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INTERNALLY COOLED & LIGHTWEIGHT RADIAL TURBINE WHEELS FOR GAS TURBINES

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ABSTRACT

By increasing the operating temperature of a MGT such that TiT are 1200C, cycle efficiencies of >40% are possible.

In collaboration with the University of Bath, HiETA Technologies have designed, manufactured and physically tested a lightweight and internally cooled radial turbine wheel, theoretically capable of operating at 1200°C TiT.

Exploiting the design freedoms of AM, together with the capability to process the Nickel Super Alloy CM247LC, a novel design was created combining the required internal structure of the wheel with a targeted internal cooling method. Topology optimisation was used to guide the required structural requirements, whilst a full conjugate heat transfer CFD model was created to model the effect of cooling on the wheel.

Taking a standard automotive turbo charger as a baseline to reference against, the AM cooled wheel was tested back to back with the solid wheel, at the same design point using the same test hardware.

Due to limitations on the hot gas stand, it was not possible to test at 1200°C inlet temperatures, and so the wheels were tested at 720°C TiT and 70,000rpm. Compared to the solid wheel baseline, the cooled wheel showed a LE temperature reduction of 60°C, a TE reduction of 100C and mid blade reduction of 90-100°C, whilst being 22% lighter. The results from the test correlated very closely to the CFD results, validating the accuracy of the model.

CFD was then used to predict the temperature reduction at 1200C turbine inlet temperature. At this condition it is expected that temperature reductions of 200°C at LE, 250°C at TE and 180-200°C at the mid blade would be presented, bringing the wheel well within the operating temperature range of CM247LC.

NOMENCLATURE

AM – Additive Manufacture
CFD – Computational Fluid Dynamics
FEA – Finite Element Analysis
HIP – Hot Isostatic Pressing
MGT – Micro Gas Turbine
TE/LE – Trailing edge/Leading Edge
TiT – Turbine Inlet Temperature

1. INTRODUCTION

By increasing the operating temperature of a MGT such that turbine inlet temperatures are 1200°C, cycle efficiencies of >40% are possible. Historically, the combination of traditional manufacturing techniques and material capability present barriers to achieving this for radial type gas turbine engines. Axial gas turbines have used active cooling for many years to achieve turbine inlet temperatures in excess of 1200°C.

In collaboration with the University of Bath, HiETA Technologies have designed, manufactured and physically tested a lightweight and internally cooled Radial turbine wheel exploiting the design freedoms of Additive Manufacturing (AM). The objective was to prove that operation in turbine inlet temperatures (TiT) of 1200°C was possible. In addition, actively cooling the turbine wheel, increases the component life whilst light weighting reduces wear on bearing components.

2. PROJECT APPROACH

To achieve the objective two approaches were combined; HiETA developed the capability to process a high temperature resilient Nickel Super Alloy material CM247LC. Secondly, AM was exploited to create a novel design combining the required internal structure of the wheel with a targeted internal cooling system.

Taking a standard automotive turbo charger as a baseline to reference against, the AM cooled wheel was tested back to back against the solid wheel, at the same design point using the same housings and bearings.

Topology optimisation was used to guide the required structural requirements, whilst a full conjugate heat transfer CFD model was created to model the effect of the cooling on the wheel. The wheels were then manufactured by HiETA, before being tested at the University of Bath's Hot gas stand.

The hot gas stand at Bath can be configured to supply separate feeds to the compressor and turbine side as two separate closed loops. This provided an opportunity to supply the cooling air to the turbine wheel from the compressor flow. The compressor loop maintained a constant 1.5barg at compressor inlet, providing a positive driving pressure to supply cooling air through a hollow shaft and to the internal chambers of the turbine wheel, exiting at the turbine wheel TE (see Figure 1).

