DESIGN LESSONS FOR ADDITIVE MANUFACTURED SMALL RADIAL FLOW TI-6AL-4V TURBINES FOR APPLICATION IN ORGANIC RANKINE CYCLES

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ABSTRACT

There is growing concern about the negative impact that fossil fuels have on climate change. Utilisation of waste heat will contribute to a smaller carbon footprint and reduced fossil fuels usage. The Organic Rankine Cycle (ORC) is a technology that is ideal to recover energy from waste heat. The present study aims to develop and characterise small radial inflow turbines for application in ORCs. For small systems it can be difficult to conventionally produce small intricate turbines. Additive manufacturing (AM) is an attractive technology to produce turbines for such systems. AM also makes it possible to manufacture one-off designs with little material wastage for custom sized systems. Titanium Ti-6Al-4V is used for the AM process due to its high specific strength. This paper reports the design, intended characterisation process as well as the design lessons learned for the additive manufacturing of a small Ti-6Al-4V radial inflow turbine for application in ORCs.

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Table 1 – List of symbols

Description	Symbol
Temperature	K
Efficiency	η
Enthalpy	s
Entropy	h
Working fluid velocity	c
Relative velocity	w
Blade velocity	U
Number of blades	Z
Angle of working fluid	α
Blade angle	β
Rotor blade thickness	t
Rotor blade tip height	s
Blade incidence angle	i
Enthalpy loss coefficient	ζ
Flow coefficient	Φ

1. INTRODUCTION

Fossil fuels have a significant impact on the global economy as well as on the environment. It is currently the main energy source used to power modern industry [1]. In 2011 it was reported that approximately 80% of energy was produced using fossil fuels, consisting mainly of oil, coal and natural gas [2]. It is desirable to improve the efficiency of current technologies relying on fossil fuelled power.

Combined heat and power (CHP) processes are attractive to recover waste heat from exhaust gasses. The waste heat expelled in a process can be utilised in a CHP process and converted into electrical energy, therefore increasing the process efficiency [3]. The Organic Rankine Cycle (ORC) is an attractive cycle for the recovery of low grade waste heat from exhaust gasses, when employed in CHP processes [4].

This study focuses on small scale ORC systems that can be easily be integrated into current systems for the recovery of waste heat. Additive manufacturing (AM) is considered attractive for the production of components for such systems. To produce intricate small radial inflow turbines for smaller applications poses significant challenges using conventional tooling and manufacturing techniques.

AM can be used to create more complex features and profiles for small turbines, which is expensive or impossible with conventional tooling and machining methods [5]. A small radial inflow turbine will be produced through AM and will thereafter be characterised.

Once there is a good understanding of the characteristics of the small AM produced turbines, the designs can be optimised in further studies. It is expected that this study will demonstrate the advantage of employing AM for the construction of small radial inflow turbines over conventional production methods. AM will allow the turbines' shapes and profiles to be altered in ways conventional tooling cannot achieve [6].

2. LITERATURE REVIEW

2.1 Turbines

There are multiple turbine types that can be selected for use in an ORC. Two of the turbine types that are attractive for this process are radial flow turbines and axial turbines. For this study the radial inflow turbine was selected due to its small component numbers and its suitability for small turbine applications

The radial inflow turbine can easily be adapted for various different working fluids [7]. Further advantages are the simpler blade profiles of these turbines and their robustness, allowing for higher operating speeds [8].

2.1.1 Small scale radial turbines

It is important to design the turbine to be as efficient as possible, although this study is more focused on understanding the design limitations and possibilities of AM turbines and their corresponding characteristics; which will form the baseline for future research and development. Small radial inflow turbines work most effectively at the following conditions [9]:

- Head coefficient greater than 1.0 and smaller than 6.0
- Flow coefficient greater than 0.095 and smaller than 0.8

- Specific speed greater than 0.2 and smaller than 1.0

The size of the turbine is also of importance. Increasing the size of the turbine will also increase the power that can be produced, but then a greater flow rate is needed. Therefore in order to maximise the efficiency of the turbine an inlet diameter smaller than 160mm is ideal [9].

2.2 Production method

To produce small and intricate components AM is an attractive method for situations where conventional tooling would be impractical or expensive [10]. AM can create components with a high degree of accuracy using a wide variety of different materials and alloys. Selective laser melting (SLM), an AM technology, is especially suitable for the production of metallic components. It allows for very precise control over geometry, mechanical and thermal properties, by altering the laser conditions [6].

