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The design, development and testing of a non-uniform inlet temperature generator for the QinetiQ transient turbine research facility

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Abstract

This paper presents the design, development and testing of a non-uniform inlet temperature generator for the QinetiQ Isentropic Light Piston Facility, a short duration turbine research facility. Major modifications were made to the facility to incorporate a non-uniform inlet temperature generator following a pilot study where a two-dimensional inlet section of the facility was replicated. The inlet region was modified to allow injection of cold gas at the hub and casing to generate the radial profile, whereas cold gas was injected from upstream turbulence rods to generate the circumferential variation (*hot spots*). Two configurations of *hot spots* were generated and characterised for both temperature and pressure. Heat transfer results at 50% span for the nozzle guide vane aerofoil are presented with and without inlet temperature non-uniformity.

Nomenclature

T_{max}	peak combustor exit temperature
T_{avg}	area averaged combustor exit temperature
$T_{max,\ radial}$	maximum temperature of the circumferentially averaged radial profile
$\Delta T_{combustor}$	temperature rise across the combustor
$T_{coolant}$	coolant temperature injected through casing, hub endwalls and turbulence rods
T_{mean}	mean temperature of the flow
T_{radial}	radial temperature of the flow circumferentially averaged
T_{local}	local temperature of the flow
OTDF	overall temperature distortion factor $(T_{local} - T_{mean}) / (T_{mean} - T_{coolant})$
RTDF	radial temperature distortion factor $(T_{radial} - T_{mean}) / (T_{mean} - T_{coolant})$

Introduction

The heat transfer rates to the first stage turbine blades and vanes in the gas turbine have been studied for many years. The designer's desire for increased efficiency and thrust, by increasing the turbine inlet temperature, has motivated these investigations. These components are usually cooled using air taken from the engine compressor, which imposes a performance penalty and hence has to be kept to a minimum This entails the designer requiring accurate prediction methods to design an efficient cooling system. Nearly all turbine aerodynamics and heat transfer investigations have utilised uniform inlet temperature profiles to uncomplicate experimental hardware required. Butler (1986) and Shang (1995) have presented some experimental investigations with inlet temperature non-uniformity. In the real engine environment the combustion system delivers a temperature profile that has both radial and circumferential gradients. The radial gradients occur as a result of coolant being applied to the endwalls of the combustion chamber, whereas the circumferential gradients occur due to the dilution flows and the discrete fuel injection. In order for the turbine designer to tailor effectively the aerofoil and endwall heat loads, with cooling flows, detailed knowledge of the non-uniform gas path through the turbine system is required. Measurements obtained from actual gas turbine combustors show large radial and circumferential variations in the outlet flow (see Figure 1). High frequency measurements taken at exit to a combustor show that gas temperatures can vary both temporally and spatially between stochiometric and compressor discharge levels.

Standard instrumentation employed in gas turbine engines during testing does not provide the necessary measurements to assess the impact of inlet temperature non-uniformity on the aerofoils and endwalls. Most research turbine facilities do not have the capability to simulate radial and circumferential inlet temperature non-uniformity at engine representative operating conditions. The net result is that the majority of flow physics associated with turbine aerodyanamics and heat transfer are well understood with uniform inlet temperatures and can be taken into account during the design process. Clearly the turbine design methods can only be as good as the experimental data they have been developed and validated against, and hence there exists a desire to move research test facilities closer to the real engine condition. There is clear evidence that a non-uniform inlet temperature profile has a significant impact on a turbine systems aerothermal performance and life assessment.

The objectives of this paper are to describe the design and implementation of a non-uniform inlet temperature generator for the QinetiQ Isentropic Light Piston Facility (ILPF). The generator design and implementation forms part of a large pan-European programme, Turbine Aerothermal External Flows (TATEF), funded under the European Union's Brite Euram Fourth-Framework initiative. The programme involved extensive aerodynamics and heat transfer measurements in the ILPF with and without inlet temperature non-uniformity. However, the primary objective of this paper is to discuss the design and development of the non-uniform inlet temperature generator.

The objectives of the non-uniform inlet temperature generator were, to give engine realistic radial and circumferential temperature profile within the existing rig constraints.

