Figure 1 shows a typical shell and tube heat exchanger that is widely used in the industry.

Figure 1: Typical shell and tube heat exchanger [3]

The basic principle is that the larger the surface area inside a heat exchanger is, the more efficient the heat exchanger is because of larger heat transfer rate. Due to the space requirements of devices, however, there is a growing need for efficient heat exchangers with **less size** and **less weight** [2]. In order to achieve this, many scientists have been exploring a new structure called gyroid structure for a new heat exchanger design. Gyroid structure is a type of Triply Periodic Minimal Surface (TPMS) structures that can be used to define an internal volume that maximizes surface area and strength while minimizing mass [4] as shown in Figure 2. A repeating gyroid architecture can be used for heat exchangers because the effectiveness of heat exchange is linked to its surface area—the larger the surface area, the more opportunity the fluids have to pass their thermal energy from one to the other [2]. This means that objects with large surface areas can cool or heat fluids faster than those with more limited surface areas.

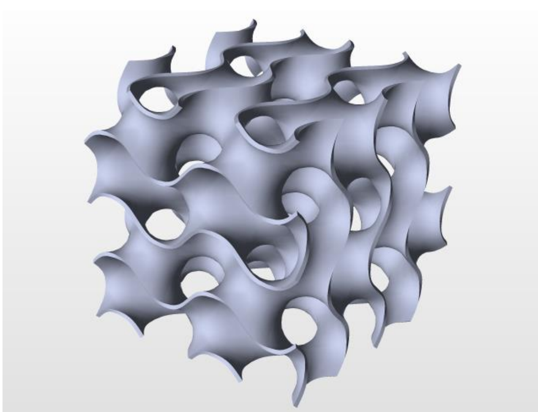

Figure 2: Gyroid structure [5]

The hypothesis is that gyroid structures are useful in heat exchanger design, as they can optimize heat transfer to be **more efficient**, compared to traditional heat exchanger designs. To compare a gyroid structured heat exchanger to a commercial one, a gyroid heat exchanger was designed and 3D printed. Figure 3 shows a WiseWater brazed plate heat exchanger. It was used in the experiment as an example commercial heat exchanger because it is one of the most common heat exchanger design and it can be easily purchased on online shopping sites, such as Amazon. This heat exchanger itself already has a high efficiency. It is made of a series of 10 metal sheets with specific corrugated shapes stacked on top of each other. A thin rectangular channel is formed between the various plates, and heat exchange is carried out through the plates. The dimension of the commercial heat exchanger is 3"W x 8"H [6].

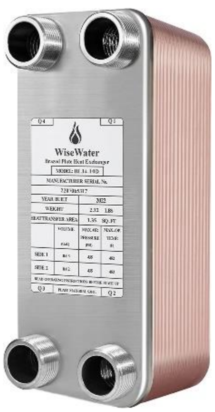

Figure 3: WiseWater brazed plate heat exchange [6]

Figure 4 is a picture of the first design of a gyroid structured heat exchanger. It was designed by using a design software. This print could not be used to take data because there was a leakage issue at the inlets and outlets due to 3D printing issue, and cold fluid and hot fluid were mixed inside the heat exchanger even though they were not supposed to. Thus, a new gyroid structured heat exchanger was designed, taking the printing quality of the 3D printers on campus into account. Figure 5 shows the updated gyroid structured heat exchanger. With the new design, there was no mixing of cold fluid and fluid, and the leakage was minimized. The dimension of the gyroid heat exchanger is about 2” x 2”, which is one sixth in size of the commercial heat exchanger. Heat transfer rate, q, of the designed gyroid structured heat exchanger was measured and compared with that of the commercial plate heat exchanger to show that gyroid structures are useful in heat exchanger design, as they can optimize heat transfer to be more efficient, compared to traditional heat exchanger designs.

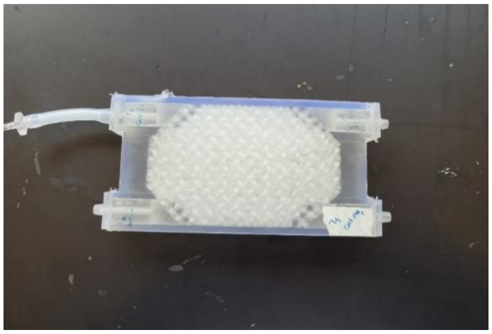

Figure 4: The first gyroid structured heat exchanger (Designed by Abel Solomon)