Using SLM to produce small radial turbines for experimentation, this study can determine future possible applications or situations where SLM of Ti-6Al-4V turbo machinery components would be the preferred method of production. By determining the effect that the surface finish has on the efficiency of the small radial turbines it can be correlated and used for future development.

AM also has the benefit of reducing the parts count, by allowing certain parts to be produced partially or fully assembled. This can reduce and simplify assembly of the turbine and eventually the complete ORC system. It can also be used to produce more complex structures that can be used to save weight on the finished turbine and supporting components. In future the intension is also to produce turbine rotors with imbedded heat transfer channels that could enhance performance and efficiency.

2.3 Material selection

There is a wide range of materials available that are suitable for the production of a small radial inflow turbine. In order to make a selection it is important to assess the working conditions of said turbine. Due to the turbine being small, it will be rotating at high rotational speed and consequently will experience high centripetal forces. The working fluid is also at a high temperature and can possibly be corrosive.

Titanium has a low thermal conductivity while also having a high resistance to corrosion. Therefore titanium or a titanium alloy would be a suitable material for a small radial flow turbine due to its high elastic modulus and high specific strength [11].

Ti-6AL-4V is a popular material used in compressor discs, blades and stators. This is due to it having high ultimate tensile strength and Young's modulus at high temperatures [11]. These properties combined with the high corrosion resistance of titanium makes Ti-6AL-4V an ideal candidate for producing a small radial inflow turbine using AM.

2.4 Working fluid

The working fluid used in a conventional Rankine cycle is steam, but due to the lower grade heat from exhaust gasses, it is not ideal for this system. When the temperature difference is too small steam becomes less effective due to being more susceptible to losses [12]. This is due to the steam not having a high enough expansion ratio at the lower temperatures [12].

Organic fluids are preferable at the lower temperatures due to the higher expansion ratio at these temperatures [13]. This ultimately leads towards the turbine being more efficient.

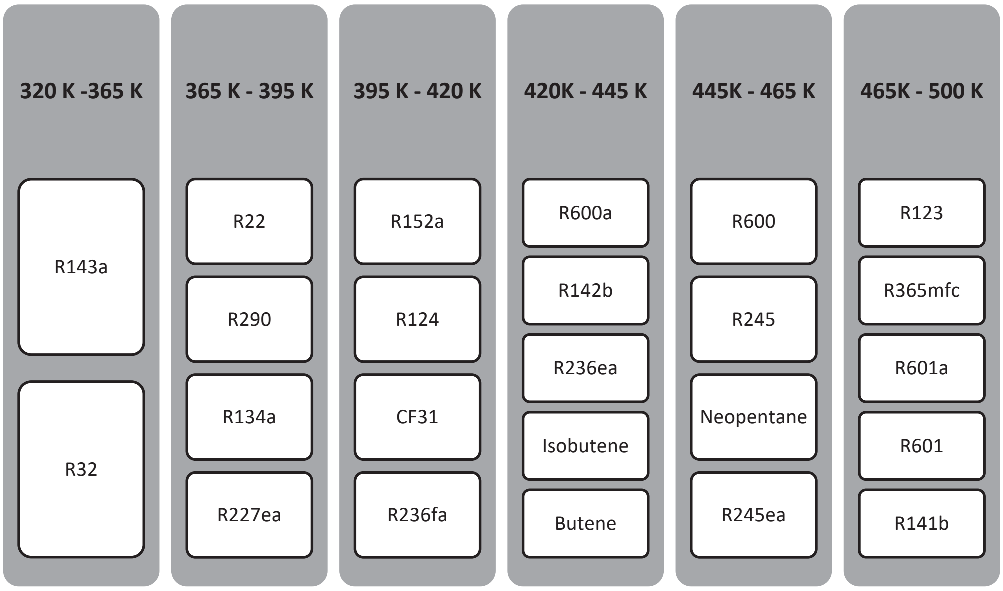

Figure 1 - Organic fluids at various temperatures for application in ORCs (adapted from [12]).

Figure 1 depicts the various working fluids that are most suited for a specific temperature range [12]. From Figure 1 it can be seen than R134a and R22 are ideal working fluids for lower temperature applications. These two working fluids are also easily acquired as they are commonly used in the refrigeration industry.

