SYNTHESIS OF A COMPACT TETRALATTICE HEAT EXCHANGER USING SOLID FREEFORM FABRICATION AND COMPARISON TESTING AGAINST A TUBE HEAT EXCHANGER

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Abstract

The challenge for Solid Freeform Fabrication (SFF) lies in fabricating complex parts that are not possible by conventional manufacturing means. The goal was to apply SFF techniques to complex geometry heat exchangers. The heat exchanger structure is modeled after the covalently bonded carbon atoms of a diamond. The tetrahedron diamond lattice, or Tetralattice, is a repeating lattice unit that forms a network of channels to form the heat exchanger. Electroforming methods creating Tetralattice were applied to synthesize an air-oil compact heat exchanger. After production, the heat exchanger was tested and compared with an industry standard heat exchanger for performance evaluation.

Introduction

A heat exchanger is a device that facilitates transfer of heat from one fluid stream to another [1]. Power generation, heating and air conditioning, aerospace mechanisms, chemical processing, oil refining, and the operation of virtually all types of vehicles depend on heat exchangers of various configurations. This research is intended to develop a compact heat exchanger that is compact, lightweight, and reliable.

A heat exchanger gains the classification of a compact heat exchanger (CHE) if its characteristics include a surface area to volume ratio (b) greater than 212 ft^2/ft^3, or 17.68 in^2/in^3. In the case of an air-oil compact heat exchanger, the flow passage area on the air side must be many times greater than that on the liquid side. One method widely accepted in industry is to employ banks of round tubes with circular disk fins. This arrangement is referred as a Tube-Fin Heat Exchanger. The other classification of a compact heat exchanger is the Tube-Plate Heat Exchanger, where two parallel plates, separated by fins or spacers, define each channel. Both the tube-fin and the plate-fin are formulated from the shell and tube heat exchanger, which was used as the industry standard for the comparison testing stage of this research.

Heat exchanger design has been limited due to conventional methods of manufacturing. Traditionally heat exchangers have been manufactured by creating channels for the internal fluids by extruding, stamping, or assembling machined parts with various hardware, such as fins, into a structure that is easy to manufacture. SFF unlocks the imagination to create complex networks for fluid flow and heat transfer, were previously teetering on the realm of impossible.

Objective

This work explores the synthesis of a Tetralattice (TL) air-oil compact heat exchanger (TL AOHE) directly from a CAD design using SFF processing and the Electroforming Process. A tube CHE was also manufactured to do a comparative analysis with the TL AOHE. The following four research objectives will be presented in the subsequent sections of this paper:

- Comparative testing theory
- Approach
  - Air-Oil Tetralattice CHE synthesis
  - Tube CHE synthesis
  - Comparison testing experimentation
- Results from comparison testing
- Discussion of results

Theory

While traditional modes of manufacturing lies in material removal, SFF lies in the additive realm of manufacturing. With this additive philosophy, it is possible to create complex geometries such as three-dimensional lattice structures. Tetralattice (TL) is one such structure, modeled after the covalent carbon bonds that form the tetrahedron characteristic of a diamond [2]. Arrays of TL units form complex structures as well as complex channels within objects. This complexity can result in unmatched characteristics. Recently, TL applications in the areas of gradient materials, conformal heating and cooling, transfer systems, and stress reductions are being discovered [3].

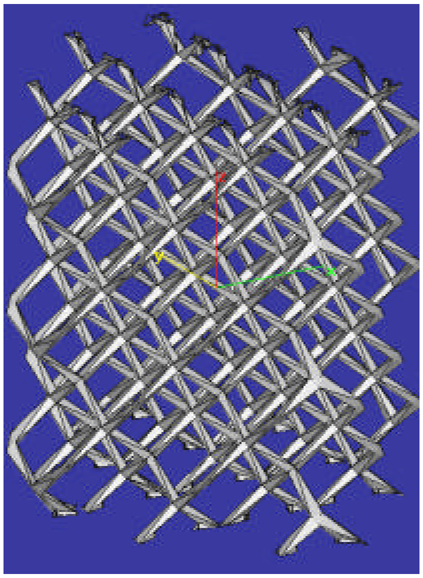

Figure 1. Tetralattice configuration for use in the TL AOHE

The structure shown in Figure 1 is the TL, which was created for the air-oil compact heat exchanger. This geometry is beneficial due to the high surface area to volume ratio (b), which is not the only factor, but an extremely important one when discussing compact heat exchangers.

