DEVELOPMENT AND CHARACTERISATION OF A TI6AL4V ADDITIVE MANUFACTURED COMPACT COUNTER-FLOW HEAT EXCHANGER FOR APPLICATION IN ORGANIC RANKINE CYCLES

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Abstract

Micro Organic Rankine Cycles possess the ability to increase the efficiency of various systems by utilising their waste heat. The waste heat is captured by means of a heat exchanger and converted into useful energy to aid the existing system. Traditional manufacturing methods for heat exchangers limit their size or design. Additive manufacturing bridges the gap with its ability to produce intricate designs with great accuracy. The paper discusses the development and characterisation of an additive manufactured compact counter-flow heat exchanger for application in Organic Rankine Cycles.

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1. INTRODUCTION

The high energy demand of the modern world is pushing engineers to improve the efficiency of current energy producing equipment [1]. An increase in efficiency will alleviate the effect of global warming by lessening the production of greenhouse gasses. Various technologies exist to accomplish this and the technology of interest in this study is the Organic Rankine Cycle (ORC). An ORC operates on the same principles as a conventional steam Rankine cycle with the difference being it utilises organic fluids instead of water. These systems are implemented to capture the waste heat from existing systems, in return improving efficiency. The waste heat is captured by means of a heat exchanger (evaporator) and used to produce additional power via a generator [2,3].

Reducing the size of conventional ORCs would allow domestic users to benefit from this technology [4]. However, reducing the size decreases the manufacturability of the various components. Traditional methods used to produce these components are either limiting their size or design [5]. Additive manufacturing (AM) is considered to be a viable method for manufacturing these components [6,7]. The AM process involves material being joined layer upon layer to produce the desired part [8]. This technology opens a world of opportunities to develop intricate parts as one solid body.

One technology that could substantially benefit from AM is micro-channel heat exchangers. Traditional methods for producing microchannel heat exchangers are time-consuming and are limited to basic designs [5]. 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 [9]. Implementing high effectiveness small-channel and micro-channel heat exchangers in ORCs allows a reduction in the size of these cycles to implement on systems producing low-grade waste heat, such as flue gas.

The purpose of this study is to develop, characterise and refine the design and AM methodologies for additively manufactured Ti6Al4V compact counter-flow heat exchangers for application in ORCs. A mathematical model was developed to aid in the preliminary heat exchanger design. The preliminary design was adapted for AM with design considerations provided by the Centre for Rapid Prototyping and Manufacturing (CRPM) at the Central University of Technology (CUT). Validation of the mathematical model against experimental results will be undertaken in future.

This paper discusses the process followed to design compact counter-flow heat exchangers for AM. It includes design lessons learnt for additive manufactured Ti6Al4V heat exchangers. Results from the one-dimensional mathematical model are also discussed and an outline of the planned experimental setup is given.

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 high effectiveness due to its ability to operate with close approach temperatures [10]. 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 [11].

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 a better understanding of the possibilities and limitations of additive manufactured Ti6Al4V compact heat exchangers.

2.2 Production methods

Conventional production methods like X-ray lithography (LIGA), chemical and silicon etching and diamond or wire machining are used to produce contemporary compact heat exchangers. These methods either limit the design complexity or require more than one process to produce a heat exchanger [5,9].

Additive manufacturing, particularly selective laser melting (SLM), is a well-suited technology for the creation of complex parts with good accuracy ($\pm 50\,\mu m$) [12]. Components manufactured from Ti-6Al-4V through SLM also achieve ultimate tensile stresses close to that obtained through conventional processes making SLM a viable method to produce intricate parts such as compact heat exchangers in a variety of metallic materials [13, 14].

2.3 Material selection

Additive manufacturing possesses the ability to produce parts in a variety of materials [8], with the titanium alloy 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 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, warpage and fatigue effects are minimised during thermal cycling [15].