For initial experimentation air will be used to characterise the turbine. This will give a good indication of the performance of the turbine. Thereafter characterisation with one or more organic fluids will be conducted.

3. TURBINE DESIGN METHODOLOGY

3.1 Methodology

The turbines will be experimentally characterised. Test turbines will be produced using SLM and then tested. The test turbines were designed using optimal design conditions, after which the design was finalised by adjusting the parameters due to restrictions imposed by the SLM process.

Parameters that influenced the design of the turbine include size constraints, as the premise of the study is for small radial inflow turbines. The rotor diameter was restricted to 40mm and limited by safe operation of rotational speeds which were estimated as 80 000 revolutions per minute for testing. Ti-6Al-4V was selected to be the material of construction for the turbine rotor due to its high strength to weight ratio, as well as its resistance to corrosion [14].

Three turbine rotors with three different sets of guide vanes, were designed. This was done to determine the effect of these variables on the turbine characteristics. Losses that were considered included inter alia:

- Losses from the tip clearance
- Loss of kinetic energy at the exhaust
- Impeller losses
- Losses due to friction
- Other losses like leakage, flow and bearing losses

3.2 Turbine Design

To characterise the performance of the turbine it is important to first design the turbine theoretically. The theoretical turbine design will in future be compared to the experimental turbine.

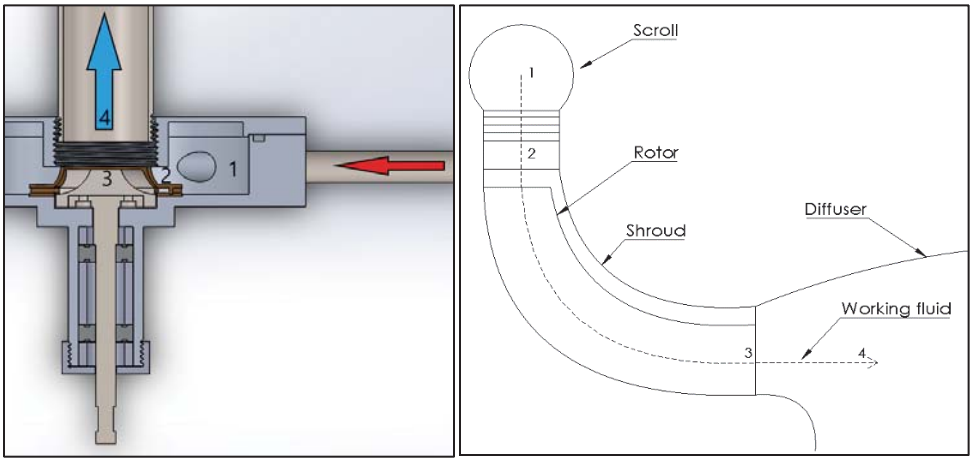

Figure 2 – Radial inflow turbine diagram (adapted from [15]**.**

Figure 2 depicts a diagrammatical view of a typical radial inflow turbine. It shows the path of the working fluid through the turbine. At point 1 the air will enter the turbine at the scroll, where it is distributed to all of the nozzles. From point 2 it passes through the nozzles onto the rotor blade inlet and the working fluid leaves the rotor at point 3 before it passes through point 4 which is the diffuser. The experimental turbine will not have a diffuser. Therefore point 3 represents the point where the working fluid is expelled to the atmosphere.