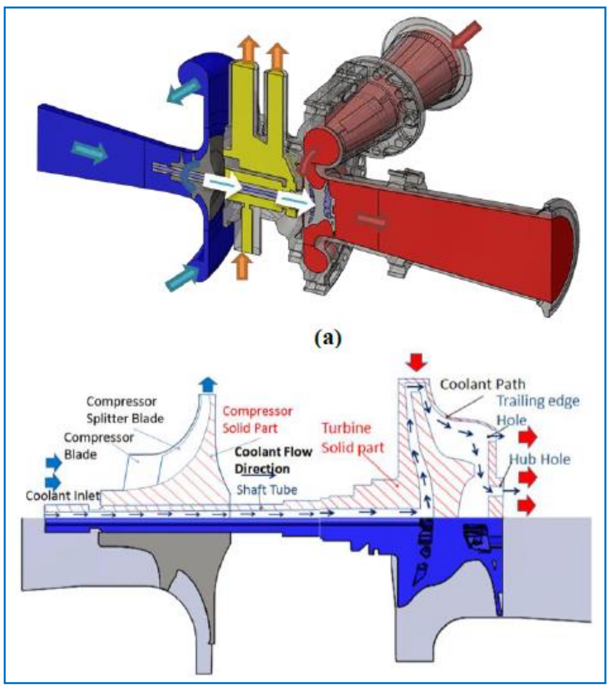


Figure 1: Overview of test configuration and flow paths of turbine and compressor flows [1]

3. MATERIAL DEVELOPMENT

To achieve the objective of operating at 1200°C TiT, a suitable material had to be chosen. CM247-LC, a two phase, high gamma prime content Nickel super alloy was chosen due to it's excellent high temperature strength, creep and oxidation resistance. CM247-LC holds these performance properties up to 1050°C metal temperature, and so coupled with active cooling this material would be operational in 1200°C environment and potentially beyond.

To additively manufacture components in any material, optimum machine process parameters must be derived. This involves a design of experiments activity, where different laser parameters and scan strategies are investigated to give optimum material density and geometric conformity. This is particularly challenging in high gamma prime alloys such as CM247, as they suffer from micro-cracking being present in the "as built" condition. This drastically reduces the fatigue and creep life of the material. As such, post manufacture heat treatments must be carried out such as HIP and Solution heat treatments. The HIP closes the micro cracking, whilst the solution and age heat treatments provide the optimal microstructure (see Figure 2). Mechanical properties of the material were then verified through tensile, fatigue and stress rupture testing, whilst the geometric conformity was verified through 3D scanning and destructive inspection.

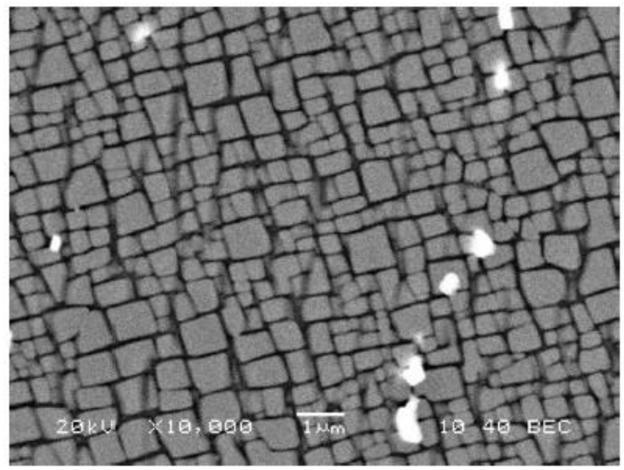


Figure 2: Regular Gamma-Gamma Prime CM247-LC microstructure achieved with optimal processing

Due to tight project timescales the material development and design stages had to be carried out in parallel. To de-risk this, an established material was chosen to manufacture the demonstration wheels. Inconel 625 was chosen as the mechanical properties matched the hot gas stand testing conditions required.

4. DESIGN

To supply cooling air taken from the compressor side, the benefits of AM were exploited by manufacturing the turbine wheel and shaft as one piece. This integration enabled a hollow shaft allowing the cooling air to flow through into the turbine wheel (Figure 1). This is not suggested to be a production solution due to the shaft dynamic implications associated with a hollow shaft but acted to serve feasibility purposes. With the rough architecture defined, detailed design was carried out.

4.1 Structural optimisation

Topology Optimisation was used to identify the required load bearing structure for the wheel to perform at the test conditions; 70,000rpm, 720°C TiT. Varying mass reduction targets were set until a picture of the load paths through the wheel were understood. This enabled a cooling regime to be fitted into wheel, whilst avoiding compromising the structure of the wheel too greatly (see Figure 3).

