THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN THERMO AND FLUID DYNAMICS

Experimental Investigation of the Aerodynamics and Heat Transfer in an Intermediate Turbine Duct

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Abstract

In today's aero engines with large bypass ratios the difference in diameter between the high pressure turbine and the downstream turbine, being either an intermediate or low pressure turbine, is large. There is also scope to further increase it, to increase the efficiency of the downstream turbine and enabling use of larger diameter fans. Hence, there is a need to guide the flow in between these two entities. This is carried out through an intermediate turbine duct. The flow through the duct includes a number of complex phenomena affecting the performance of this component. This includes secondary flow structures, risk of separations, strong vorticity, high temperatures etc. This thesis investigates two different designs of the intermediate turbine duct, which have been tested in two different experimental facilities, the Chalmers Large-Scale Low-Speed Turbine Facility and the Oxford Turbine Research Facility. Both configurations consists of a full high pressure turbine stage (stator and rotor) and an intermediate turbine duct with a low turning vane. At Chalmers, the emphasis was at steady aerodynamic measurements including static pressure, total pressure and flow angles within the duct. In Oxford, the experimental campaign mainly regarded heat transfer measurements on the intermediate turbine duct vane surface at discrete positions. However, the results included in this thesis are mainly static pressure distributions from the first part of the campaign, along with some heat transfer results. This set of experimental data, from two different facilities and designs, enables the validation of current and future numerical methods to well-defined test cases.

Keywords: Experimental, Aerodynamics, Heat Transfer, Gas Turbine, Intermediate Turbine Duct

List of publications

This thesis is based on the work contained in the following publications:

1 M. Johansson, V. Chernoray, L. Ström, J. Larsson and H. Abrahamsson, 2011, Experimental and Numerical Investigation of the Aerodynamics of an Intermediate Turbine Duct, *Proceedings of ASME Turbo Expo 2011*, June 6-10, Vancouver, Canada

2 M. Johansson, K. Chana, T. Povey, F. Wallin and H. Abrahamsson, 2013, Aerodynamic and Heat Transfer Measurements on an Intermediate Turbine Duct Vane, *Accepted for publication in Proceedings of ASME Turbo Expo 2014*, June 16-20, Düsseldorf, Germany

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Only a life lived for others is a life worthwhile.
- Albert Einstein

Nomenclature

Glossary

C_{Ma}	Mach number coefficient.
C_β	Yaw angle coefficient.
C_{p_0}	Total pressure coefficient.
I	Electrical current $[A]$.
I_{in}	Constant electrical current through gauge $[A]$.
Ma	Mach number.
N	Number of points in sampled signal.
R	Electrical resistance $[\Omega]$.
R_{in}	Electrical resistance at T_{in} $[\Omega]$.
Re	Reynolds number.
T	Temperature $[K]$.
T_0	Total temperature $[K]$.
T_g	Gas temperature $[K]$.
T_w	Wall temperature $[K]$.
T_{in}	Temperature when $R = R_{in}$ $[K]$.
V	Voltage $[V]$.
V_{in}	Initial voltage $[V]$.
α	Diffusivity $[m^2/s]$.
$\alpha_{R/T}$	Temperature coefficient of resistivity $[1/K]$.
$\dot{m}$	Mass flow rate $[kg/s]$.
γ	Ratio of specific heat.
h	Impulse response function.
i	Summation variable.
n	Sample number.
p_0	Total pressure $[Pa]$.
p_{avg}	Pressure, averaged $[Pa]$.
p_a	Pressure, left probe tube $[Pa]$.
p_b	Pressure, middle probe tube $[Pa]$.
p_c	Pressure, right probe tube $[Pa]$.
q	Heat flux $[W/m^2]$.

Acronyms

BPR	Bypass Ratio.
CFD	Computational Fluid Dynamics.
FACTOR	Full Aerothermal Combustor Turbine interactiOn Research.

HPT	High Pressure Turbine.
IPT	Intermediate Pressure Turbine.
ITD	Intermediate Turbine Duct.
LPT	Low Pressure Turbine.
LSLS	Large-Scale Low-Speed.
LVDT	Linear Variable Differential Transformer.
NFFP	National Aviation Engineering Research Programme.
NGV	Nozzle Guide Vane.
OTRF	Oxford Turbine Research Facility.
TFHTG	Thin-Film Heat Transfer Gauge.