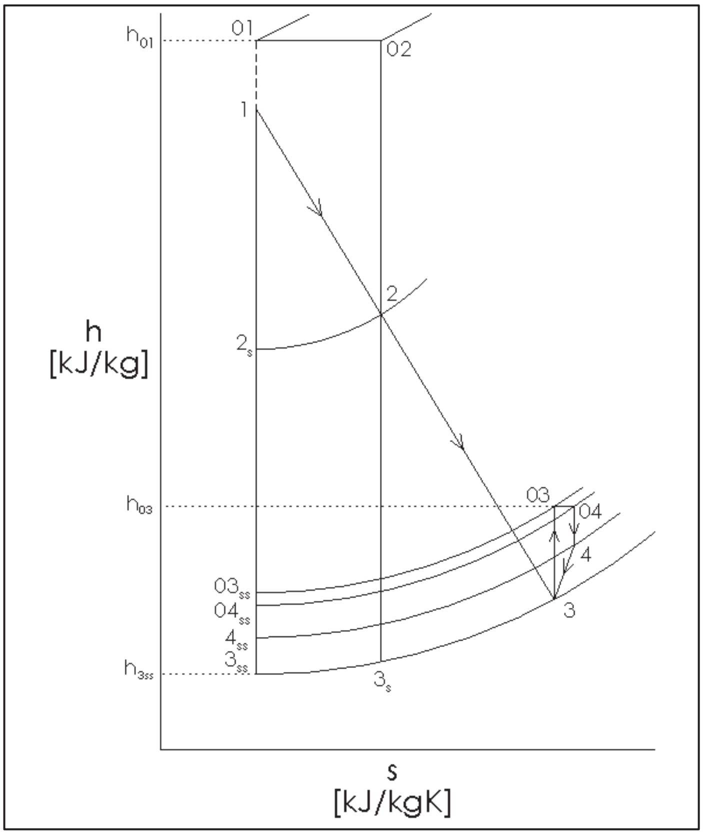

Figure 3 - Mollier diagram (adapted from [15]**).**

From the design, the process can be plotted on a Mollier diagram. For an ideal turbine the Mollier diagram is depicted in Figure 3. The subscript s depicts an ideal isentropic process and the 0 in front of a number indicates the stagnation conditions.

Figure 3 is a useful diagram to depict the energy in the working fluid throughout the turbine. If the energy content of the working fluid at turbine inlet and turbine exit, as well as the power delivered by the turbine, are known then efficiency of the turbine can be calculated. This is done by dividing the power generated from the turbine by the difference in the power of the working fluid at turbine inlet and outlet.

From Figure 3 the enthalpy values for points 1 to 3 can be acquired to calculate the energy difference in the working fluid between points 1 and 3 **[15]**:

$$\eta_{ts} = \frac{h_{01} - h_{03}}{h_{01} - h_{3ss}} \qquad (1)$$

Where,

$h_{01} - h_{03}$ Actual heat lost through the process

$h_{01} - h_{3ss}$ Ideal heat lost through the process

Equation 1 shows the total to static efficiency of the turbine, which is used to gauge how effective the theoretical turbine is. This theoretical value can then be compared to the experimental efficiency to determine the performance of the turbine.

3.2.1 Impeller design

To design the impeller the following design specification was used:

- The turbine should produce 500W of power at the shaft
- It must be a small 90° inflow radial turbine for which a 40mm rotor diameter was selected
- The rotor must be produced using AM/SLM
- Ti-6AL-4V was the selected material

These specifications was used as a starting point to theoretically develop a turbine. Nominal conditions was selected as this makes for the most theoretically efficient turbine. Practically nominal conditions are not always the most ideal conditions as the working fluid is not always delivered at design point conditions. However for testing it will provide a good baseline for characterisation of the turbine.

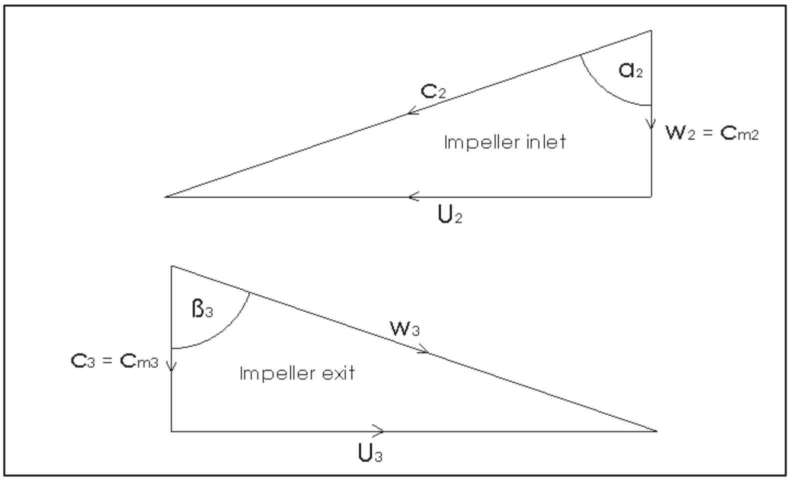

Figure 4 - Velocity triangles of turbine (adapted from [15]).