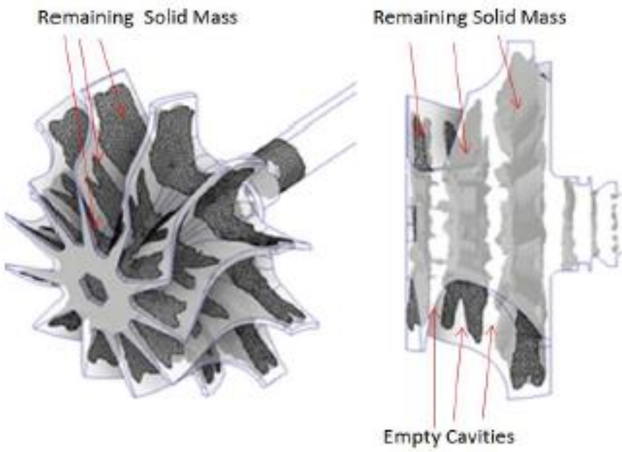
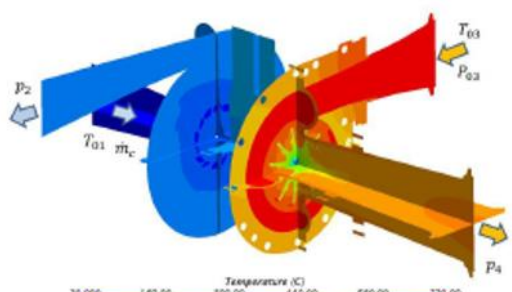


Figure 3: Topology optimisation output showing key areas of structure [1]

4.2 CFD & FEA

CFD was then used to guide the design of the internal cooling passages. These were designed to target the hottest components of the wheel – the leading edge, blade chord and surface areas. Conjugate heat transfer CFD was carried out in Star CCM+ creating aerothermal fields, which were then used to assess the solid stress of designs, ensuring they were within material limitations. An accurate model of the turbine and compressor side including housings and bearings were analyzed. This is shown in Figure 4 together with the boundary conditions.



Boundary Condition	Symbol	Value
Compressor inlet mass flow	$\dot{m}_c$	0.069 kg/s
Compressor inlet temperature (total)	T_{01}	23.5 °C
Compressor outlet pressure (static)	P_2	2.3 bar
Turbine inlet temperature (total)	T_{03}	720 °C
Turbine inlet pressure (total)	P_{03}	1.37 bar
Turbine exit pressure (static)	P_4	1 bar

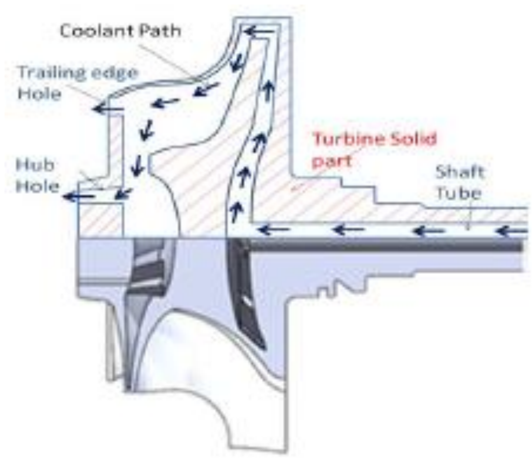
Figure 4: Overview of CFD model & boundary conditions [1]

4.3 Final Design

Several design iterations were carried out until optimal cooling flow conditions were achieved, whilst maintaining required structural integrity. Figure 5 shows the final wheel design, with cooling flow coming through the shaft into a central gallery, where it is fed toward the leading edge of each blade. The cooling flow then travels along the blade chord, spreading out over the surface of the blade before exiting at two points at the trailing edge. The discharge cooling flow from the wheel mixes with the mainstream flow downstream of the trailing edge causing a complicated flow distribution (Figure 6). This together with the parasitic effect of bleeding air from the compressor flow has negative impacts on the overall efficiency, but as demonstrated in section 6, the benefits from actively cooling the wheel far out way this.