Contents

1 Introduction

In an aero engine the Intermediate Turbine Duct (ITD) is situated between the upstream High Pressure Turbine (HPT) and downstream Intermediate Pressure Turbine (IPT) or Low Pressure Turbine (LPT), depending on engine configuration. It serves the purpose of guiding the flow from a relatively small diameter HPT to a larger diameter IPT or LPT. Typically it includes a vane, transferring structural loads from the core of the engine to external parts, as well as supplying oil and air to the core. An axial cross-section of a typical ITD is shown in Figure 1.0.1 together with its neighbouring components. In today's engine development there is a trend towards higher Bypass Ratios (BPRs). This demands a larger diameter fan, which in turn decreases the rotational speed due to limitations in fan tip velocity. To power the larger fan, a larger LPT is needed, achieved either by increasing the number of stages and/or increasing its diameter. Moving towards the latter choice has the benefit of for example saving overall weight. However, an increase in LPT diameter requires an ITD with a larger radial offset. This can be dealt with by either extending the axial length of the ITD and hence adding weight, or by designing it to be more aggressive, i.e. increasing its radial offset while keeping its axial length. To keep the engine cost and weight down the latter alternative is the preferred, although introducing a number of issues that needs addressing in the design process. To keep the performance of the ITD, no flow separation is allowed within it at design conditions. However, by designing it as being more aggressive there is an increased risk of this occurring, especially along the casing close to the inlet and along the hub close to the exit of the ITD due to adverse pressure gradients, as discussed in Göttlich et al. [1].

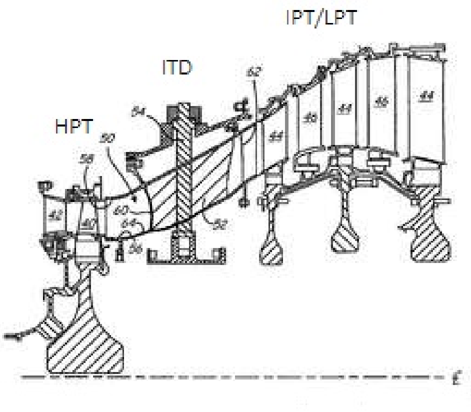


Figure 1.0.1: *Typical ITD in an aero engine, from [2].*

The vane within the ITD has historically, when included, only been carrying structural loads and supplying the engine core with oil and air. In today's trend towards higher BPR engines and more aggressive ITDs, there is a scope within letting the vane carry aerodynamic loads, i.e. turning the flow within the ITD. If the duct and vane is designed to deliver an exit flow in accordance with the design inlet conditions of the downstream IPT/LPT, the Nozzle Guide Vane (NGV) upstream of the turbine can be removed. This would allow for an axially shorter and hence lighter component. By designing a vane that carries aerodynamic load, the risk of flow separation within the duct is reduced since the effective curvature seen by the flow is reduced due to an increase in flow path within the ITD. This however, increases the surface friction within the ITD which contributes to the total pressure losses. The designs evaluated in this thesis feature a low turning vane, giving that the configurations are targeted towards a counter rotating turbine configuration. This means that the shafts, and hence high pressure and intermediate/low pressure turbines/compressors spin in opposite directions. With this the amount of turning within the ITD, needed to meet the inlet conditions of the downstream IPT/LPT, is reduced.

Also, in modern aero engines where HPT entry temperatures are continually increasing, it is of greater importance to understand the behaviour of the working gas and its effect on its surroundings. With further elevated temperatures within the downstream ITD, use of highly sophisticated materials and cooling needs to be addressed. This increases the manufacturing costs and affects the overall engine performance, since compressed air needs to be taken from upstream components for cooling purposes.

1.1 Description of work

This thesis presents experimental work that has been performed at Chalmers University of Technology and University of Oxford.

The first part describes the work performed at Chalmers, where the Chalmers Large-Scale Low-Speed (LSLS) Turbine Facility has been utilized to investigate the aerodynamics in an ITD fitted with a low turning structural vane. A seven-hole pressure probe has been traversed, covering a whole passage both upstream and downstream of the vane and measuring the flow angle, total pressure and velocity fields. The ITD vane was fitted with static pressure tappings along five heights. The measurements have been carried out at three different inlet conditions defined as on-design, high load and low load. This have been achieved by varying the turbine speed, and hence the turbine exit swirl angle.