In Figure 4 there are two velocity vector triangles, with the top triangle depicting the velocity vectors of the working fluid at the rotor blade inlet and the bottom triangle the working fluid at the rotor blades' exit. These velocity vector triangles can be used to calculate the geometry of the turbine. Turbine specific work is determined with [15]:

$$\Delta W = \frac{1}{2}\left[\left(U_2^2 - U_3^2\right) - \left(\omega_2^2 - \omega_3^2\right) + \left(c_2^2 - c_3^2\right)\right] \qquad (2)$$

Where,

$U =$ Velocity of the blade

$\omega =$ Relative velocity of the working fluid

$c =$ Velocity of the working fluid

Equation 2 can be used to determine the power that the turbine will produce. Theoretically the power equation is used to calculate these velocities in order to provide 500W of power.

Firstly the inlet conditions was calculated (design point 2 on the Mollier diagram). The inlet angle (α_2) of the working fluid was also calculated. This is important as an ideal inlet angle is crucial to the performance of the turbine.

The exit conditions can be calculated using the rotor loss coefficient that varies between 0.70 and 0.85 for properly designed turbine rotors [15]. This provided the exit velocity of the working fluid. Thereafter blade exit angles (β_3) were selected. Three exit angles were selected for three different sets of rotors. These angles were: 0°, 25° and 50° respectively. This was done to ensure that the effect the exit angle has on the turbine performance can be accounted for when characterising the turbines.

A simple blade profile was used for the rotor blades with an incedence of 5°. This was done to reduce the amount af variables that can influence the performance of the turbine. Later studies can then use more intricate blade profiles that can then be compared with these to determine the performance increase or decrease at different operating conditions.

Selecting the number of rotor blades was done using Glassmans' emperical relationship between the inlet angle and the number of blades [15]:

$$Z = \frac{\pi}{30}(110 - \alpha_2)\tan\alpha_2 \qquad (3)$$

Where Z is the number of blades for the rotor. For smaller turbines Glassman's correlation is preferred as using other correlations results in turbine rotors that have too many blades for the small size of the turbine. The turbine rotors were designed to have 10 blades each.

3.2.2 Guide vane design

The guide vanes were designed by using the inlet angle of the working fluid to the rotors and the area needed for the mass flow rate to provide the required inlet velocity. The area was determined to provide an inlet velocity that ensures that the maximum rotational speed is approximately 80 000 rpm. This is due to restrictions of the bearings used and safe operation requirements.

The guide vanes acts as guides to the working fluid to direct the working fluid to the rotor at a desired angle and velocity. This inlet angle and the amount of guide vanes were selected for optimal nominal conditions for the turbine.

The guide vanes were to be produced using AM/SLM. Three sets were designed in order to determine losses that will occur due to the clearance between the rotor tip and the guide vane insert, as well as the influence of the inlet angle. The material that was used was also Ti-6AL-4V so that the guide vane inserts can be produced at the same time as the rotors to reduce production time and costs.

3.2.3 Turbine specifications

Table 2 – Turbine rotor specifications.

Description	Turbine rotor 1	Turbine rotor 2	Turbine rotor 3
r_2	20mm	20mm	20mm
r_{3s}	16mm	16mm	16mm
r_{3h}	6mm	6mm	6mm
Blade height	10mm	10mm	10mm
Z	10	10	10
i	5°	5°	5°
β_3	50°	25°	0°
t	0.5mm	0.5mm	0.5mm
s	2.5mm	2.5mm	2.5mm
Base plate thickness	5.2mm	5.2mm	5.2mm
Material	Ti-6AL-4V	Ti-6AL-4V	Ti-6AL-4V

Table 2 summarises the specification of the three different turbine rotor designs. The only difference between these three turbine rotors is the exit angle of the blades. The turbine rotor with a 50° angle at exit is expeted to be the most efficient, as it is the closest to the nominal design angle of 57.2°. The designs were slightly altered from ideal conditions due to physical limitations and constraints of manufacture by means of SLM, as well as having three different data point equally seperated.

The relatively thick rotor backplate is required to ensure that there is enough depth to connect the shaft to the turbine using M3 machine screws. The M3 tapped holes will be produced with the thread and then cleaned up using a die after the SLM manufacturing process. This ensures that the locations of the hole are very accurate and saves time due to not having to drill and tap the holes afterwards.