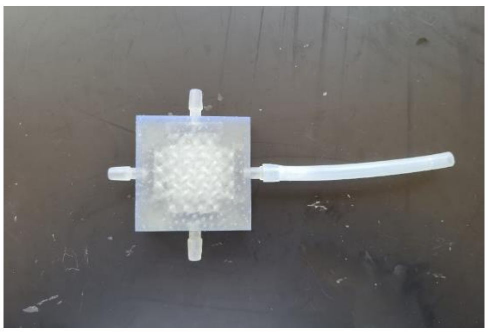

Figure 5: Updated gyroid structured heat exchanger (Designed by Abel Solomon)

Methods

To compare the efficiencies of the commercial heat exchanger and the gyroid heat exchanger, heat transfer rate was calculated for both hot fluid side and cold fluid side by using the heat transfer rate equation,

$$q = \dot{m}\ Cp\ \Delta T$$

where q is heat transfer rate in W, $\dot{m}$ is mass flow rate in kg/s, Cp is specific heat capacity in J/kg*K, and ΔT is the temperature difference between inlet and outlet in K [7]. Efficiencies of the heat exchangers were calculated by using the efficiency equation,

$$\eta = \frac{qc}{qh}$$

where η is efficiency, q_c is heat transfer rate of cold fluid side in W, and q_h is heat transfer rate of hot fluid side in W [7]. The pumps on the hot fluid and cold fluid sides tell us the mass flow rates. Assuming that the change of specific heat capacity due to temperature changer is negligible, a constant specific heat capacity for water, 4180 in J/kg*K [7], was used for calculations. Since mass flowrate and specific heat capacity values are known, heat transfer rate, q, for hot and cold fluid sides can be calculated by measuring the temperature change, ΔT, for each.

Two pumps were used to send hot fluid and cold fluid into the heat exchanger at a constant flow rate. A heater was set to around 60℃ to keep the hot fluid at the same temperature throughout the experiment. The temperatures at the hot inlet and outlet and cold inlet and outlet of the heat exchangers were measured using thermocouples and PicoLog, which is a device to read and analyze thermocouple measurements, until they reach steady state. Figure 6 shows the experimental setup for the commercial heat exchanger. Figure 7 shows inlets and outlets of the commercial heat exchangers with thermocouples attached to PicoLog. The black Styrofoam insulation was added around the heat exchanger to minimize heat loss to the environment.

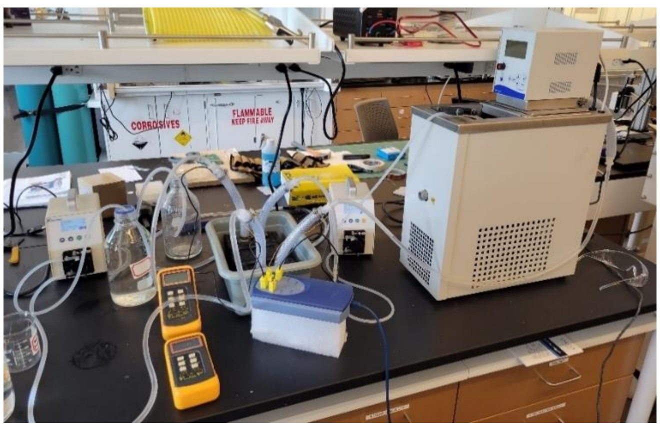

Figure 6: Experimental setup for the commercial heat exchanger

Figure 7: Inlets and outlets of the commercial heat exchangers with thermocouples

Figure 8 shows the experimental setup for the gyroid heat exchanger. Figure 9 shows inlets and outlets of the gyroid heat exchangers with thermocouples attached to PicoLog. Though the gyroid heat exchanger was a lot smaller than the commercial one, it was also surrounded by black Styrofoam insulation to minimize heat loss to the environment.