Figure 5: Cooled Wheel Final Design [1]

5. MANUFACTURE



The wheels were manufactured using the AM technique Selective Laser Melting (SLM) on a Renishaw AM250 platform (Figure 7). This powder bed AM technique, involves layers of metal powder spread across an inert build area, before a Ytterbium Fibre laser fully melts the required cross sectional geometry on the layer to the two previous layers. The result is a complete part built up of discreet layers.

An important decision made during the design stage is the direction the wheel was built in. This is important as it effects several features, including the consistency of the blade profile and the requirement for internal cavity supports which leveraged the support of CFD since internal cavity support must remain in situ and thus modify the cooling flow and heat transfer. Building the turbine in the vertical direction with the inlet of the turbine on the build plate offered a number of advantages and a few challenges (Figure 8). First, by removing the 'nose' of the wheel and building the blades off of the base-plate, the blades are rigidly supported minimizing thermal distortion.

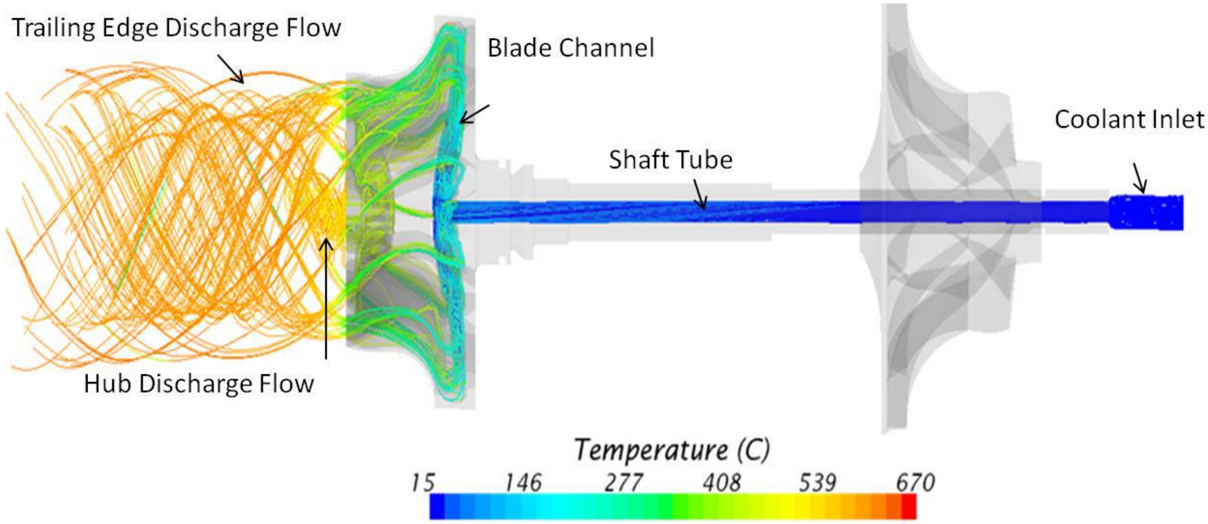


Figure 6: Streamlines of coolant flow from compressor to turbine [1]

Second, the shaft could be built onto the turbine wheel directly removing the need to weld a separate hollow shaft in the post build phase. However, this did mean that there were internal unsupported surfaces that required supporting during the AM build phase. Figure 8 shows the solution selected – a series of pillars that presented little restriction to the cooling air flow but allowed the internal geometry to build successfully in this orientation.

Once built, the turbine wheels were removed, and the unused powder was recovered. To remove powder from the internal structure of the wheel, HiETA employed their proprietary vibrational powder removal techniques. Following powder removal, the parts were GOM scanned to ensure geometrical conformance prior to undergoing a heat treatment cycle. Following this, the wheels were removed from the build plate via Electrical Discharge Machining (EDM), and the temporary support structure was removed. Accurately controlled features such as the blade tip and wheel back face were then post machined, before the wheels were balanced and assembled into the turbocharger test hardware.