Description of the experimental facility and the MT1 turbine

The Isentropic Light Piston Facility (ILPF) is a short duration wind tunnel (see Figure 2), capable of testing an engine size turbine at the correct non-dimensional parameters for fluid mechanics and heat transfer. Originally used to test a single HP turbine stage (Hilditch et al., 1994), the facility was extended in 2000 to 1.5 turbine stages (Chana 2001), with the installation of an IP stator. A novel feature of the facility is the aerodynamic turbo-brake (Goodisman et al., 1992), which is on the same shaft as the turbine and is driven by the turbine exit-flow. At the design speed the turbobrake power is matched with the turbine, and thus the turbo-brake maintains constant speed during a run. To isolate the IP vane from downstream interactions, by means of a choked throat, and to maintain the correct radial distribution of static pressure in the IP vane exit flow, a novel Deswirl System - an impulse-type stator - was employed downstream of the IP vane (Povey et al., 2001). A schematic of the working section is shown in Figure 3

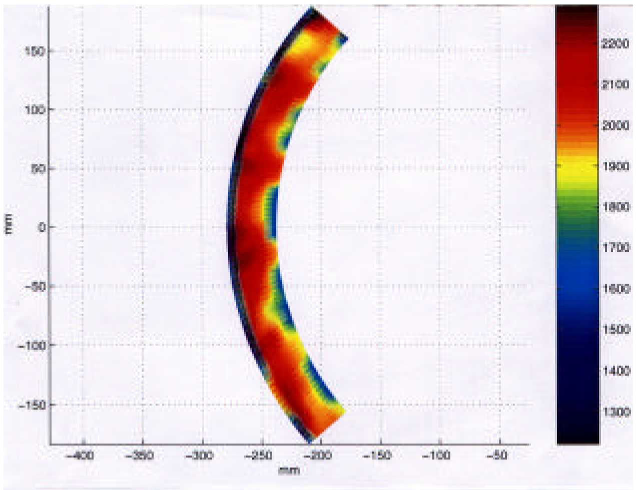

Figure 1. Measured combustor exit temperature profile

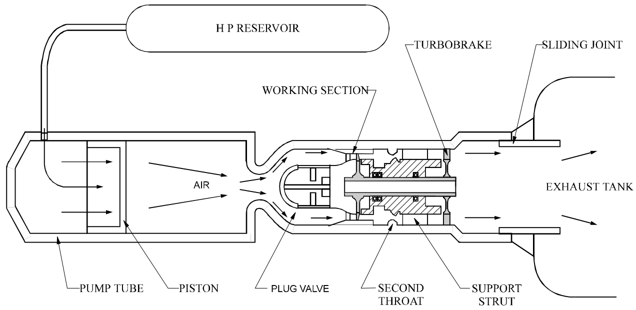

Figure 2. Schematic of the Isentropic light piston Facility

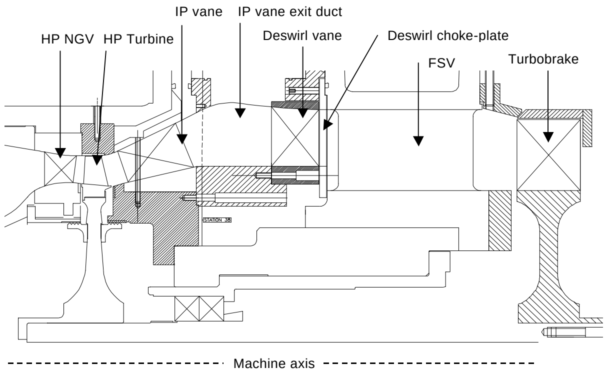

Figure 3: The working section of the Isentropic Light Piston Facility.

High pressure feed cylinders fire a piston down a piston tube, isentropically compressing and heating the working gas (air) inside the tube. When the desired pressure is reached the compressed air is suddenly discharged, by means of a fast acting valve, into the working section. Typically, steady conditions are achieved for 500 ms. The turbine stage was a modern high pressure Rolls-Royce aero-engine design with stage pressure ratio of 3.2 and nozzle guide vane (ngv) Reynolds number of 2.54E6. The stage is unshrouded and blade counts for the HP stator, HP rotor, and the IP stator are 32, 60 and 26 respectively. Table 1 gives the predicted and achieved operating conditions of the stage. The predictions were performed using the Rolls-Royce Q263 through flow solver.