The second part describes the work performed at University of Oxford where the Oxford Turbine Research Facility (OTRF), a high-speed transient turbine facility has been utilized to investigate the aerodynamics and heat transfer in an ITD with a low turning structural vane. This measurement campaign includes an extensive amount of instrumentation, from which the results are not fully presented within this thesis. The aerodynamics has been investigated with the aid of a three-hole probe traversed downstream of the vane covering about 1.5 vane passages. Static pressure tappings have been fitted on the vane surface at three different heights as well as on the hub and casing endwalls upstream, in the passage and downstream of the vane. The total pressure has been measured with five Pitot probes sitting on the leading edge of a vane. The heat transfer has been measured using the in-house developed Thin-Film Heat Transfer Gauges (TFHTGs) that has been glued onto the vanes. They are located at three different heights as well as on the casing upstream of the vane. To ensure that the facility is performing in accordance with its design a number of measurements are taken for every run including accelerometers, vibrometers, pressure tappings, thermocouples etc.

1.2 Aims

This research aims to investigate the highly complex flow through an ITD and its influence on the heat transfer of its components. This will lead to a better understanding of the phenomena that governs the flow through such a geometry. With a better understanding the numerical methods used today can be further enhanced and the relatively large uncertainties introduced when designing a new engine component can be reduced. The work presented here also serves the purpose of laying the foundation of a large data base with well-known boundary conditions and accurate results to which numerical methods can be validated.

2 Background

The flow through an ITD is highly complex due to periodical unsteady effects caused by the passing upstream HPT rotor. These effects are listed below and interact with each other throughout the ITD.

- Rotor wakes with periodic change in flow angles.
- Secondary flow vortices influencing the boundary layers.
- Rotor tip leakage with high energy flow close to the shroud.
- Swirl angles being different from axial and with spanwise variation.
- Trailing edge shocks in the case of a transonic HPT (not applicable in this study).

The ITD is in essence a diffuser guiding the flow from a small diameter HPT to a larger diameter IPT/LPT. To understand the flow through an ITD, studies trying to describe individual flow phenomena (as listed above) entering the ITD and its influence on the ITD flow and performance has previously been conducted. At University of Durham a series of experiments were performed to study the influence of blade wakes, swirl, diffusion rates and the inclusion of an ITD vane. Dominy et al. [3] utilised the University of Durham Swan Neck Duct Facility to study an ITD configuration, first with a uniform inlet and then with swirl vanes (axial flat plates) installed looking at the effect of blade wakes onto the flow. It was found that the addition of simple blade wakes had a strong influence on the ITD flow in terms of spanwise flow transport within the wake and strong secondary flows that lead to total pressure distortions. It was also shown that a minor distortion at the ITD inlet has disproportionately large influence on the ITD exit flow structure. In Dominy et al. [4] the swirl vanes were turned to generate an ITD inlet flow with a swirl of 15 degrees. The introduction of swirl was shown to skew the rotor wake when passing through the ITD, which in term is shown to change the distribution of loss at the exit compared to the case without inlet swirl. Norris et al. [5] performed experiments looking at the effect of diffusion rates by comparing two different ITD configurations with the same overall area ratio but different axial lengths and hence diffusion rates. It was shown that the spanwise pressure gradient, which strongly influences the secondary flows, was increased around the first bend of the ITD increasing the boundary layer thickness along the shroud and hence the losses within this region. Norris [6] investigated the effect of including a structural vane within the ITD. The shorter duct in Norris et al. [5] was equipped with evenly spaced vanes and a comparison was made. The obvious blockage effect of the vane was noticed to have a severe effect on the total pressure losses within the ITD. However, when including the vane no changes was made to compensate for the reduction in flow area though this part of the ITD. It was also shown to modify the structure of the secondary flows caused by the upstream rotor wakes by suppressing or supporting the boundary layer growth on either side of the vane. When these two flows interact at the trailing edge of the vane, the low energy zone is caused to lift off the shroud surface and create a loss core still visible at the exit of the ITD. The findings by Dominy et al. and Norris et al. was later confirmed in a two part study by Hu et al. [7] and Zhang et al. [8] who studied the effect of varying the inlet swirl angle either in the top half of the channel or in the bottom. A spanwise migration of fluid within the rotor wake was found and the variation in inlet swirl angles was shown to skew the wake differently through the ITD, affecting the strength of the counter-rotating vortices appearing where the wake meets the endwalls.