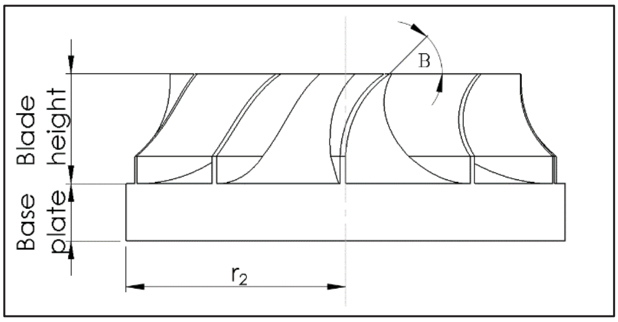

Figure 5 –Blade profiles of turbine rotors.

Manufacturing of the blade profile of the turbine rotor, through SLM, is expected not to render problems due to the selected blade profile (refer to Figure 5). In future studies, more complex profiles, with embedded heat transfer channels, will be researched and developed in order to maximise turbine efficiency.

Table 3 - Guide vane inserts specification.

Description	Guide vane insert 1	Guide vane insert 2	Guide vane insert 3
r_{inside}	20.5mm	20.75mm	20.5mm
$r_{outside}$	30.5mm	30.5mm	30.5mm
Passage height	2mm	2mm	2mm
Total height	12mm	12mm	12mm
Number of passages	9	9	9
α_2	65°	65°	55°
Clearance	0.5mm	0.75mm	0.5mm

From 3 it can be seen that insert 1 and 2 has different inside diameters and that insert three has a different inlet angle to the rotors. The difference in the clearance is to determine the losses caused by the clearance in the turbine. Where the difference in angle is to determine the effect that the inlet angle has on the performance.

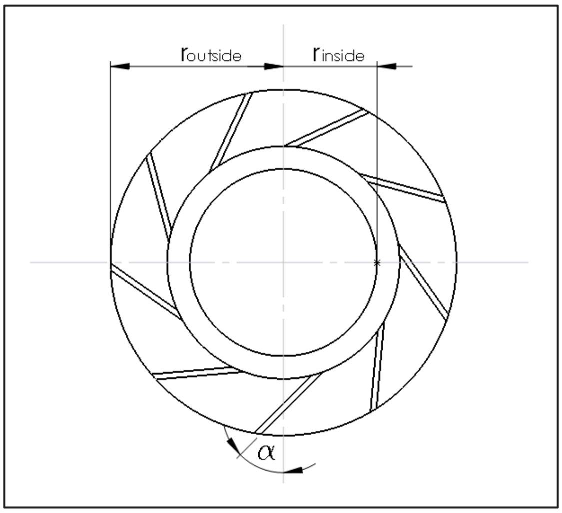

Figure 6 - Guide vane inserts.

The guide vane inserts had to be produced in two parts as can be seen in Figure 6. This was due to the small passage height and the requirement for supporting structures in the guide vane passage. These supporting structures cannot be removed after production, therefore it had to be produced in two parts in order to allow easy removal of the supporting structures afterwards.

The bottom part of the insert will lay on the base of the casing where the top part is placed into the fitting grooves. The casing then fastens in such a manner as to press the top securely into the bottom to ensure proper control over flow direction.

3.2.4 Expected influence of clearances and other losses

In order to compare the theoretical model with the experimental one it is important to calculate the theoretical losses. The purpose of the study is to determine the effect that the production method has on the performance of the turbine. The effect of the surface roughness are one of the important parameters on turbine performance to be investigated.

In order to determine the effect that the surface roughness has on the turbine all other losses must be accounted for. These losses include inter alia the losses through the guide vanes, rotor losses and tip clearance losses.

The losses due to the tip clearance will be calculated using different clearances. By changing the clearance the effect that this has on the performance can be isolated and calculated. Whereas the losses through the nozzles tend to be very small with a coefficient of between 0.9 – 0.97 [15]. This value can be estimated to a reasonable degree of accuracy using the nozzle’s (guide vane insert) flow coefficient.

$$\zeta_N = \frac{1}{\phi_N^2} - 1 \qquad (4)$$

Equation 4 is used to calculate the flow coefficient of the nozzle.

The rotor losses are due to the energy lost from the working fluid as it passes over the rotor blades. This will include the losses due to the effects of the surface roughness due to the production method, namely SLM.