Parameter	Predicted Q263	Measured: Uniform inlet	Measured: OTDF
Inlet total pressure (bar)	4.6	4.6 ± 2%	4.6 ± 2%
Nominal mean inlet total temperature	444	444 ± 2%	444 ± 2%
HP stator exit hub isentropic Mach	1.054	1.034 ± 2%	1.063 ± 2%
HP stator exit casing isentropic Mach	0.912	0.925 ± 2%	0.926 ± 2%
Speed (rpm)	9500	9500 ± 2%	9500 ± 2%
Rotor exit hub static pressure (bar)	1.434	1.428 ± 2%	1.451 ± 2%
Rotor exit casing static pressure (bar)	1.439	1.435 ± 2%	1.453 ± 2%
Rotor relative inlet total pressure (bar)	2.697	2.707 ± 2%	No data
IP stator exit hub static pressure (bar)	0.883	0.869 ± 2%	0.886 ± 2%
IP stator exit casing static pressure (bar)	1.158	1.097 ± 2%	1.121 ± 2%

Table 1: Operating point of the ILPF 1.5-stage turbine for OTDF and Uniform inlet distributions.

The radial and circumferential non-uniform inlet temperature generator

1. Simulation of RTDF/OTDF

The time-averaged gas temperature at exit to a combustion system varies in both radial and circumferential directions because of incomplete mixing of hot and cold gas streams. The radial profile is a direct consequence of the combustor liner cooling, this may be tailored to minimise blade stresses at root and tip and the position of the peak temperature may be optimised. The cirumferential peaks are a consequence of discrete fuel injectors and combustor dilution air. The peaks of these, know as *hot spot,s* are in various circumferential positions relative to the ngvs, obvious ones are where the *hot spot* may be aligned with the ngv passage or the ngv leading edges. For the engine the location of the *hot spots* will depend on the number of ngvs to fuel injectors as there is generally one *hot spot* per fuel injector and will of course vary from engine to engine. In the study reported here the number of *hot spots* is 32, the same as the number of ngvs. The system was designed to allow the *hot spots* to be rotated to any relative position to the ngvs. However, the results presented here are from two positions, where the *hot spots* are first aligned with the centre of the ngv passage and second the ngv leading edges. Clearly there are advantages and disadvantages in both *hot spot* positions, particularly in combination with ngv film cooling. The management of *hot spots* is discussed in detail by Sharma et al., (1998).

To relate radial and circumferential temperature variations from test rigs to engines, or visa versa, Overall Temperature Distortion Factor (OTDF) and Radial Temperature Distortion Factor (RTDF) distribution parameters are used. The definitions of these parameters for engines as proposed in the literature are given here:

$$OTDF = \frac{T_{\max} - T_{avg}}{\Delta T_{combustor}}$$

$$RTDF = \frac{T_{\max,radial} - T_{avg}}{\Delta T_{combustor}}$$

However, in relating these to a test rig the ΔT combustor temperature is not valid and hence the parameters are redefined for comparison with engine data in the following manner:

$$OTDF = \frac{T_{Local} - T_{mean}}{T_{mean} - T_{coolant}}$$

$$RTDF = \frac{T_{radial} - T_{mean}}{T_{mean} - T_{coolant}}$$

2. Pilot study

To reduce the risk of temperature generator integration with the ILPF a pilot study was carried out by the Department of Engineering Science at Oxford University. Initially a computational study was carried out to investigate the means of generating radial temperature non-uniformity in the ILPF through injecting cold air out of the hub and casing endwalls upstream of the turbine. Circumferential non-uniformity was proposed using cold air injection from radial bars fitted in the inlet section. However, existing bars fitted to the inlet for generating turbulence was also proposed. The computational investigation showed this geometry, together with control of the cold air flow rates, should permit the degree of combined radial and circumferential temperature variation to be tuned to match a range of current engine representative conditions. However, to reduce the risk further a scale model of the aforementioned configuration was manufactured and tested at Oxford.

The model had the same cross-sectional dimensions of the ILPF to avoid side-wall effects, however the section was two-dimensional. Detailed area traverses were carried at the ngv leading edge locations with fast response thermocouples. The turbulence rods were replicated in the same way as the ILPF to allow cold air to be injected for the circumferential profile. Various hub and casing injection geometeries were tested to optimise the radial temperature profiles. The investigation showed that annular slots on both the hub and casing endwalls gave better profiles than the existing perforated ones fitted to the ILPF. For the circumferential profile cold air was injected from the turbulence rods. The modifications made to the turbulence rods to give the required circumferential temperature profile are given in the following section.