3. METHODOLOGY AND DESIGN CONSIDERATIONS

Table 1: List of symbols

Symbol	Description
ε	Heat Exchanger Effectiveness
q	Heat transfer rate
$\dot{m}$	Mass flow rate
c	Specific heat capacity
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
Subscripts	
i	Inlet
e	Exit
m	Mean

3.1 Theoretical design

For the preliminary design of the heat exchanger, the effectiveness-NTU method was used; the method is generally preferred for analysis and design of heat exchangers [16,17,18].

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

$$\text{Effectiveness} = \varepsilon = \frac{\text{Actual Heat Transfer}}{\text{Maximum Heat Transfer}} \quad 1$$

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

$$q = \dot{m}_h c_h (T_{hi} - T_{ho}) = \dot{m}_c c_c (T_{co} - T_{ci}) \quad 2$$

$$q_{\max} = (\dot{m}c)_{\min} (T_{hi} - T_{ci}) \quad 3$$

The core pressure drop across the heat exchanger is calculated with equation 4; which incorporates entrance-, core friction-, flow acceleration-, and exit- losses:

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

A one-dimensional mathematical model was created implementing the above-mentioned equations in Engineering Equation Solver (EES). With the mathematical model, the theoretical performance can be predicted for a specific heat exchanger design. For this study three compact counter-flow heat exchangers were produced, each with different channels sizes namely 0.5, 1 and 2mm, transferring 3kW heat theoretically, when water is used as the fluid being heated. Initial testing and characterisation will be done with water, due to its ease of use. Later testing and characterisation will be conducted with an organic fluid.

3.2 Computer-aided design models

The results from EES gave a good indication of how many channels and what length of channels are required to attain a theoretical 3kW of heat transfer for each of the selected channel sizes. The inlet conditions for all the heat exchangers remained the same with the only difference being the channel's size, number of channels and the length. The design results are listed below.

3.2.1 Design 1

Heat exchanger width	72	mm
Heat exchanger height	27	mm
Channel length	30	mm
Channel size	0.5x0.5	mm
Wall thickness	0.35	mm
Number of channels per row	20	
Number of rows	11	
Estimated heat transfer with steam and water	3012	W

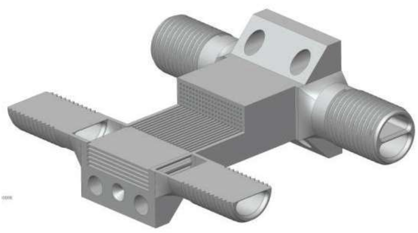


Figure 1: Design 1: 3-D Clipped Section

3.2.2 *Design 2*

Heat exchanger width	80	mm
Heat exchanger height	38	mm
Channel Length	40	mm
Channel size	1x1	mm
Wall thickness	0.35	mm
Number of channels per row	16	
Number of rows	12	
Estimated heat transfer with steam and water	3071	W

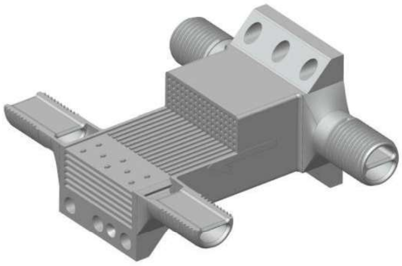


Figure 2: Design 2: 3-D Clipped Section

3.2.3 *Design 3*

Heat exchanger width	100	mm
Heat exchanger height	109	mm
Channel Length	50	mm
Channel size	2x2	mm
Wall thickness	0.35	mm
Number of channels per row	26	
Number of rows	26	
Estimated heat transfer with steam and water	3008	W