Figure 7: AM250 machine used to manufacture the turbine wheels and manufactured wheels on base plate

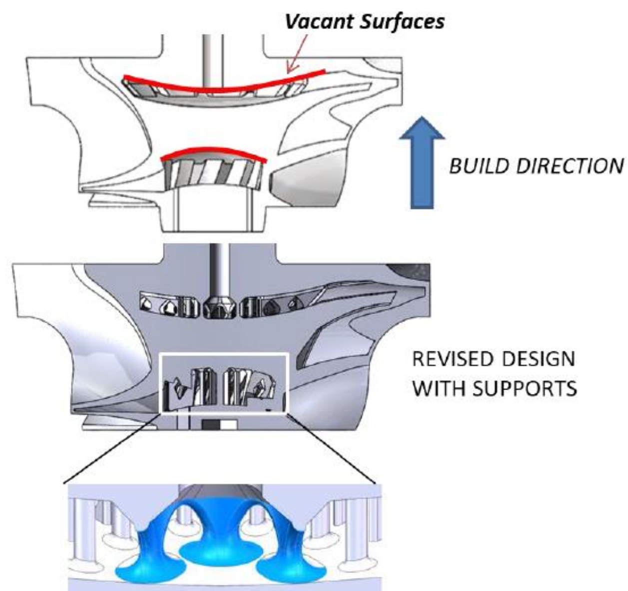


Figure 8: Build direction and internal supporting structures introduced within hollow cooling passage [2]

6. PHYSICAL TESTING

6.1 Test Rig

The hot gas stand at the University of Bath is designed for high temperature radial turbomachinery testing. The experimental facility consists of two flow networks that supports turbocharger testing where there is a turbine and a compressor connected by a common shaft. Both loops are supplied through a set of compressors; whilst the turbine side is then electrically heated prior to turbine inlet and the compressor loop travels through a heat exchanger to maintain a constant temperature at compressor inlet.

To measure the performance parameters of both compressor and turbine, temperature and pressure at inlet and outlet are measured. Static pressure is pneumatically averaged across the pipe through a four-port manifold. Temperature is logged using four probes (thermocouples for the turbine, PRT - Platinum Resistance Thermometer for the compressor) set at different depths as shown. These four temperature readings are then numerically averaged for a single static temperature. Total temperatures are calculated from the mass flow and local density assuming constant cross-sectional velocity. Figure 9 shows the layout of the compressor and turbine under test. These sections require significant insulation to ensure that temperatures measured are not subject to heat transfer between the stage and the measurement position.

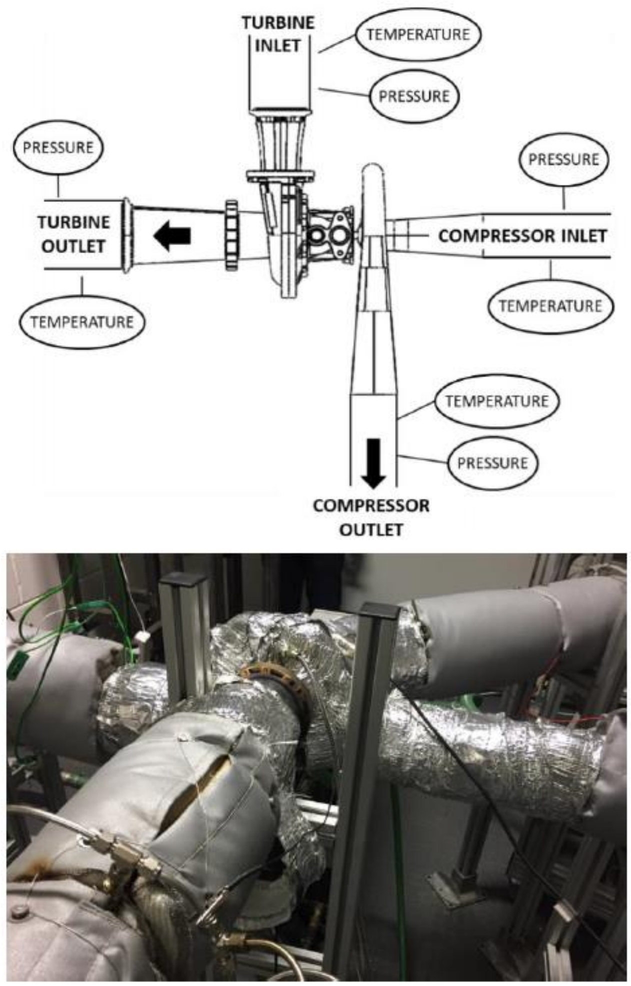


Figure 9: Pressure and temperature measurement locations with photograph including insulation [2]