3. ILPF mechanical design and installation

RTDF was implemented on the ILPF by using part of the existing inlet boundary layer bleed facility. The inlet section, which houses the plug valve, has radial ports open to annular plenum chambers at the casing and via spokes to the hub. Between these plenum chambers and the gas path were perforated annular plates originally used for inlet boundary layer bleed. These plates were replaced with non-perforated ones to allow injection through slots as the pilot study showed. The annular plates were fitted such that they formed an injection slot between the plate and casing housing. A similar arrangement was fitted on the hub wall. Figure 4 shows how the new plates are fitted in relation to the working section to form the injection slots. In addition to forming slots for injection, the plates were designed to provide flow resistance to help smooth out any non-annular flow effects caused by discrete feed ports. Modifications to the casing were carried such that the existing annulus was preserved, however this was not possible on the hub wall where the new plates are of a larger radius causing the annulus height to be reduced slightly. The change in annulus is considered to be small and upstream of the contraction and hence would not cause any significant adverse flow effect.

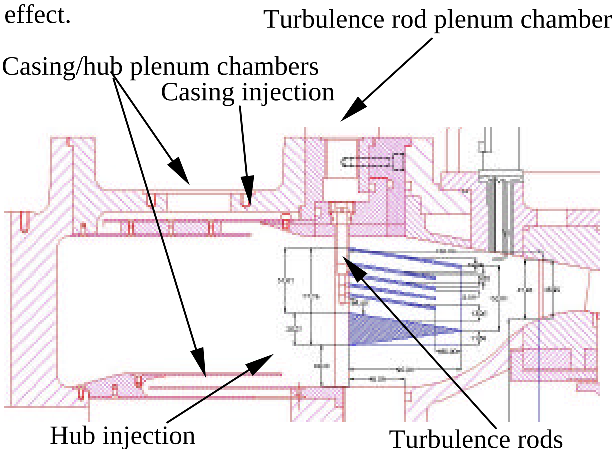

Figure 4. OTDF installation to the Isentropic Light Piston Facility

For the OTDF profile generation the turbulence rods were initially modified as in the aforementioned pilot study. The *hot spot* was thus to be generated by operating the ILPF tunnel temperature at close to the required peak temperature and by injecting cold air from the turbulence rods a *hot spot* could be produced in the centre of the rods. There are 32 turbulence rods and 32 ngvs and hence a *hot spot* per ngv would be produced. To change the position of the *hot spots* relative to the ngvs the turbulence rods were designed such that they could be rotated in the circumferential direction.

However, during early commissioning tests it became apparent that the cold air injected from the turbulence rods was mixing out such that almost no circumferential temperature profile was detectable at the ngv leading edge plane. Increasing the mass flow from the turbulence rods did not affect the mixing significantly. To overcome this over mixing, small tapering duct sections with internal vanes were added to the turbulence rods, to reduce the mixing and direct the flow better. A schematic of these vanes is shown in Figure 4 (in blue). This reduced the distance over which the profile could mix with the freestream and gave the required circumferential profile. Changing the mass flow through the hub, casing and turbulence rod systems independently showed that the system could match the targeted profiles and enhance the profiles significantly if required. Figure 5 shows a photograph of the installation showing the turbulence rods with and without ducts.

Three new coolant supply systems were installed for the cold air supply to the turbulence rods, casing and hub injection systems.