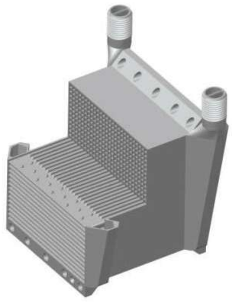


Figure 3: Design 3: 3-D Clipped Section

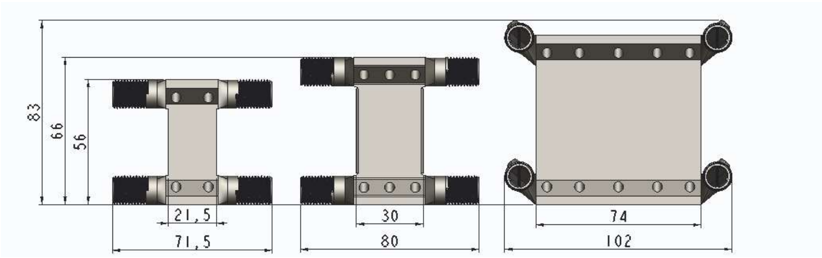


Figure 4: Size comparison of the three heat exchanger designs, front view

As the channel size is increased the total heat transfer diminish, requiring more and longer channels to achieve the 3kW of heat transfer (*cf*. Figure 4).

3.3 Design Considerations

Numerous design and manufacturing considerations informed the eventual design and configuration of the heat exchangers discussed in this paper. The design considerations resulted from literature and consultation with expert process engineers at CRPM. Optimising designs for any AM technology reduces time and/or cost by eliminating the need for unnecessary supports and cutting down on post-processing. A detailed article discussing the design considerations was written by Venter, Jacobs and Du Preez [19]. A List of design improvements suggested by the CRPM engineers are listed below:

- Manufacturing orientation:
  Selecting the correct manufacturing orientation can eliminate the need for unnecessary supports.

- Holes and circular sections:
  Holes and circular sections are preferably manufactured with its axis in the vertical direction, otherwise supports or scaffolding are required.

- Sections at an angle:
  Any sections that form an included angle with the horizontal of less than 35° should be supported.

- Threaded holes, drilling and tapping:
  Carefully consider manufacturing parts with threads smaller than M10 as the thread definition is poor. Tapping or drilling holes smaller than M6 is not advised as the hardness of Ti6Al4V poses a problem.

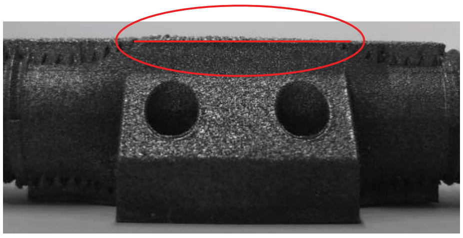
- Cleaning and examination:
  The design must facilitate post-processing such as removal of supports and removal of excess powder.

- Minimum thickness and surface roughness:
  Achievable limitations should be considered for the designs, keeping in mind the minimum wall thickness and surface roughness of 'as manufactured' parts. The minimum wall thickness for SLM of Ti-6Al-4V is in the order of 0.35 mm.

3.3.1 Unsuccessful prints

Although every precaution was taken to ensure that the heat exchangers will be manufactured correctly, there are always unforeseen difficulties with new technology. The first two manufacturing attempts failed. Further investigation revealed build-up of material on the top layer of the part causing the recoating arm, of the SLM machine, to collide with the part and stopping the printing process. Build-up problems were experienced during the first two manufacturing attempts.

Design 1



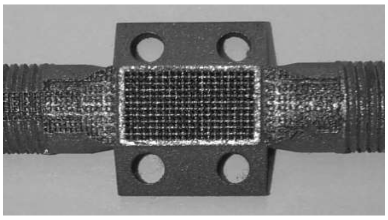
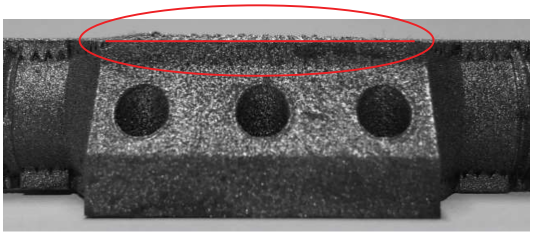