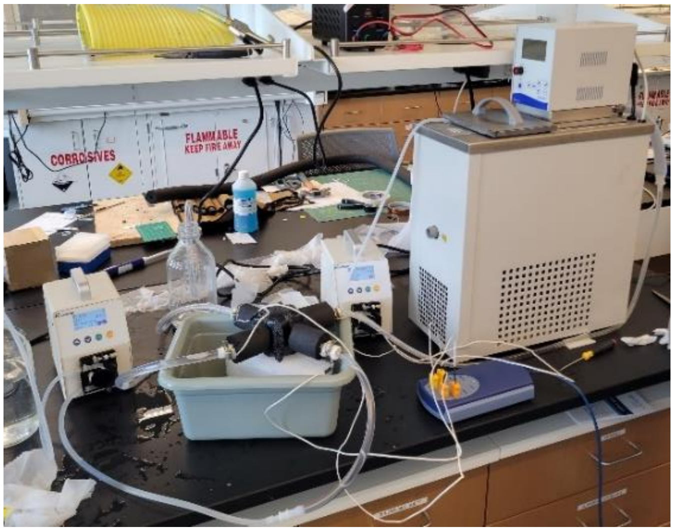

Figure 8: Experimental setup of for the gyroid heat exchanger

Figure 9: Inlets and outlets of the gyroid heat exchanger with thermocouples

Keeping the cold fluid flow rate at 10 mL/min, the experiment was repeated for three different hot fluid flow rates, 20, 30, and 50 mL/min. Using the temperature difference between the inlet and the outlet after they reached steady state, heat transfer rate for hot fluid (q_h) and cold fluid (q_c) as well as efficiency were calculated and recorded in Excel for both the commercial and gyroid heat exchangers.

Results and Discussion

Figure 10 and Figure 11 show a temperature history plot and a heat transfer rate history plot for the commercial heat exchanger respectively. The hot fluid flow rate was 30 mL/min, and the cold fluid flow rate was 10 mL/min. The temperature history plot shows how cold outlet, hot inlet, and hot outlet temperatures increase over time until they reach steady state. The temperatures after they reached steady state were used for heat transfer rate calculations. The cold inlet temperature should remain constant in theory, but it is increasing a little bit over time. The thermocouple reading might have been affected by heat from the metal part of the heat exchanger.

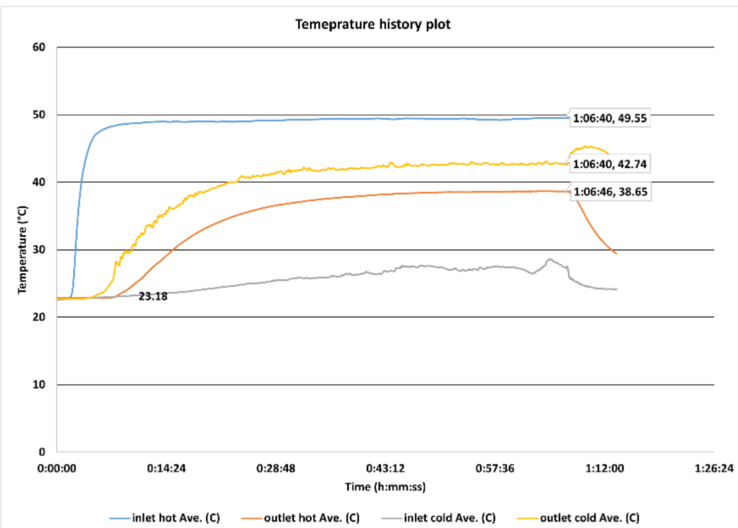

Figure 10: Temperature history plot for the commercial heat exchanger

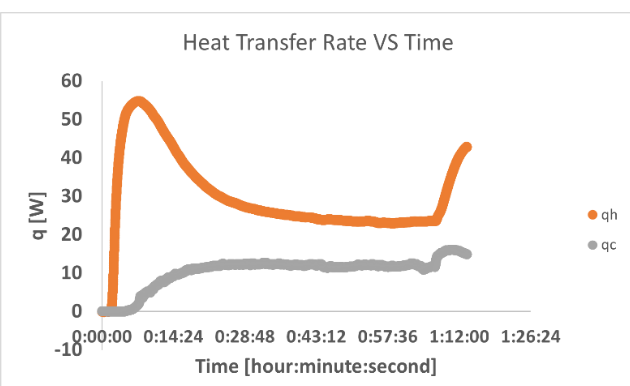

Figure 11: Heat transfer rate history plot for the commercial heat exchanger

Table 1 lists the values that were used to calculate the heat transfer rate for hot fluid and cold fluid. Heat transfer rates for hot fluid and cold fluid were calculated to be about 23.5 W and 14.4 W respectively.

Table 1: Heat transfer rate calculation for the commercial heat exchanger

	T_inlet (°C)	T_outlet (°C)	ΔT	m. (kg/s)	Cp (J/kg.K)	q (W)
Hot	49.5	38.6	-10.9	0.000516	4180	-23.5325
Cold	24	42.7	18.7	0.000185	4180	14.44869

The same experiment was repeated for the gyroid structured heat exchanger. Figure 12 and Figure 13 show a temperature history plot and a heat transfer rate history plot for the gyroid heat exchanger respectively. The hot fluid flow rate was 30 mL/min, and the cold fluid flow rate was 10 mL/min. The temperature history plot shows how cold outlet, hot inlet, and hot outlet temperatures increase over time until they reach steady state. The temperatures after they reached steady state were used for heat transfer rate calculations.