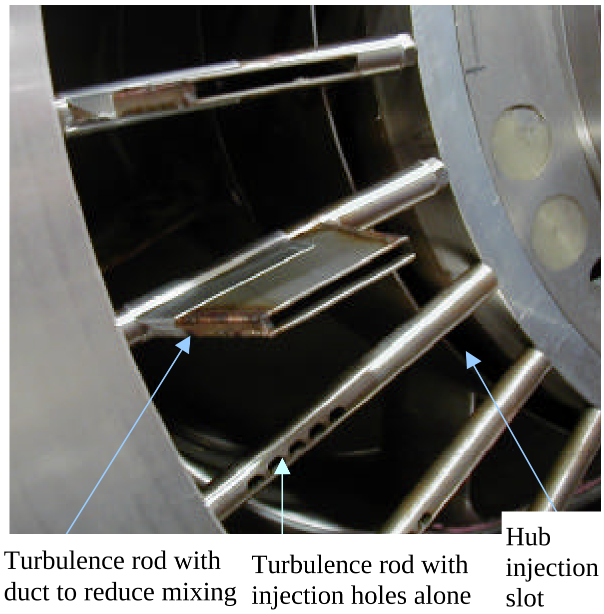

Figure 5. Turbulence rods with and without ducts fitted

The hub, casing and turbulence rod systems are similar, incorporating reservoir feeds via calibrated orifice plates. All three systems are independent and can be filled to the required pressure levels to give the mass flow needed. To control and monitor the mass flow calibrated orifice plates were fitted in the supply connectors. For the hub and casing coolant supply systems a much larger mass flow was required.

5. Instrumentation

The standard technique of using thermocouples was used to measure the temperature profile generated at the ngv leading edge plane. Since the size of the thermocouple bead has a significant influence on the measured temperatures, beads of 0.25 μm were used.

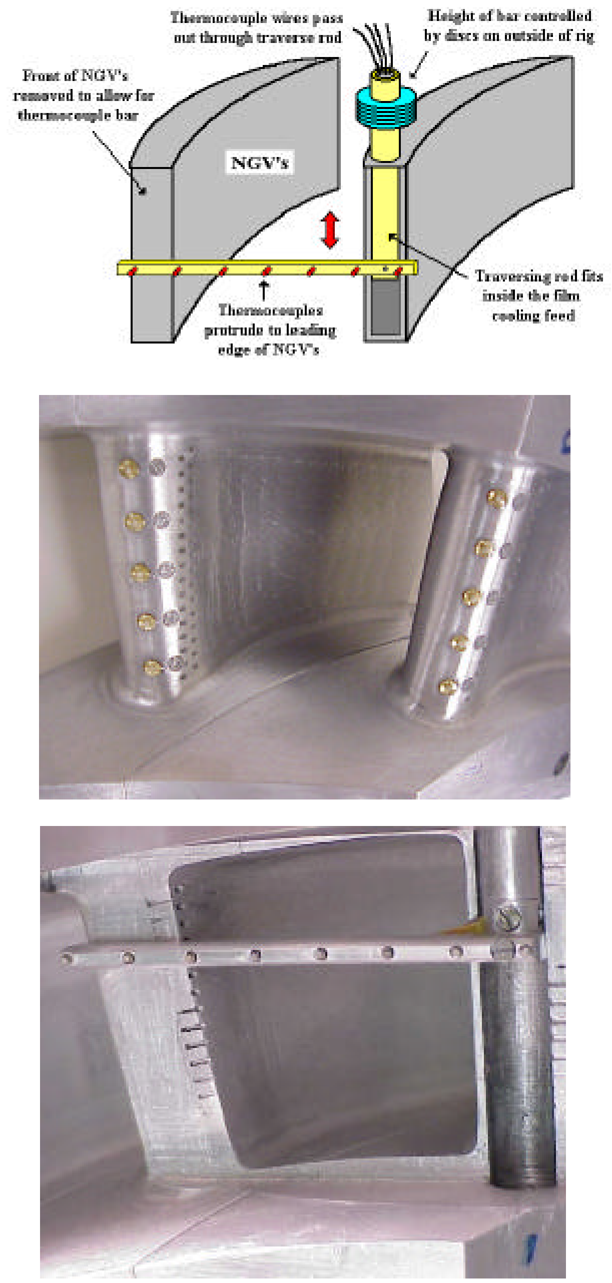

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Figure 6. Stage inlet total temperature instrumentation

The inlet temperature profile was measured using two types of instrumentation, one where the radial profile was measured with thermocouples fitted at the leading edges of two ngvs and the other where an area coverage was possible. For the area coverage the leading edges of two ngvs were machined to fit a horizontal bar with seven thermocouples covering just over an ngv pitch. This horizontal bar could be moved between runs in the radial direction to build a complete area map. A schematic and a photo of the inlet measurement systems are shown in Figure 6. The measurement point of the thermocouples was carefully positioned at the leading edge plane of the ngvs for two reasons. Firstly to establish the exact profile seen at the ngv inlet plane and secondly, to keep the measurement in a higher Mach number region. The Mach number at the ngv leading edge plane is of order 0.1 whereas just upstream of the ngvs is of order 0.05.