6.2 Thermal History Paint

Thermal History Paint (THP) was applied to the turbine wheels in order to track the thermal history during the high temperature tests (Figure 10); analysis of the paint post-test allowed the maximum exposed temperature to be deduced. This is done by a company using proprietary in house technique to an accuracy of within 5°C. The paint was applied over the turbine wheel before the test and protected during the balancing procedure. Several material samples were also supplied for calibration purposes.

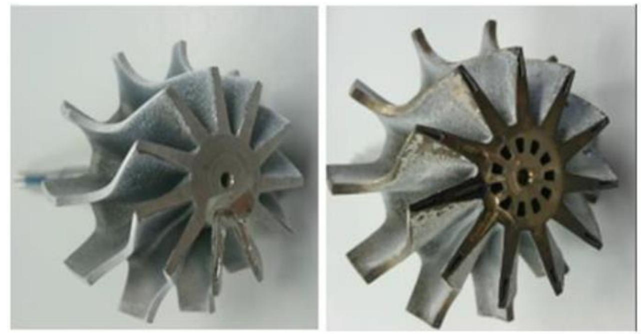


Figure 10: THP coated solid and cooled turbine wheels [2]

During the high temperature tests, the turbine inlet temperature was increased incrementally from atmospheric temperature to an upper limit of 720°C, for both the uncooled baseline and cooled wheels. Once at the maximum temperature, the turbine rotor was held at steady-state condition for fifteen minutes.

After the high temperature experiments were completed, the two painted wheels were sent back for analysis. The temperature at three points along each blade mid-span were taken and used to ascertain the average blade temperature. The standard deviation across all blades was 4°C for the solid wheel and 10°C for the cooled wheel. A more comprehensive analysis was then conducted on one of the eleven turbine blades, in each case. The temperature distribution was probed at three span-wise and several axial locations, both on the pressure side (PS) and suction side (SS) of the blade.

6.3 Test Results

Table 1 shows the temperature values measured at 40 locations from leading to trailing edge for both the cooled and uncooled baseline. These locations are shown from the perspective of a meridional projection in Figure 11. Points are marked 1 to 4 from hub to shroud in the span-wise direction, with ten locations recorded in the streamwise direction from leading edge to trailing edge resulting in a total of 40 points for both blades.

From Table 1 the average temperature difference between the baseline solid and cooled wheels can be seen. It shows the cooled wheel having leading edge 55-60C cooler, the trailing edge 60°C cooler, with the mid blade surface 70-90°C cooler. It is therefore, immediately clear that the cooled wheel is operating significantly cooler than the solid baseline.

Temperature /C		A	B	C	D	E	F	G	H	I	J
Baseline	**1**	603	609	600	593	576	571	582	585	581	591
	2	603	609	607	591	582	578	573	584	580	589
	3	589	601	614	595	583	579	581	589	582	586
	4	592	604	611	602	590	586	580	584	593	597
	AVG	*597*	*606*	*608*	*595*	*583*	*579*	*579*	*586*	*584*	*591*
Cooling	**1**	534	544	514	497	489	483	496	499	508	529
	2	548	548	549	518	503	475	487	488	505	518
	3	547	552	550	541	514	485	475	486	505	530
	4	540	547	555	542	514	494	499	510	527	547
	AVG	*542*	*548*	*542*	*525*	*505*	*484*	*489*	*496*	*511*	*531*
Avg difference		***55***	***58***	***66***	***71***	***78***	***94***	***90***	***90***	***73***	***60***

Table 1: Temperature measurements on blade surface [2]