In the next section of this paper, the TL AOHE is compared to a tube CHE. Both CHEs are manufactured in the exact same fashion. Each prototype of the compact heat exchanger has been designed to have approximately the same volume of internal fluid and was tested under the same conditions. A tube CHE, which is the basis of all CHEs, gives approximations of the overall effectiveness of the TL AOHE verses other compact heat exchangers in industry. The TL AOHE has a very high b ratio, 364.44 in^2/in^3, in comparison to a simple tube compact heat exchanger, 164.56 in^2/in^3, comprised of the same volume.

The hypothesis of this research is that the TL AOHE will have a much greater overall rate of heat transfer (Q) than the tube CHE due to the high b value. The rate of heat transfer (Q) was found through experimentation. The theoretical overall heat transfer coefficient (U) was also calculated to help evaluate the TL AOHE before testing. Through the aid of tables and convection heat correlation equations, the convective heat transfer coefficients (h) for both the inside and outside fluid flow of each compact heat exchanger were calculated. Substituting these values (h_i, h_o) into equation 1 below, the overall heat transfer coefficient (U) for both CHEs were found [4,5].

$$\frac{1}{UA_o} = \frac{1}{h_o A_o} + \frac{\ln(\frac{r_o}{r_i})}{2\Pi kL} + \frac{1}{h_i A_i} \qquad (1)$$

Note: k = Thermal Conductivity & L = specified length

The theoretical heat transfer coefficient (U) for the tube CHE ant TL AOHE are 0.550 $KJ/hr*in^2*K$ and 1.059 $KJ/hr*in^2*K$ respectively. Based on these values, the TL AOHE transfers heat at a rate that is 193% more efficient than the tube CHE. These two pieces of experimental and theoretical evidence help support the hypothesis of a greater rate of heat transfer for the TL AOHE. To verify the afore theory, working models of each heat exchanger were synthesized by various SFF techniques, using a material capable of withstanding high temperatures.

Approach

Utilizing SFF technology, a proprietary process was used to generate a bismuth expendable core. Cerro-bismuth was chosen due to its low melting point, as well as the alloy’s high electric conductivity properties. These two factors are imperative in the synthesis of the copper TL AOHE.

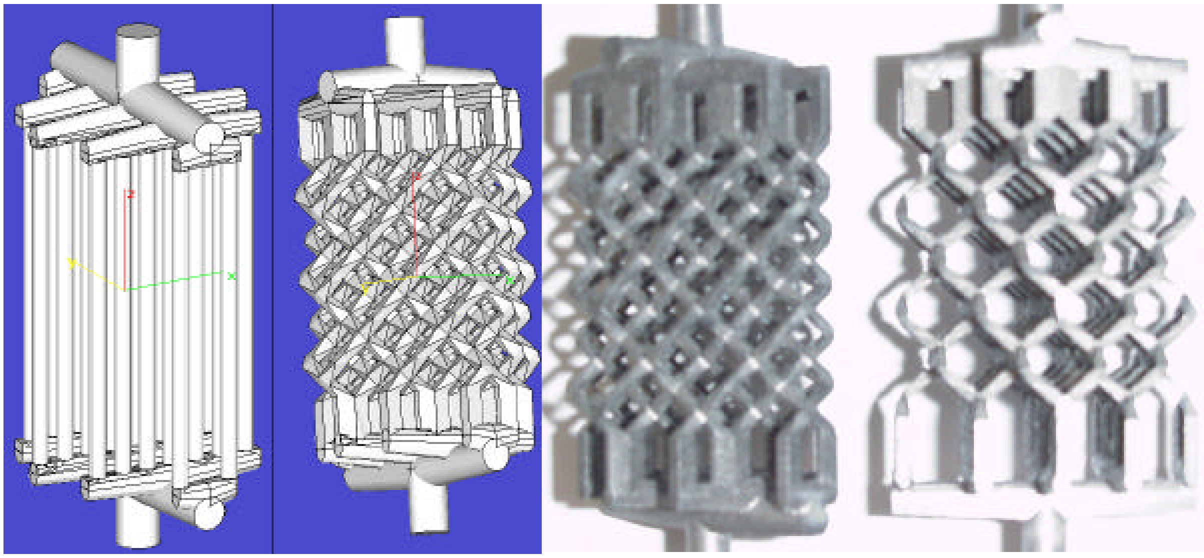

Figure 2. (Right) CAD Drawings of TL AOHE and tube compact heat exchangers, (Left) TL AOHE Bismuth Expendable Cores