For inlet total pressure measurements the horizontal thermocouple bar was replaced with one fitted with pneumatic tappings. This was again moved between runs to obtain area coverage. To measure the pressure fluctuations in order to assess the inlet turbulence levels, high frequency pressure transducers were used.

Commissioning tests

The tests with uniform and non-uniform temperatures at inlet to the stage have been conducted at the same nominal design conditions. The area mean temperature in both cases was kept constant at 444K and with the same rotational speed between the two tests, the corrected speed ($N/\sqrt{T}$) will be the same. Radial and circumferential temperature profiles were adjusted to achieve this criterion by varying the mass flow injected through the hub and casing to vary the radial profile and the mass flow through the turbulence rods to adjust the circumferential profile. This required the nominal mainstream gas temperature of 444K, from the uniform inlet temperature tests, to be increased to 480K. Particular attention was paid to ensure that the turbine inlet total pressure was not modified. A full area traverse was carried out at inlet to the stage to confirm that the mean total pressure was unaltered. A further point to note is that although extra mass flow has been added to the working section, which should increase the run time, the run time has actually reduced. This is because the tunnel compression required to achieve a higher peak inlet temperature, causes the piston to travel further in the pump tube during the compression process. This leaves a smaller pump tube volume for the run duration in comparison to the uniform tests. The inlet total pressure has been measured at 7 radial heights using a horizontal bar with 8 pneumatic pitot probes fitted at the leading edge of the ngv. Figure 7 shows the inlet total pressure measurements taken with the tunnel configured for OTDF1. Pitot numbers 2 and 7 are axially aligned with the leading edge of the ngvs. Overall the variation in the total pressure along the span is negligible. At the leading edges of the ngvs a small reduction in the pressure level is caused by the presence of the ducts added to the turbulence rods. However, this reduction in total pressure is only 0.15% and is considered negligible.

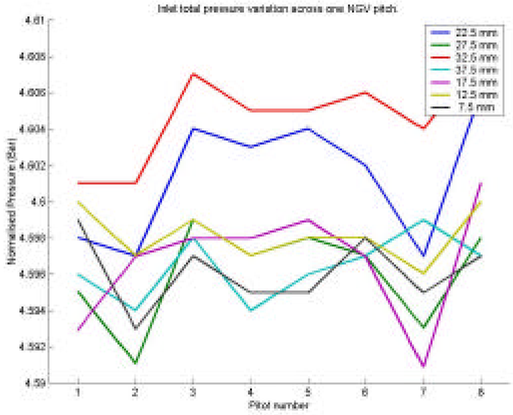

Figure 7. Stage inlet total pressure measurements.

Figure 8 shows sample stage inlet total temperature traces against time, for uniform, OTDF1 and OTDF2 configurations, at mid-span. These measurements were taken at the ngv leading edge and hence for OTDF2 the temperature is higher. Notably, the inlet temperature fluctuations on the trace from the non-uniform inlet configurations have increased markedly from those with the uniform inlet. It should be noted that this is not as a result of increased turbulence in the flow but as a result of cooler and warmer air mixing from different radial and circumferential positions, caused by the turbulence.

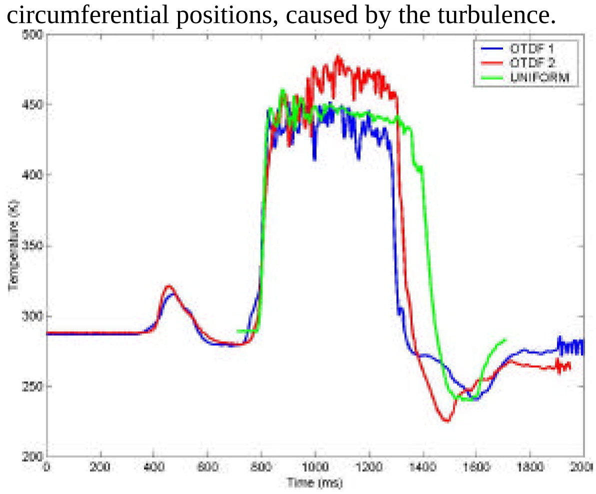

Figure 8. Inlet total temperature measurements with uniform,OTDF1 and OTDF2 configurations

Hence, the temperature gradient acts as a marker for the turbulence causing lower temperature fluid to be locally replaced with higher temperature fluid. In the case of a uniform inlet temperature profile the turbulence would not be detected in this way. The length scale of the turbulence will be of the order of the diameter of the turbulence rods. High frequency total pressure measurements at inlet to the stage are planned to quantify this effect.