The unfinished surface produced with SLM is expected to cause a slight increase in resistance and therefore increase the drag over the surface. This should result in the flow coefficient over the rotors to be slightly higher, reducing the efficiency of the turbines. If this causes a significant reduction in efficiency of the turbine, follow up studies can be done to improve the surface finish of the rotor blades. Candidate methods to improve surface finish are electro plating, shot peening and polishing.

4. EXPERIMENTAL METHODOLOGY AND DESIGN

4.1 Experiment design

4.1.1 Measured parameters

In order to determine the efficiency of the turbine it is important to measure certain parameters that will be used to compare the experimental turbine with the theoretical turbine. These parameters are:

- Inlet pressure and temperature
- Outlet pressure and temperature
- Mass flow rate of the working fluid
- Rotational speed of the turbine shaft
- Torque produced by the turbine shaft

The inlet and outlet conditions will allow to set up a theoretical model using the Mollier diagram for each set of experimental results. This will ensure that the theoretical conditions are similar to the experimental conditions.

The rotational speed and torque of the turbine will be used to calculate the actual power that is created by the turbine. This value can then be compared to the theoretical value to determine the performance of the turbine.

4.1.2 Experimental equipment and setup

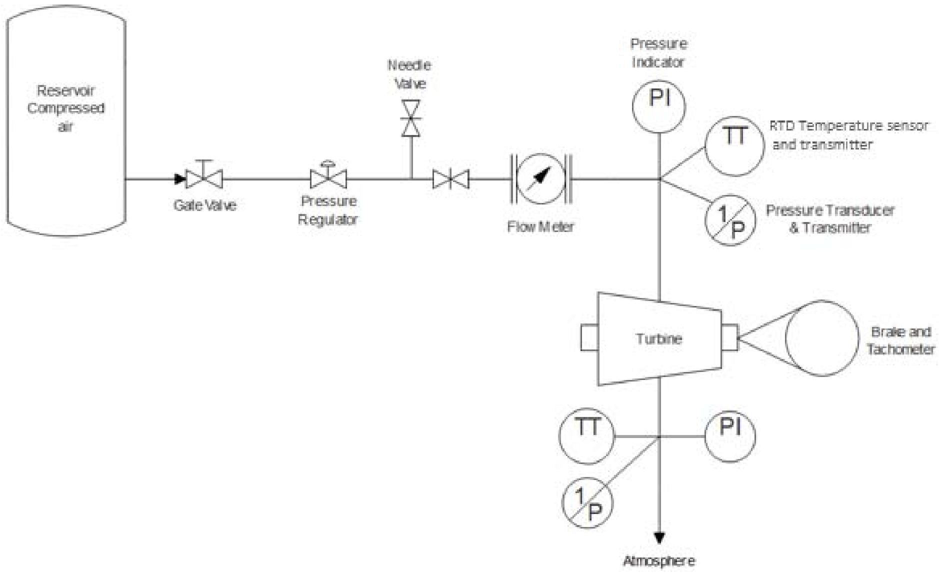

Figure 7 – Process flow diagram of the experimental setup.

Figure 7 depicts a process flow diagram of the experimental setup on which instrumentation position and type is also shown. The working fluid will be introduced into the system via a gate valve, after which a pressure regulator will regulate the pressure of the fluid. Two needle valves will be used to adjust the flow rate with precision. After the working fluid has passed through the turbine it will be expelled into the atmosphere.

To record the inlet and outlet temperatures RTD temperature probes will be used to ensure accurate results are captured. The inlet and outlet pressures are recorded using pressure sensors. This recorded data is then sent to a data acquisition system using transmitters in order to record the results.

The flow rate will be measured with a rotameter. Shaft torque is measured with a Prony brake that applies a load to a load cell. In conjunction with the tachometer the power of the turbine can be calculated.

4.1.3 Experiment Conditions and recording of results

Experimentation will be conducted at steady state conditions. This means that the mass flow rate will be constant throughout the system and that the turbine runs at a constant speed. This will negate any transience at start-up and effects due to the inertia from the mass of the turbine and shaft.

The percentage of error of each piece of equipment will also be brought into account. Using the ISO type B uncertainty analysis [16]. A type B analysis has to be used due to the scarcity of data available. A coverage factor of two will be used to obtain a confidence level of 95%.