To finish the CHEs formation, the electroforming process was used for the production due to its very high dimensional accuracy. The only limitation is the accuracy possible in machining the mandrel (expendable core), which can be in the order of 2.5 micrometers. With the aid of SFF, this process fit the description perfectly.

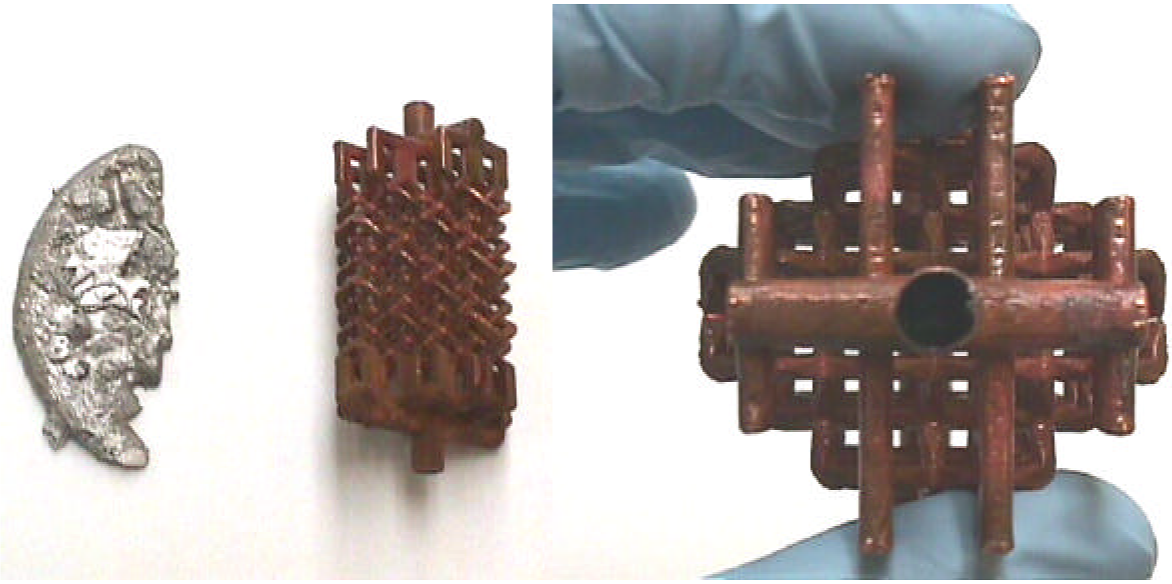

Figure 3. Expendable core removed, fully functional TL AOHE is synthesized

The electroforming process was used to apply a thermally conductive metal (copper) to the complex geometry. Electroforming is defined as the production or reproduction of articles by electrodeposition upon a mandrel or mold that that is subsequently separated from the electrodeposit [6]. A mandrel is a form used as a cathode in electroforming-in this case, it is the Cerro-Bismuth expendable core.

The first step before the actual plating experiment setup was to figure out how to plate the TL AOHE expendable core from a 360-degree range. A copper tube with copper end caps proved to be the best and most cost effective alternative. This configuration also serves as the anode, as well as the container, for the Copper Sulfate solution. The same process was used to manufacture the tube CHE. Both CHEs were electroplated until an average wall thickness of approximately 0.030” was achieved.

The final phase in the TL AOHE synthesis was the removal of the Cerro-Bismuth expendable core. The copper electroform is separated by melting out the expendable core, and at that point in the process, the TL AOHE is a fully functional apparatus. A vacuum process that was enacted at 82 degrees C (355 K), which is slightly above the melting point of the Cerro-Bismuth, removed the expendable core. After steady state temperatures were reached, heated glycerin was forced through the heat exchanger to remove the core. Figure 3 illustrates the results from the glycerol vacuum process.

