DESIGN CONSIDERATIONS FOR DEVELOPING AN ADDITIVE MANUFACTURED TI-6AL-4V COMPACT COUNTER-FLOW HEAT EXCHANGER FOR APPLICATION IN ORGANIC RANKINE CYCLES

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ABSTRACT

Additive manufacturing has the ability to produce parts not previously possible with conventional methods. While this technology enables the production of highly complicated parts, there are still design considerations to conform to. A literature study indicated that there is little information available on how to design compact heat exchangers for additive manufacturing. This paper discusses the design considerations for producing compact counter-flow heat exchangers by means of additive manufacturing for application in Organic Rankine Cycles.

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1. INTRODUCTION

With the current high demand for energy, engineers all over the world are aiming to increase the efficiency of energy producing equipment [1]. Increasing the efficiency will reduce the production of greenhouse gasses, lessening the effect of global warming. Various methods exist to accomplish this. The method of interest in this study is the Organic Rankine Cycle (ORC). An ORC operates on a similar base as a conventional steam cycle for energy conversion, this cycle however uses organic fluid instead of water. It is implemented to improve the efficiency by utilising waste heat, captured by means of a heat exchanger (evaporator) and used to produce additional power via a generator [2,3].

Large scale ORCs are already implemented in numerous power plants over the world [4]. Micro ORCs are more compact systems that can be utilised by domestic users (1-10kW) [5]. Miniaturising such system would be possible by using additive manufacturing (AM) processes.

The AM process involves material being joined layer upon layer to produce the desired part [6]. This technology opens a world of opportunities to develop intricate parts as one solid, which was not previously possible with traditional manufacturing methods [7,8]. One technology that could substantially benefit from additive manufacturing is micro-channel heat exchangers. These devices achieve a very high surface area per unit volume due to small channel sizes.

Traditional methods for producing micro-channel heat exchangers is time consuming and are limited to basic designs [9]. With the ability to produce walls with thicknesses of less than 200 μm these devices can evolve from its former conventional manufactured designs to increase its effectiveness [10].

Implementing high effectiveness micro-channel heat exchangers in ORC allows a reduction in size of these cycles to implement on systems producing low grade waste heat such as flue gas. The main focus of the study is the development and characterisation of Ti-6Al-4V compact counter-flow heat exchangers for production with AM with application in ORC's.

Although additive manufacturing is a versatile technology, there still remain limitations to which a design should adhere to. This paper outlines the design considerations that were considered during the design of a Ti-6Al-4V compact heat exchanger.

2. LITERATURE REVIEW

2.1 Heat exchangers

Heat exchangers are devices used to transfer heat between two or more fluids, either to capture or reject excess heat. This study focused on compact counter-flow heat exchangers. The above-mentioned heat exchangers have a high effectiveness due to its ability to operate with close approach temperatures [11]. The ratio of the actual heat transferred to the maximum possible heat transfer is known as the effectiveness of a heat exchanger. High effectiveness is particularly beneficial in power-producing systems [12].

A simple heat exchanger design was considered for this study to minimise the effects of uncertainty and simplify the characterisation process. The characterisation of these heat exchangers would allow better understanding of the possibilities and limitations of additive manufactured compact heat exchangers.

2.2 Production methods

X-ray lithography (LIGA), chemical and silicon etching and diamond or wire machining are traditionally used to produce compact heat exchangers. These methods either limit the design complexity or require more than one process to produce a heat exchanger [9,10].

Additive manufacturing is a well suited method to create complex parts with great accuracy ($\pm 50\ \mu m$) [13]. A well suited AM technology for creating metallic parts is selective laser sintering (SLS). Therefore, SLS is considered to be a viable method to produce intricate parts such as compact heat exchangers in a variety of metallic materials.

2.3 Material selection

Additive manufacturing possess the ability to produce parts in a variety of materials [6], with Titanium (Ti-6Al-4V) being the material of interest in this study. Ti-6Al-4V is a well suited material for producing compact heat exchangers, with its high specific strength ($\pm 930\ MPa$) the heat exchangers' channel walls can be thinned down significantly to reduce heat transfer resistance. Furthermore, Ti-6Al-4V has exceptional corrosion and good fluid erosion resistance and with its low thermal expansion coefficient ($\pm 8.6\ \mu m/m.℃,\ 0-100℃$), warpage and fatigue effects are minimised during thermal cycling [14].

3. METHODOLOGY AND DESIGN CONSIDERATIONS

Table 1: List of symbols.