The mean measured radial temperature profiles, circumferentially averaged for the uniform, OTDF1 and OTDF2 configurations are given in Figure 9. Area plots showing the measured inlet temperatures during the OTDF1 and OTDF2 tests are given in Figure 10.

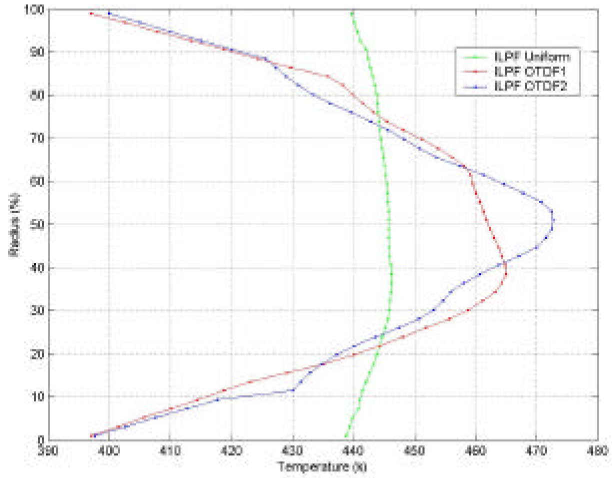

Figure 9. Circumferentially averaged inlet total temperature profiles

The geometric leading edge of the ngvs coincide with the edges of the plot in this figure. Thus, OTDF1 has the *hot spot* at the centre of the passage whereas OTDF2 has the *hot spot* impinging on the ngv leading edge. Notably the location of the *hot spot* for OTDF1 is not central to the ngv passage despite the turbulence rods being carefully aligned with the ngv leading edges. The flow local to the ngv leading edge is

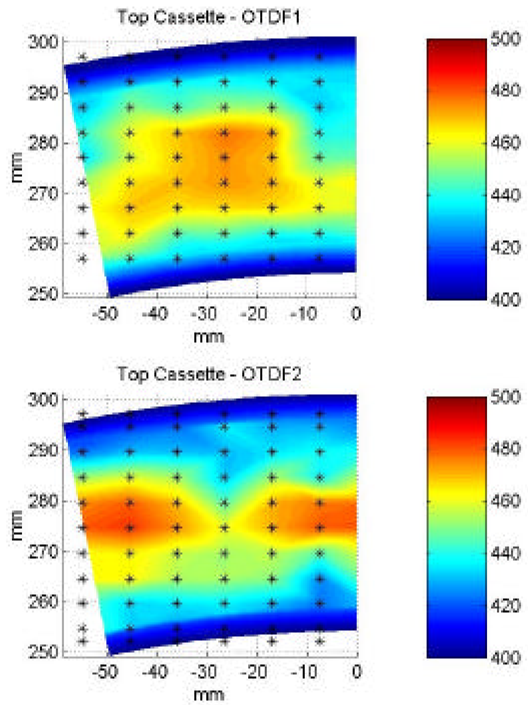

Figure 10. Measured OTDF1 and OTDF2 temperature profiles.

convected towards the pressure side of the vane. Hence, the *hot spot* is also shifted towards the pressure side of the vane. For the OTDF2 measurements the *hot spot* is evidently aligned with the leading edges of the ngvs. However, there is a small difference in the *hot spot* height between the suction side and the pressure side, the lower temperature is located more central to the passage. The inlet temperature profiles around the circumference from ngv passage to passage was found to be similar, checked by taking measurements at three locations (see Figure 11). The stars indicate the locations of the data points. The figure also gives the average profile, evaluated from the three measured profiles.