5. DISCUSSION

5.1 Design Lessons

Support structures:
During the design process, in conjunction with the Centre for Rapid Prototyping and Manufacturing (CRPM), at Central University of Technology, Free State, certain design lessons were learned. One hurdle was that support structures were required for guide vane passages. This was due to the width of the passage that supplied the working fluid to the turbine.

The passage height was too small to allow the support structures to be removed afterwards. The solution was to manufacture the guide vanes as two parts, eliminating the need for support structures completely.

Surface roughness:
The SLM process produces surface finishes in the order of $30\,\mu m$, which can be considered as coarse in the intended application. The impact of such a coarse surface finish on turbine performance will be negative. It is uncertain by how much the efficiency will suffer and is an objective of this study.

Orientation during manufacturing:

Component orientation, during the SLM process, has a significant impact on manufacturing cost. Build height must be minimised since build cost is a function of material usage and machine time. In selecting the orientation it is also important to consider the limitations of the SLM process. Horizontal structures for example require support structures to prevent sagging.

The SLM process has limitations on incidence angle of produced wall sections without support. The current limitation is 35° with respect to the vertical plane. These structures must later on be removed manually. It is therefore important to carefully consider the manufacturing orientation and limitations on build angles when designing the component. It cannot be done without intimate knowledge of limitations of the SLM process. It is best done in conjunction with experienced SLM manufacturing engineers.

<u>Reduction of parts count:</u>
The ideal is to minimise the parts count. There are however limitations imposed by build orientation and manufacturing cost limits. In this case the option of a solid turbine rotor-shaft assembly was considered. However that would imply that the shaft had to be produced in the vertical position with the turbine rotor centred and perpendicular to it. Another possible orientation option would be to produce the shaft in the horizontal position with the turbine rotor centred and perpendicular to it.

Both these options would require excessive support structures and the build time, and thus costs, would significantly increase. There is thus a limitation in the parts count reduction achievable.

<u>Design flexibility:</u>
Although the SLM process allows for significant design flexibility there are SLM process and cost limitations that must be taken into account when designing an AM radial inflow turbine. Wall thickness and radii limitations makes it difficult to produce thin walled and sharp edged sections which must, if desired, be produced by post-production machining.

<u>Screw threads:</u>
Another limitation from the SLM process was manufacturing the screw thread required at the bottom of the rotors. This will be overcome by manufacturing guide holes with screw thread where the screw thread will be manually tapped afterwards to clean up the screw thread.

<u>Material:</u>
Due to the high rotational velocity of the turbines it is subjected to high centrifugal forces that induce stress in the material. The magnitude of the force is a result of the weight of the rotating mass and the velocity at which it rotates. Using Ti-6Al-4V the blade thickness of the rotor can be reduced due to the high specific strength. This in turn allows for higher safe operating speeds, which increase the performance of the turbine.

The SLM process used to manufacture the rotors requires sufficient thickness to ensure the structural integrity of the material. The blade thickness of the rotors could have been made smaller, but due to restrictions because of the SLM process a safe blade thickness of 0.5mm was selected.

The high yield strength at higher temperatures and corrosion resistance of Ti-6Al-4V makes this an attractive material for an ORC turbine. This is due to the turbine operating at elevated temperatures for extended periods of time. Retaining a high strength at higher temperatures will ensure a longer life for the turbine. Some refrigerants used in ORCs is corrosive and Ti-6Al-4V's resistance to corrosion also improves the life of these turbines.

6. SUMMARY AND CONCLUSION

This study has so far highlighted design lessons and limitations using the SLM to produce components for small radial inflow turbines. Most of the manufacturing obstacles can be overcome through selection of configurations suitable for SLM. This research will create a baseline for future research and development of more complex impellers; and to reduce the parts count of these turbines.

The article on the design lesson learned is based on a work in progress for characterising turbines produced using SLM. In the near future, results from the experimentation will give an indication of the performance of turbines produced using SLM. This will assist in understanding the viability of the SLM process to produce radial inflow turbines for application in ORCs.

It will also be the basis for further studies on improving the current turbine design. Especially investigating more complex blade profiles, lower parts counts and faster production times. All of which can either increase the efficiency of the turbine or reduce production costs. These will in turn lead to optimising a complete ORC system and the optimisation thereof.

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