Symbol	Description
ε	Heat exchanger effectiveness
q	Heat transfer
$\dot{m}$	Mass flow rate
c	Specific heat
T	Temperature
P	Pressure
G	Mass velocity
ρ	Fluid density
σ	Ratio of free-flow area to frontal area
$K_{c/e}$	Entrance/Exit loss coefficient
f_F	Fanning's friction factor
L	Length
D_h	Hydraulic diameter

3.1 Theoretical Design

A mathematical model for the preliminary design was developed with the effectiveness-NTU method. This method is generally preferred for analysis and design of heat exchangers [15].

The effectiveness of a heat exchanger is determined with equation 1:

$$Effectiveness = \varepsilon = \frac{Actual\ Heat\ Transfer}{Maximum\ Heat\ Transfer} \qquad (1)$$

The actual heat transfer is calculated by either determining the energy lost from the hot fluid or the energy gained by the cold fluid, using Equation 2. Maximum heat transfer may be calculated with the maximum temperature difference within the heat exchanger, as shown in equation 3 [15].

$$q = \dot{m}_h c_h \left(T_{h_i} - T_{h_o}\right) = \dot{m}_c c_c \left(T_{c_o} - T_{c_i}\right) \qquad (2)$$

$$q_{max} = (\dot{m}c)_{min}\left(T_{h_i} - T_{c_i}\right) \qquad (3)$$

The core pressure drop across the heat exchanger is calculated by Equation 4. This equation includes entrance-, core friction-, flow acceleration- and exit- losses [16].

$$\Delta p = \frac{G^2}{2\rho_i}\left[\left(1 - \sigma_i^2 + K_c\right) + f_F \frac{4L}{D_h}\left(\frac{\rho_i}{\rho_m}\right) + 2\left(\frac{\rho_i}{\rho_e} - 1\right) - \left(1 - \sigma_e^2 - K_e\right)\left(\frac{\rho_i}{\rho_e}\right)\right] \qquad (4)$$

With these equations a theoretical outcome can be predicted for a specific heat exchanger design. The aim of this study is to produce and characterise heat exchangers with three different channel sizes, 0.5, 1 and 2 mm which can transfer 3 kW of heat.

Mathematical models of the heat exchangers were created using Engineering Equation Solver (EES), using the above-mentioned equations. These models were then used as a guide line for the CAD models shown in Figures 1 to 9. The CAD models of the heat exchangers were sent to the Centre of Rapid Prototyping and Manufacturing (CRPM) at Central University of Technology, Free State for review.

3.1.1 *Design 1*

Details:

Heat exchanger width:	18.65	mm
Heat exchanger height:	11.00	mm
Channel length:	30.00	mm
Channel size:	0.50	mm
Number of channels:	20	
Number of rows:	11	
Estimated heat transfer:	3012	W
	20	3.012 kW

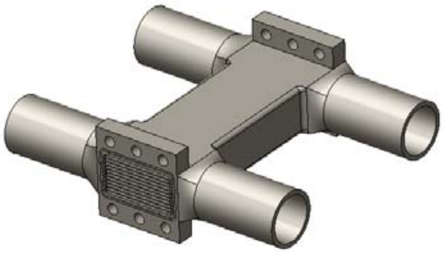

Figure 1: 3-D CAD model of design 1.

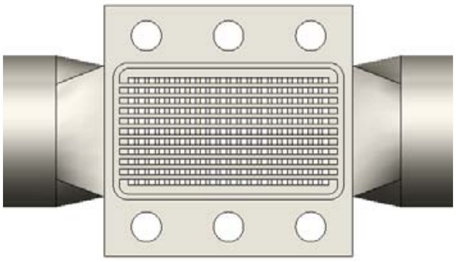

Figure 2: Side view of design 1.

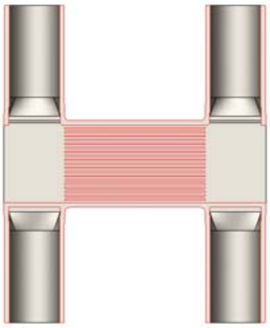

Figure 3: Top cross-section view of design 1.

3.1.2 *Design 2*

Details:

Heat exchanger width:	28.65	mm
Heat exchanger height:	21.90	mm
Channel length:	40.00	mm
Channel size:	1.00	mm
Number of channels:	20	
Number of rows:	15	
Estimated heat transfer:	3071	W
	20	3.012 kW

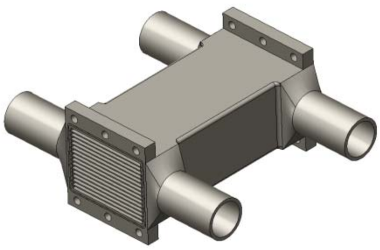

Figure 4: 3-D CAD model of design 2.