Figure 5: Design 1, 1st build attempt, side and top view

Design 2 -First attempt



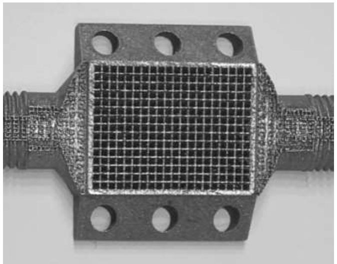
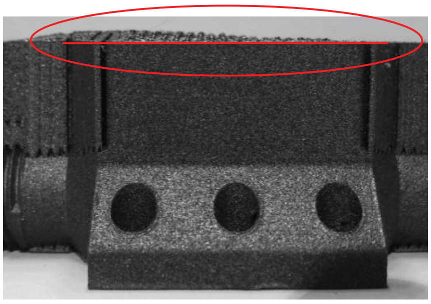


Figure 6: Design 2, 1st build attempt, side and top view

Design 2 – Second attempt



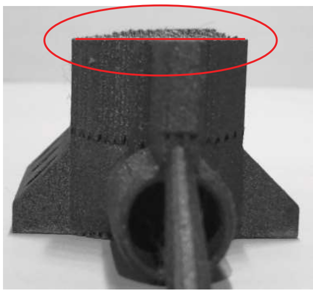


Figure 7: Design 2, 2nd build attempt, side and side 2 view

Design 3

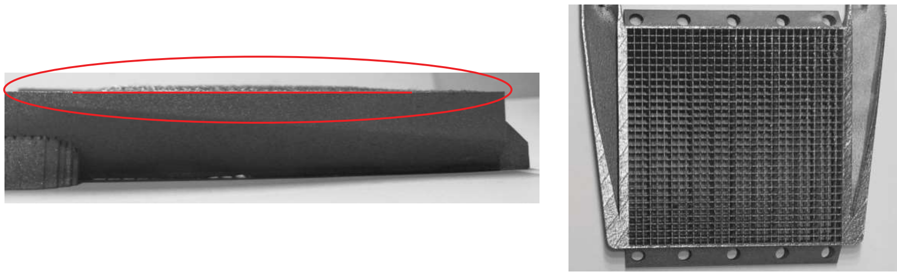


Figure 8: Design 3, 1st build attempt, side and top view

Inspecting the unsuccessful prints shows that material builds-up on one side during the manufacturing process. Looking at figure 5, it can be seen that there is approximately 0.3mm of material build-up on the left side. Figure 6, the first manufacturing attempt for design 2, shows material build-up of approximately 0.7mm on the left. Figure 7, the second manufacturing attempt of design 2, shows material build-up of approximately 1.3mm. The first manufacturing attempt of design 3 (*cf*. figure 8) shows a material build-up of 1mm approximately.

Although the printing of design 1 completed during the second manufacturing attempt, the channel walls were found to be porous. It was sent to the centre for analytics facilities (CAF) at Stellenbosch for an internal examination by means of a computerised tomography (CT) scan.

Designs 1 and 2 were considered for a second manufacturing attempt. The angle at which the recoating arm recoats the parts was changed. This enabled design 1 to print entirely with minimal material build-up, design 2 however failed once again (cf. Figure 12 & 13) building only 10mm higher before failing

3.3.2 Micro-CT scans

Three models were scanned, two of design 1 and one of design 2. With the scans the internals of the heat exchangers can be inspected. Discussed in this section are areas identified with faults within the heat exchangers.

3.3.2.1 Scan 1

The general build direction is indicated with yellow arrows and the coater direction with blue arrows in figures 9 to 17.

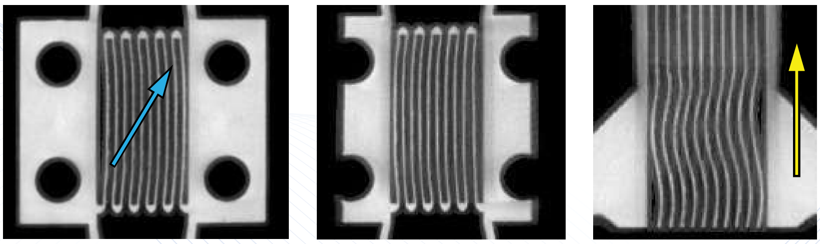


Figure 9: Scan 1, bottom manifold. Top and side view.