Now with both CHEs fully functional, it is imperative to test both of these together to see how the TL AOHE scores against industry standards. The first step in testing was to find the rate of heat transfer, as well as the overall heat transfer coefficient for both the TL AOHE and the tube CHE. Knowing the inlet and exit temperatures associated with both fluids involved with the heat exchange process, the rate of heat transfer (Q), as well as the overall heat transfer coefficient (U), can be calculated using the equation below (2).

$$Q = U \bullet A \bullet \Delta T_m = \dot{m} \bullet \Delta T \bullet C_p \quad (2)$$

Where;

Q = rate of heat transfer
U = mean overall heat transfer coefficient
ΔT_m = log mean temperature difference
A = total heat transfer area
$\dot{m}$ = mass flow rate
C_p = specific heat

It is important to test both CHEs exactly in the same manner, since they were manufactured through the same process and for a meaningful comparison of their heat transfer characteristics. A wide variety of testing procedures exist in the advancement of heat exchangers. These range from evaluations of heat transfer, pressure drop, velocity, and temperature distributions using small models to do acceptance tests of large full-scale units [7]. A medium between the cost of the test, and the value of the information to be obtained, were carefully balanced.

Both CHEs were manufactured to have relatively the same volumes, 0.020 in^3. The surface areas are not the same; this is due to the beneficial characteristics of the Tetralattice. The goal of the testing was ultimately to prove that the Tetralattice geometry is more effective design than that of a tube CHE.

The actual test setup was composed of a flow bench, convection oven, pump, pressure sensors, thermocouples, and a data acquisition unit. The thermocouples were setup at a specified distance from the inlet and outlet sides of both the hot water flow, as well as the cool airflow through the CHEs. Both of the inlet and outlet temperatures were recorded using a Data Acquisition/Switch Unit. The procedure consisted of pumping hot water through the heat exchanger and allowing the temperature to reach steady state, at that point the flow bench had to be initiated to blow cool air across the channels. Once again the temperatures were closely monitored to ensure steady state conditions were reached – of both air and water. Volumetric flow rates of both the air and the water were closely monitored as well. Both the TL and the tube CHEs were tested in the same fashion.

Two sets of experiments were conducted, one using water as the heated fluid, and the SLA CHEs for the test prototypes. The second round of test used glycerin as the heated fluid, and the actual copper CHEs (Refer to the Appendix for a picture of the actual CHEs used, as well as a picture of the testing setup).

Results From Testing

Table 1 illustrates the results from using the SLA prototypes of both CHEs. One outcome of this SLA prototype test is to see the feasibility of using SLA prototypes to get good estimates of heat transfer rate differences between heat exchanger designs. The results were recorded directly off of the data acquisition unit.

Table 1 Results from SLA CHE comparative testing

Tube Heat Exchanger				TL AOHE			
Thermocouple	Degree C	Degree K		Thermocouple	Degree C	Degree K	
Th, in	59.60	332.75		Th, in	59.60	332.75	
Tc, out	20.70	293.85		Tc, out	21.10	294.25	
Th, out	58.30	331.45		Th, out	58.10	331.25	
Tc, in	27.60	300.75		Tc, in	27.80	300.95	
	Qrts	Seconds	Qrt/Sec		Qrts	Seconds	Qrt/Sec
Flow Rate	2	86	0.0233	Flow Rate	2	99	0.0202
density (kg/cm^3)		0.001		density (kg/cm^3)		0.001	
Vol. Flow Rate (cm^3/hr)		79200		Vol. Flow Rate (cm^3/hr)		68933	
Mass Flow Rate (kg/hr)		79.2		Mass Flow Rate (kg/hr)		68.9	
Cp (KJ/Kg*K)		4.184		Cp (KJ/Kg*K)		4.184	

Table 2 shows the setup using the actual copper CHEs and glycerol as the heated fluid. Glycerol was used as the heated fluid in this particular part of the experiment due to the oxidation properties of pure copper.