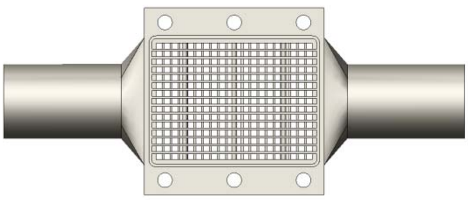

Figure 5: Side view of design 2.

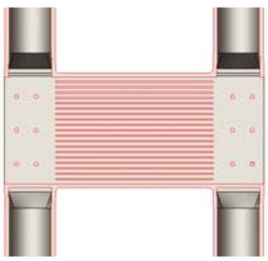

Figure 6: Top cross-section view of design 2.

3.1.3 Design 3

Details:

Heat exchanger width:	72.15	mm
Heat exchanger height:	72.15	mm
Channel length:	50.00	mm
Channel size:	2.00	mm
Number of channels:	30	
Number of rows:	30	
Estimated heat transfer:	3008	W
	20	3.012
		kW

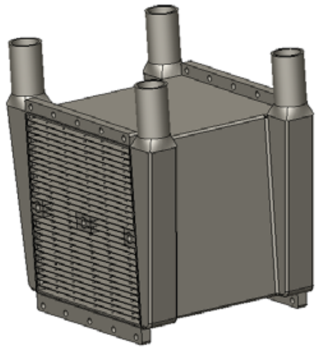

Figure 7: 3-D CAD model of design 3.

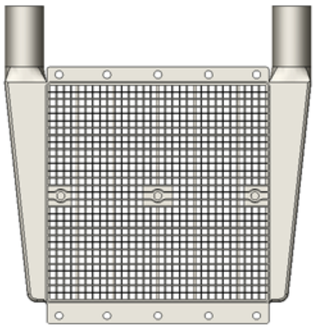

Figure 8: Side view of design 2.

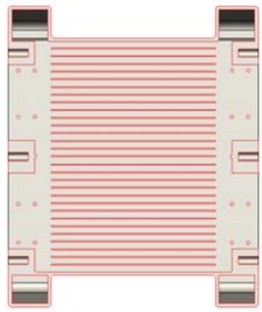

Figure 9: Top cross-section view of design 2.

3.2 Design Considerations

Design reviews are of high importance as incompatible designs will not be manufactured as desired, some of these are described below. Process engineers of the CRPM reviewed and suggested improvements to the designs to make it compatible with SLS. The following section provides design considerations which should be considered when designing similar heat exchangers for production with additive manufacturing.

3.2.1 Manufacturing orientation

Selecting the correct manufacturing orientation is an important consideration for any AM product. Therefore it was the first consideration that was addressed by the CRPM. Manufacturing of heat exchangers with the channels in a horizontal orientation, (the arrows indicate manufacturing direction shown in Figure 10), will cause the channels to deform without adding supports. Figure 11 shows, indicated in red, how the channels will deform when the heat exchanger is manufactured in the horizontal orientation. With over 200 channels per heat exchanger, adding supports within the channels would unnecessarily complicate the cleaning process afterward while increasing build time and cost. Consequently, the orientation was changed from horizontal to vertical (*as shown in* Figure 12), which ensures the channels will be manufactured square as required (*cf*. Figure 13).

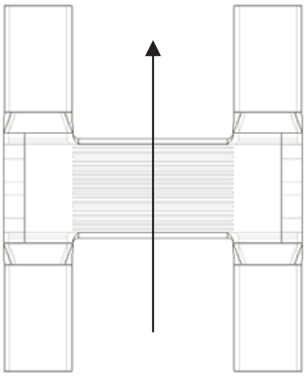

Figure 10: Horizontal Orientation.

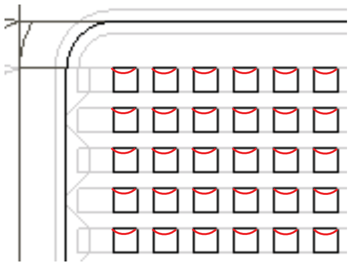

Figure 11: Result of horizontal manufacturing.