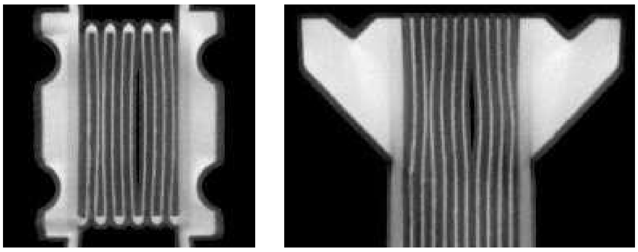


Figure 10: Scan 1, top manifold. Top and side view.

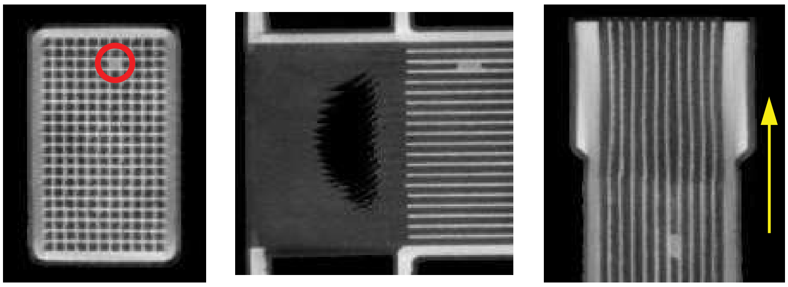


Figure 11: Scan 1, blocked channel. Top, front and side view.

3.3.2.2 Scan 2

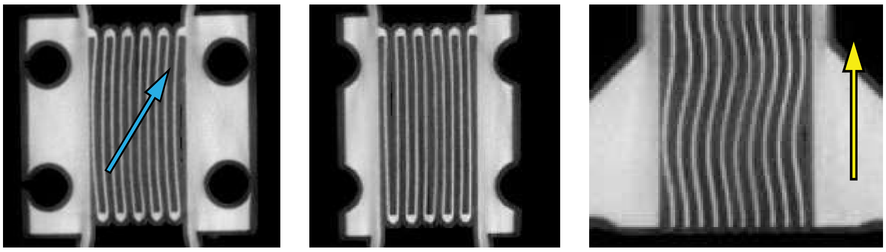


Figure 12: Scan 2, bottom manifold. Top and side view.

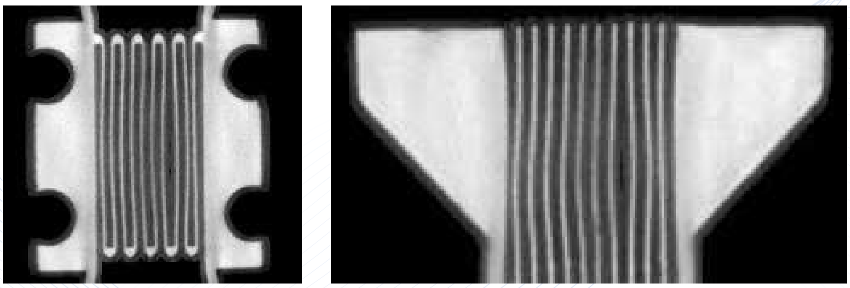


Figure 13: Scan 2, top manifold. Top and side view.

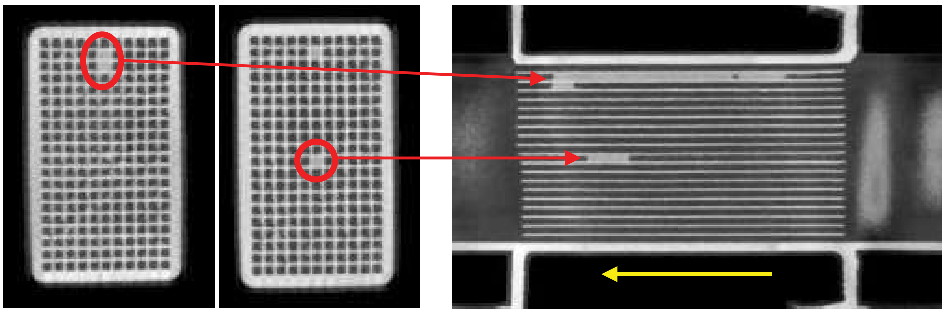


Figure 14: Scan 2, blocked channels. Top and front view.