Table 2 Results from copper CHE comparative testing

Tube Heat Exchanger				TL AOHE			
Thermocouple	Degree C	Degree K		Thermocouple	Degree C	Degree K	
Th, in	84.50	357.65		Th, in	79.00	352.15	
Tc, out	34.60	307.75		Tc, out	33.00	306.15	
Th, out	81.20	354.35		Th, out	74.02	347.17	
Tc, in	24.60	297.75		Tc, in	22.80	295.95	
	Qrts	Seconds	Qrt/Sec		Qrts	Seconds	Qrt/Sec
Flow Rate	2	25.22	0.0793	Flow Rate	2	45.58	0.0439
density (kg/cm^3)			0.00126	density (kg/cm^3)			0.00126
Vol. Flow Rate (cm^3/hr)			270071	Vol. Flow Rate (cm^3/hr)			149434
Mass Flow Rate (kg/hr)			340.3	Mass Flow Rate (kg/hr)			188.3
Cp (KJ/Kg*K)			2.39	Cp (KJ/Kg*K)			2.39
Pressure Drop (psi)			3	Pressure Drop (psi)			12

Note: the pressure drop is significantly higher for the TL AOHE

Analysis and Discussion of Results

The results of the comparison testing did in fact prove that the TL AOHE is a more effective design, but not to the extent that the theoretical values show. The theoretical calculations found the overall heat transfer coefficient to be 193% greater for the TL AOHE. Table 3 shows the rate of heat transfer (Q) values, as well as the overall heat transfer coefficients (U), for both of the CHEs.

Table 3. Heat Transfer Properties for SLA CHEs

Tube CHE	TL AOHE
Q = 430.79 KJ/hr	Q = 432.93 KJ/hr
U = 0.4326 Kj/hr*in^2*K	U = 0.480837 Kj/hr*in^2*K

From these values it is evident that each CHE SLA design has the same rate of heat transfer (Q) and also a relatively equal overall heat transfer coefficient (U). These results are not that surprising considering the low conductive properties of the SLA material. The SLA prototypes were an integral part of setting up the final test setup and establishing a solid testing procedure. Now that the SLA experiment has been conducted, it was necessary to compare the prototypes results against those of the actual copper CHEs. The Copper CHEs values of Q, and U, are shown in table 4.

Table 4. Heat Transfer Properties for Copper CHEs

Tube CHE	TL AOHE
Q = 2683.87 KJ/hr	Q = 4050.20 KJ/hr
U = 1.7554 Kj/hr*in^2*K	U = 1.7560 Kj/hr*in^2*K

Based on the copper CHE testing, the TL AOHE transfer heat at a 150.91% more effective rate than the tube CHE. That difference in heat transfer rates correlates well with theoretical values. The TL AOHE also has a slightly higher overall heat transfer coefficient (U), which confirms the theory, at least qualitatively. Both percentage values of the overall heat transfer coefficients result in values that are 48% different than those calculated theoretically. This difference is contributed to the substantial pressure drop that is associated with the TL AOHE. The mass flow rate for the tube CHE was almost twice that of the TL AOHE. The theoretical values assumed equal mass flow rates. This problem area will have to be compensated for future testing. Future complex geometries for heat exchangers will have to be planned with the increased pressure drop in mind.

Conclusion

Synthesis of complex three-dimensional functional compact heat exchangers is now possible using SFF (expendable core), and the electroforming processes. A Tetralattice air-oil compact heat exchanger was successfully synthesized and compared to a tube CHE encompassing the same internal fluid volume to evaluate its feasibility. Based on a high *b* value and a high theoretical overall heat transfer coefficient (U), the TL AOHE was thought to be a more effective heat exchanger than the tube CHE. This initial theory was proved correct by comparing both SLA and copper CHEs of both designs. In both cases the overall heat transfer coefficients were slightly higher for the TL AOHE. The copper TL AOHE transfers heat at a 151% more effective rate. Though data from the SLA CHE were inconclusive, they were an essential part of establishing an initial test setup and procedure.

Problems with the TL AOHE include high-pressure drops that result in a lower mass flow rate. This low mass flow rate could explain the 48% difference from theoretical overall heat transfer coefficient (U) values. The pressure drop will have to be accounted for in future complex geometry heat exchangers. The TL configuration could be “stretched” out in the z direction to decrease some of the sharper angles, which could lower significant pressure drops within the heat exchanger.

The next step in the attempt to reach the perfect beta value is to utilize Rapid Prototyping technology to adequately model the lung vasculature. Nature’s perfect design has a specific surface that is around two orders of magnitude greater than the best compact heat exchanger designs [8].

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Appendix: Copper CHE Testing Pictures