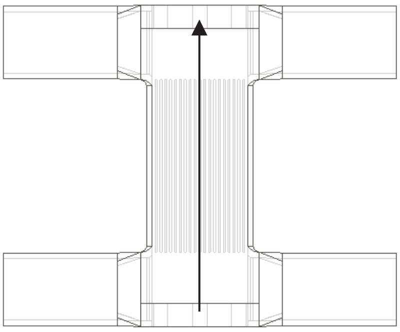

Figure 12: Vertical Orientation.

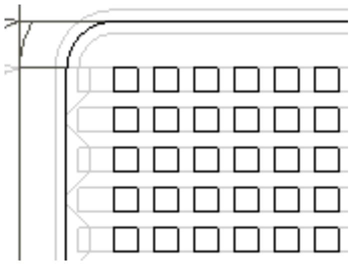

Figure 13: Result of vertical manufacturing.

3.2.2 Holes and circular sections

It is also preferred to manufacture circular sections like pipes, with their axis in a vertical direction. If it is not possible, supports should be added to sections with diameters larger than 6 mm to ensure that the circular profile manufactures correctly. Figure 14 shows a circular section manufactured without a support and it can be seen (shown in red) how the top part of the section will sag during manufacturing, indicated in red. While supports are automatically added by the software used by CRPM, one may incorporate optimized supports within the CAD model to eliminate the need for removal. Software generated supports are removed after manufacturing, thus less supports equals less labour and time. Figure 15 shows how the same profile would be manufactured with an optimized support.

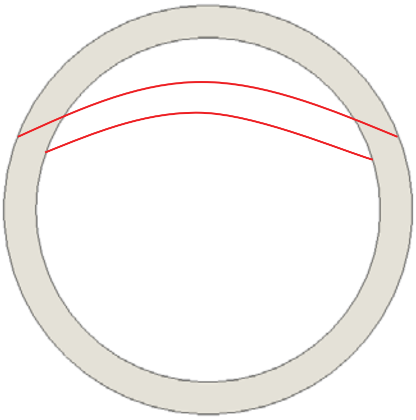

Figure 14: Circular section manufactured in a horizontal position without support.

Figure 15: Circular section manufactured in a horizontal position with support.

Holes within a body orientated in a horizontal direction also requires supports for diameters larger than 8 mm, however the CAD model can be adapted to create holes without supports. This can be achieved by changing the shape from round to a teardrop as shown in Figure 16). During the manufacturing process the teardrop shape acts as a self-supporting structure, allowing the hole to be manufactured without support.

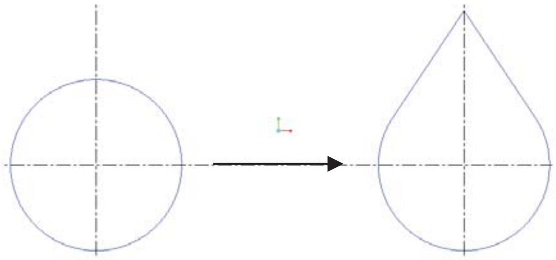

Figure 16: Shape adapted to create hole without supports.

3.2.3 Sections at an angle

Sections such as transitioning sections, where a circular section becomes square, or sections forming an angle with the horizontal should be carefully considered. If not supported, these sections could deform during the AM process. With the heat exchanger design the supports within the transition sections would not be easily accessible for removal. A solution is to keep the angle, created with the horizontal plane, larger than 35°. If the angle to the horizontal plane is less than 35°, without supports, the material could curl up during manufacturing. Figure 17 shows how a section could deform during manufacturing (indicated in red), without support structures added to an angle less than 35º. Figure 18 shows the revised section of the design with an angle greater than 35° [17]. This does however increase the entrance loss experienced within the heat exchanger and should be carefully considered. Thus, supports could not be added to this section due to access restriction.

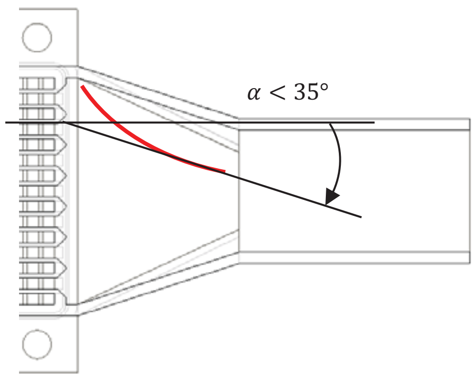

Figure 17: Transitioning section with α smaller than 35°.

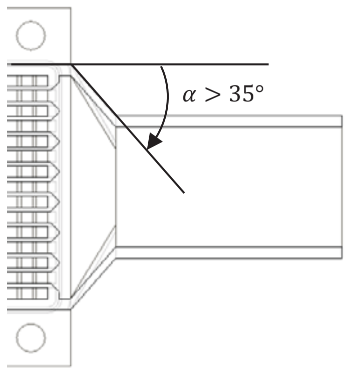

Figure18: Transitioning section with α larger than 35°.