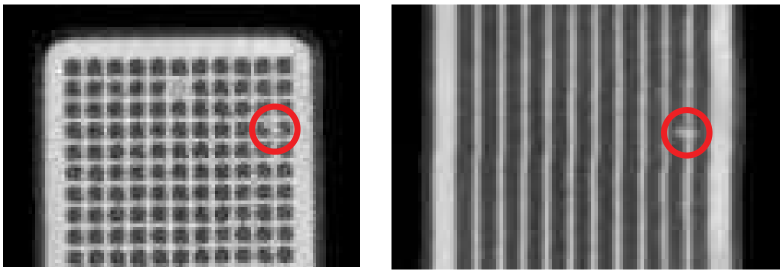


Figure 15: Scan 2, Abnormality. Top and side view.

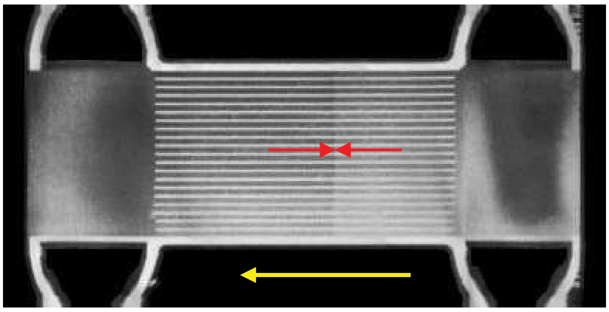


Figure 16: Scan 2, manufacturing line (indicated with red arrows). Front view.

3.3.2.3 Scan 3

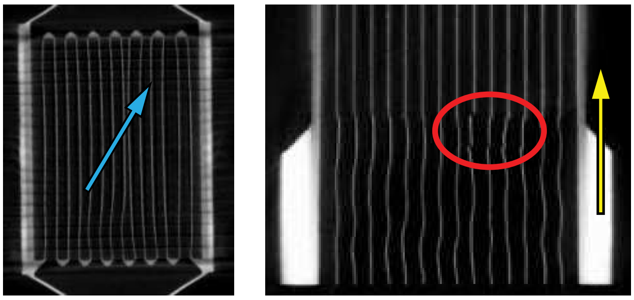


Figure 17: Scan 3, bottom manifold. Top and side view.

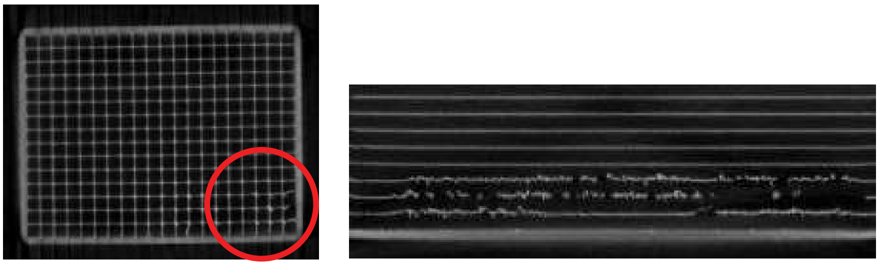


Figure 18: Scan 3, broken channels. Top and front view.

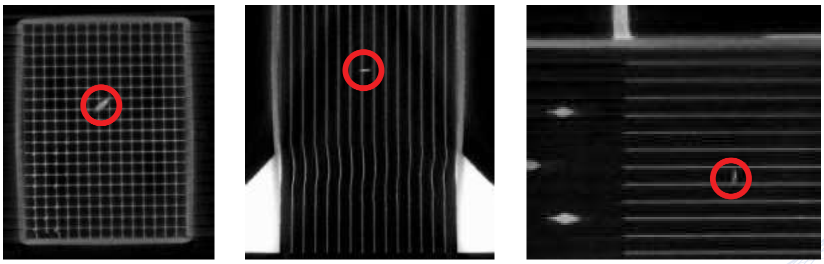


Figure 19: Scan 3, abnormality 1. Top, side and front view.