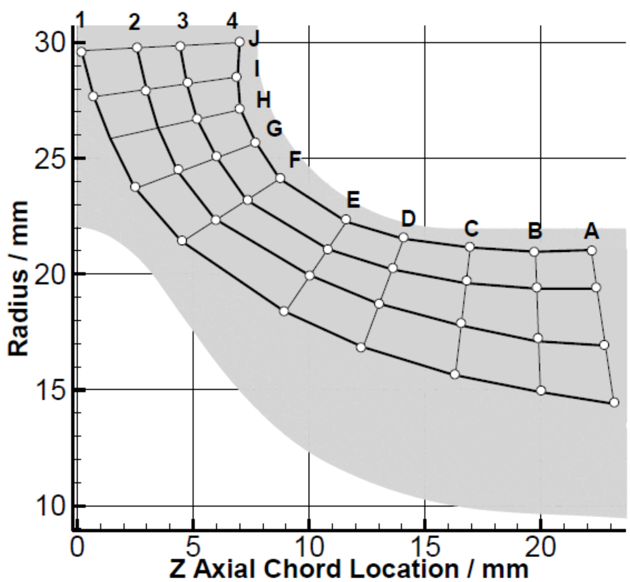


Figure 11: Measurement points on blade surface [2]

6.4 Test Results vs CFD

Given the overall objective is to demonstrate the ability to create a highly efficient MGT through raising TiT to 1200°C, it was important to validate the CFD work carried out against the test results.

Figure 12 shows the CFD predicted temperature along the blade surface of the cooled wheel vs physical test results. The trend and absolute level of temperature was very well predicted by the CFD simulation. The largest discrepancy between CFD and experimental exists at the leading edge, where the temperature difference is around ~40 °C; the difference is much smaller at the trailing edge. The thermal gradient across the cooled wheel was accurately captured by the CFD. This good correlation, validated the analysis and design work carried out, and the model used to predict performance at 1200°C TiT (see section 6.6).

6.5 Cycle efficiency impact

Whilst being able to run at hotter TiT will enable much higher turbine and system efficiencies, there is a detrimental impact on turbine efficiency from the cooling system being implemented that should be considered. Table 2 summarizes efficiencies of the baseline and cooled wheels based on the experimental data. At the test condition a drop of 0.5% in isentropic turbine efficiency was recorded. However, if we focus at the design point tested, the cooled wheel showed a leading-edge reduction of 60°C. If we consider a small recuperated gas turbine with single radial compressor and turbine with isentropic efficiencies of 0.78 and 0.8 respectively, and increase the TiT by 60°C, an increase of 2% in system efficiency is recorded, vastly outweighing the 0.5% drop in turbine efficiency.

		Baseline (EXP)	Cooling (EXP)
Turbine stat outlet temp	C	638.19	626.87
Turbine Pressure Ratio (T-S)		1.39	1.38
Compressor Efficiency	%	76.8	76.2
Turbine Efficiency ($\eta_{tur}\eta_{mech}$)	%	69.3	68.8
Oil Flow Rate	l/min	2.03	2.06
Coriolis Mass flow (g/s)	g/s	0.14	1.32

Table 2: Efficiency comparison between baseline and cooled wheel [2]

6.6 Results from 1200C TiT CFD

The boundary conditions of the CFD model were then changed to increase the TiT to 1200°C, with the same compressor conditions as tested. Both the solid wheel baseline and cooled wheels were analyzed to compare the temperature profile of the two wheels. At this condition it is predicted that temperature reductions of 200°C at LE, 250°C at TE and 180-200°C at the mid blade would be presented. These temperature reductions would bring the wheel well within the operating temperature range of CM247LC.

7. CONCLUSIONS

This paper has outlined the successful design, manufacture and physically test of a lightweight and internally cooled Radial turbine wheel, theoretically capable of operating at 1200°C TiT.

Exploiting the design freedoms of AM, together with the capability to process the Nickel Super Alloy CM247LC, a novel design was created combining the required internal structure of the wheel with a targeted internal cooling method. Topology optimisation was used to guide the required structural requirements, whilst a full conjugate heat transfer CFD model was created to model the effect of cooling on the wheel.

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8. ACKNOWLEDGMENTS

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9. REFERENCES

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2. Zhang et al. (2018). “Design of an Air-Cooled Radial Turbine Part 1: Experimental Measurements of Heat Transfer.”