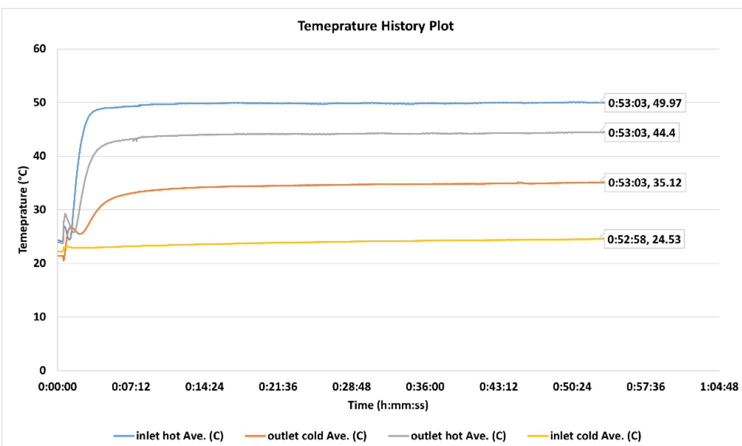

Figure 12: Temperature history plot for the gyroid heat exchanger

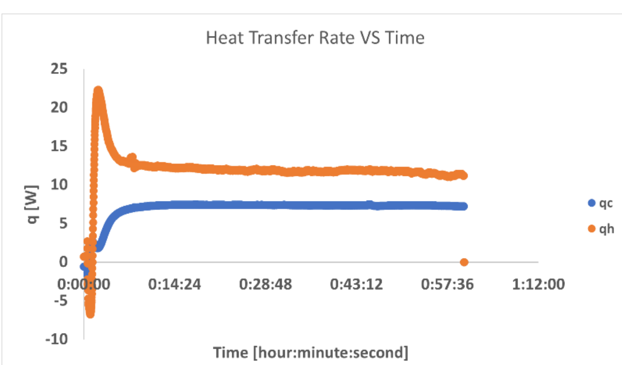

Figure 13: Heat transfer rate history plot for the gyroid heat exchanger

Table 2 lists the values that were used to calculate the heat transfer rate for hot fluid and cold fluid. Heat transfer rates for hot fluid and cold fluid were calculated to be about 11.6 W and 7.38 W respectively.

Table 2: Heat transfer rate calculations for the gyroid heat exchanger

	T_inlet (°C)	T_outlet (°C)	ΔT	m. (kg/s)	Cp (J/kg.K)	q (W)
Hot	49.97	44.4	-5.57	0.0005	4180	-11.6413
Cold	24.53	35.12	10.59	0.000167	4180	7.3777

The experiment was repeated for three different flow rates, 20, 30, and 50 mL/min for both commercial and gyroid heat exchangers. Table 3 summarizes the results, listing the heat transfer rates for hot fluid and cold fluid as well as efficiency for each flow rate for each heat exchanger. From the results, the ratios of the commercial heat exchanger q to the gyroid heat exchanger q for hot fluid and cold fluid were estimated to be 2.02 and 1.96 respectively as shown in Table 4. This shows that the heat transfer rate, q, for the commercial heat exchanger is about twice the q for the gyroid heat exchanger. Since the commercial heat exchanger was at least four times bigger than the gyroid heat exchanger we designed, if the gyroid heat exchanger is as large as the commercial one, it is likely that it has a larger heat transfer rate.

Table 3: Summary of the calculated heat transfer rate and efficiency

	Gyroid-HX			Comercial HX		
Flow Rate (ml/min)	qh (W)	qc (W)	efficiency	qh (W)	qc (W)	efficiency
20	-8.29	5.51	0.664706	-18.34	11.31	0.616685
30	-11.64	7.38	0.633752	-23.5	14.4	0.613988
50	-14.35	8.79	0.612621			

Table 4: Ratios of the commercial heat exchanger q to the gyroid heat exchanger q

Commercial:Gyroid	
qh	2.02
qc	1.96

Figure 14 is a graph that shows the change in heat transfer rate with flow rate. The heat transfer rate values for three different flow rates were plotted and a linear fit for each of hot fluid and cold fluid was found. The R^2 values for cold fluid and hot fluid were found to be 0.929 and 0.9383 respectively. If R^2 value was 1, it means that q and flow rate is perfectly linearly related.

Since the R^2 values are close to 1, it can be determined that heat transfer rate linearly increases with flow rate. It is beneficial to know because it means that heat transfer rate for different flow rates can be predicted without having to measure q for each flow rate.