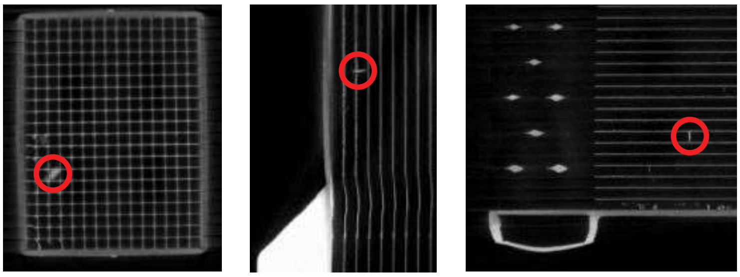


Figure 20: Scan 3, abnormality 2. Top, side and front view.

Scan 1 shows minor imperfections throughout the heat exchanger. Manifold deformation can be seen in figures 9 and 10. High stress within the manifold walls is likely the cause of this deformation. Heat build-up during manufacturing can cause the thin walls to buckle without support, thus the bottom of the heat exchanger is more deformed than the top. Figure 11 depicts a blocked channel within the heat exchanger, likely to be powder stuck within the channel.

Scan 2 shows the same minor imperfections within the heat exchanger as scan 1. Also present are two other more serious imperfections (*cf*. Figures 15 and 16). Figure 15 shows an abnormality within the heat exchanger that passes through the channel wall. This is likely some material build up (splatter) during the manufacturing process. Scan 1 and 2 was performed on the heat exchangers from the second manufacturing attempt. Figure 16 shows a feint line throughout the heat exchanger where the manufacturing process stopped and continued.

Design 2 was manufactured on the 3rd attempt and was also sent for CAT scans. Figures 17-20 shows the results for scan 3. Figure 17 shows the same manifold deformation as in the previous scans despite that design 2 has manifold channel supports. It is however worse in this case as the stress caused the channels to break. Broken channel walls can be seen in figure 18, the thicker outer wall causes a higher heat build-up inducing more stress within the channels attaching to it. Two abnormalities were found within the heat exchanger that passes through walls, likely causing fluid mixture within the heat exchanger (*cf*. Figures 19 and 20).

4. SUMMARY & CONCLUSION

There are various obstacles identified that prevented a successful heat exchanger build. However, to ensure a successful build in the future, an achievable minimum wall thickness should be selected to prevent fluid mixture and ensure pressure integrity. Additionally, the channel wall breakage and warping visible in the scans was due to a combination of the thin channel walls, heat build-up and stresses during the manufacturing process. Furthermore, channel blockage occurred only on design 1 which is a result of the small channel size. Further investigation is necessary to determine if channel blockage is due to powder stuck within the channel or if the channel was blocked during the melting process.

Moreover, it was evident that the placement of supports had a paramount effect on channel warping and breakage. Careful consideration should be given to ensure practicality of supports, minimising the obstruction of fluid flow and the increase of pressure drops. Consequently, optimum placement of supports will alleviate the effects of channel warping and breakage. In conclusion, optimal parameters should still be investigated to alleviate the above-mentioned obstacles identified when manufacturing micro-channel heat exchangers for application in ORC's.

Further investigation is required to resolve the material build-up during the manufacturing process. Changing the angle at which the recoating arm passes had a positive effect during the manufacturing process. The second design manufactured completely by increasing the angle. The porosity and broken walls found within the heat exchangers could possibly be eliminated by increasing the channel wall thickness. Another solution would be to alter the laser scan parameters to obtain a better build quality and eliminate wall porosity within the heat exchangers. Further research should be done in this regards.

Additional future research should be done to optimise the heat exchanger channels, looking for the best size, shape and length to achieve the highest possible heat transfer with minimum pressure drop.

The characterisation of these heat exchangers forms the basis for further investigation in AM heat exchanger design for application in micro ORC's at CUT.

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