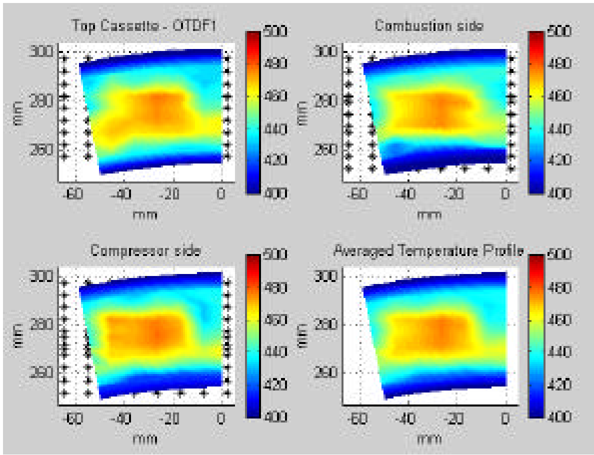

Figure 11.Total temperature distribution measurements at three locations around the annulus and the average distribution.

Figure 12 gives the uniform, OTDF1, OTDF2 and sample combustor exit measured data as OTDF values. Comparing OTDF1 with the typical combustor data shows the *hot spot* to be shaped slightly different, however the levels compare very well.

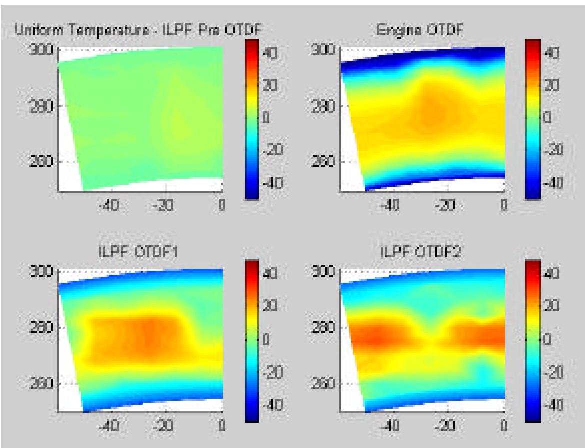

Figure 12. OTDF levels for the uniform, OTDF1, OTDF2 and typical combustor exit measurements.

Experimental results

Measurements of the ngv mid-span Nusselt number taken with the uniform, OTDF1 and OTDF2 configurations are given in Figure 13. Notably the pressure side shows almost no difference with the addition of inlet temperature non-uniformity. For the suction surface the OTDF1 results are slightly higher towards the leading edge but significantly lower towards the trailing edge, whereas the OTDF2 are higher that the uniform results.

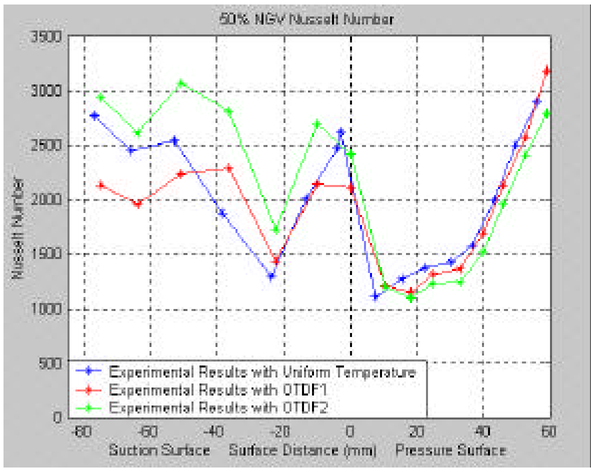

Figure 13. Nozzle guide vane surface heat transfer at mid-span.

Chana (2002) presented detailed rotor casing and tip, pressure and heat transfer measurements, with the non-uniform inlet temperature generator. Further detailed results from the tests with and without inlet temperature non-uniformity are to be presented in a follow on paper on the ngv.

Conclusions

This paper presented a non-uniform inlet temperature generator that was successful designed, developed and installed to the QinetiQ Isentropic Light Piston Facility. The generator was shown to match engine realistic profiles of RTDF and OTDF. The system has the capability of rotating the *hot spot* circumferentially relative to the nozzle guide vanes. The area mean inlet temperature was kept constant between the uniform and non-uniform inlet conditions. Measurements confirmed that the inlet total pressure was not modified with the addition of the non-uniform generator.

Nozzle guide vane data taken at mid-span with and without inlet temperature non-uniformity showed the pressure surface heat transfer not be affected by the addition of RTDF/OTDF, whereas the suction side showed higher heat transfer with the OTDF2 case and lower with the OTDF1 case.

Acknowledgements

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