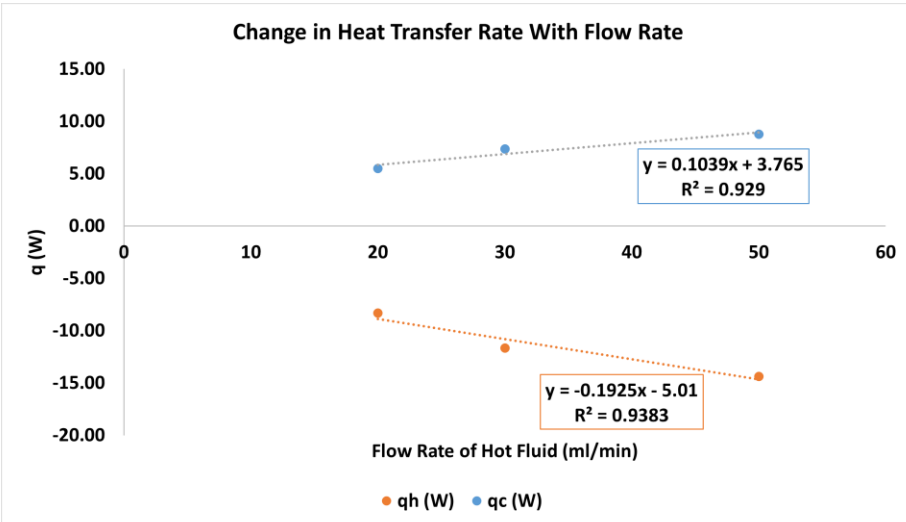

Figure 14: Change in heat transfer rate with flow rate

There is heat loss (q_h-q_c), which is heat that gets lost to the environment during the experiment. Heat loss affects the heat transfer rate measurements, so it needs to be minimized. To minimize heat loss and uncertainty in data, at least three things that could be improved. The metal connecting parts of the commercial heat exchanger that are exposed to the environment can be minimized by carefully adding more Styrofoam insulation around them. The leakage at the connecting parts of both commercial and gyroid heat exchangers can be minimized by applying tape or paste and improving 3D printing quality. Drying Styrofoam insulation around the heat exchanger before the experiment will help minimize heat loss and ensure the effective insulation. Since specific heat capacity of liquid water is larger than that of air, if the insulation is wet before the experiment for whatever reason, it means that the insulation is not as effective and that more heat will get lost to the environment. Additional measurements, such as pressure drop and internal volume, should be taken to properly compare different heat exchangers.

Conclusion

There is a growing need for efficient heat exchangers with **less size** and **less weight**. Gyroid structure is a type of Triply Periodic Minimal Surface structures that define an internal volume that maximizes surface area and strength while minimizing mass [4]. In order to test our hypothesis that gyroid structures are useful in heat exchanger design as they can optimize heat transfer to be **more efficient**, a gyroid structured heat exchanger was designed and 3D printed. The heat transfer rate, q, for the gyroid structured heat exchanger was measured and compared to the values of a commercial heat exchanger. Heat transfer rate, q, for hot and cold fluid sides were calculated by measuring the temperatures at inlets and outlets of each heat exchanger with the use of thermocouples, pumps, and PicoLog. It is found that the heat transfer rate, q, for the commercial heat exchanger is about twice the q for the gyroid heat exchanger. Since the commercial heat exchanger was at least four times bigger than the gyroid heat exchanger we designed, if the gyroid heat exchanger is as large as the commercial one, it is likely that it has a larger heat transfer rate. It is also found that heat transfer rate linearly increases with flow rate with a R^2 value of 0.93~0.94, which means that heat transfer rate for different flow rates can be predicted without having to measure q for each flow rate.

For future experiments, a gyroid heat exchanger that is as large as the commercial one needs to be designed and used for the experiment so that the results of the two heat exchangers can be compared properly. Additional measurements, such as pressure drop and internal volume, should be taken to properly compare different heat exchangers. In addition, heat loss (q_h-qc), which is heat that gets lost to the environment during the experiment, affects the heat transfer rate measurements, so it needs to be minimized. To minimize heat loss and uncertainty in data, there are at least three things that could be improved. The metal connecting parts of the commercial heat exchanger that are exposed to the environment can be minimized by carefully adding more Styrofoam insulation around them. The leakage at the connecting parts of both commercial and gyroid heat exchangers can be minimized by applying tape or paste and improving 3D printing quality. Lastly, drying Styrofoam insulation around the heat exchanger before the experiment will help minimize heat loss and ensure the effective insulation.

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