3.2.4 Threaded holes, drilling and tapping

The ability additive manufacturing possesses to create intricate parts as one is very appealing, although not always preferred. For simplicity it is sometimes necessary to use fasteners to join the manufactured part to existing parts.

The heat exchanger design consists of three parts, two end flanges and a body. These parts will be joined with M4 screws. Threaded holes are thus required within the body of the heat exchanger. The initial idea was to manufacture the heat exchanger body with threaded holes. Process engineers of the CRPM advised that holes smaller than M10 has poor thread definition and should be added after the manufacturing process by drilling and tapping the holes manually.

After a consultation with the CRPM machinist, he indicated that it is possible to drill and tap M4 threaded holes into Ti-6Al-4V, but it is a difficult task. The hardness of the material may cause the taps to break when tapping holes smaller than M6. He suggested manufacturing the holes as clearance holes and using standard nuts and bolts to fix the flanges to the heat exchangers' body.

3.2.5 Cleaning and examination

After manufacturing, the part needs to be cleaned. This entails the removal of excess powder, support structures and rough edges that might have been created during the AM built process. After production, un-sintered powder would be present within the heat exchangers' core. This excess powder can then be removed with compressed air. The difficulty of this process would increase greatly if the core of the heat exchanger is completely enclosed. Therefore, the heat exchangers were designed with open ends which would allow visual inspection of the heat exchanger internal structure. During assembly, these ends are closed with flanges, as mentioned in the previous section and shown in Figure 19). This can also be used for service inspections and cleaning during the life cycle of the heat exchangers.

The supports created during the AM process were removed using conventional methods such as wire cutting, grinding, sawing, and drilling. The position of internal supports should be carefully considered as they need to be accessible for removal after manufacturing. The heat exchanger design has minimal internal supports and is designed to form part of the heat exchanger as they are not accessible for removal.

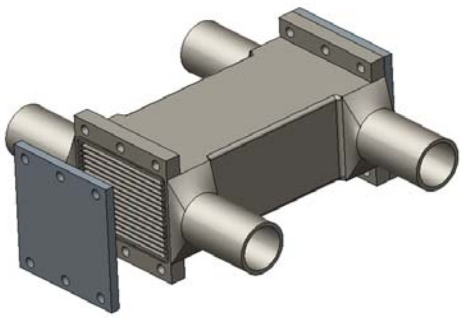

Figure 19: 3-D model with flanges.

The channel walls are extremely thin (0.35 mm) and it would be difficult to visually inspect their integrity throughout the channels. Thus, the heat exchangers will be sent to Stellenbosch University for internal examination of the channels' wall integrity by means of a computerized axial tomography (CAT) scan. Channel wall porosity present within the walls which would cause fluid mixture between the primary and secondary fluid streams, which is highly undesirable.

3.2.6 Minimum thickness and surface roughness

The achievable limitations should be kept in mind when designing any part for additive manufacturing. One of the main limitations is the minimum wall thickness that can be achieved using the DMLS AM process. The minimum wall thickness recommended for Ti-6Al-4V is 0.35 mm, as thinner thicknesses are too fragile according to the CRPM process engineers. Using a minimum thickness for the heat exchanger channel walls reduces the heat transfer resistance which improves the heat transfer.

The surface roughness of additive manufactured parts varies along its axis's and should thus be considered when designing a part. A study done at the CRPM revealed that the top surface, regarding the build direction, of a part is considerably smoother than the side surfaces, with the average surface roughness of $Ra = 5.9\ \mu m$ and $Ra = 14.5\ \mu m$ respectively [18]. According to Kandlikar SG [19], a pipe with a higher surface roughness yields greater heat transfer. The velocity boundary layer is broken, increasing the heat transfer within the channel [20]. Thus, manufacturing the heat exchangers with the channel walls to have a greater surface roughness would improve the heat transfer. This consideration refers back to the manufacturing orientation.

4. CONCLUSION

Using design considerations provided by CRPM and other sources, heat exchangers will be produced for testing and characterisation. This research will produce design considerations, design lessons and thermo-hydraulic characteristics for additive manufactured compact counter-flow heat exchangers, produced from TI-6AL-4V, for application in Organic Rankine Cycles. Although these considerations were guided by the heat exchanger design, they are still applicable to other additive manufacturing designs.

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