While these already mentioned studies describe the effects of individual phenomena they do not address the combination of them, nor do they include any rotating parts, which highly influence the flow. Performing studies of this sort demands more complicated test facilities and hence larger funding, especially when introducing rotating parts. The European Union funded two framework 6 projects, AIDA and AITEB-2 that aimed to address this. A new facility was built at Chalmers University of Technology, used to study both the aerodynamic (AIDA) and the aerothermal (AITEB-2) performance of two different ITD designs downstream of a HPT stage. The facility is of a LSLS type, since many of the flow phenomena found at engine speed can be studied at lower speed. The AIDA configuration was equipped with a vane at the exit of the ITD and measurements included area traverses, static pressure tappings, oil-film visualisation, hot-wire anemometry and LDV, used to in detail describe the flow through this configuration, see Axelsson [9]. Findings included for example the unsteady behaviour of the flow exiting the turbine stage. The AITEB-2 configuration did instead include a structural load carrying vane located further upstream within the ITD. Measurements included area traverses, static pressure tappings, oil-flow visualisation and infra-red thermography, see Arroyo [10]. The focus was on the heat transfer of the ITD and vane, and results showed impacts from the unsteadiness of the upstream stage, as well as wakes from the upstream NGV. The impact of the tip leakage flow on the heat transfer of the ITD shroud wall and vane was discussed. Since a flight mission of today includes conditions where the ITD would see a variety of inlet conditions, both these configurations were also evaluated under off-design conditions. By altering the turbine speed, the inlet swirl angle was varied. Measurements in the AIDA configuration showed that the off-design conditions changed the flow within the ITD, but it still managed to deliver an exit flow in accordance with its design, although with a higher pressure loss coefficient, see Axelsson et al. [11]. However, the AITEB-2 configuration (Arroyo et al. [12]), which had its vane located closer to the ITD inlet, showed a significantly larger sensitivity to off-design conditions. The tip-leakage flow was found to impinge, with a high incidence angle, on the suction side of the vane, forming a large vortex. A large separation was found for the low load case (large ITD inlet swirl angle) along the pressure side of the vane close to the hub, due to the difference in swirl angle in the tip-leakage region.

The EU project AIDA also included a rebuild of the Transonic Test Turbine Facility (TTTF) at Graz University of Technology as described in Göttlich et al. [13], to allow for testing of different ITD configurations. Within AIDA, three different set-ups were studied under various conditions, for example inlet Ma and rotor tip gap size. These were summarised by Göttlich [14], along with other studies. By increasing the tip gap size, it was found that the total pressure loss was increased. The majority of the total pressure loss in the ITD was generated past the first bend of the ITD, although no difference between the two tip gap sizes was shown here. The difference was instead found further downstream, where the impact of the tip gap flow is shown in a larger part of the flow field. The third of these configurations was designed to be very aggressive and include flow separation within the ITD, to create a test case to which Computational Fluid Dynamics (CFD) models can be validated and passive flow control concepts can be tested. It was shown that the efficiency of the separated ITD was very poor, due to a large region of recirculation close to the shroud, around the first bend of the ITD. When comparing with CFD results, it was found that when using mixing planes between the components of the turbine stage, this phenomena was not captured and the pressure losses were under-predicted. Within a later EU project (DREAM), a further development of the TTTF included a second rotor, giving a two stage, two shaft turbine facility as described in Hubinka et al. [15]. With this, an integrated concept with splitter vanes introduced in between the already existing turning vanes was studied by Spataro et al. [16, 17]. It was found that the integrated concept increased the uniformity of the ITD exit flow, in terms of wakes and secondary vortices, which in turn increased the overall performance of the downstream LPT stage.

Experimental studies of the flow through an ITD has also been performed at the Von Karman Institute of Technology, where the Compression Tube Facility has been utilized for this. Billiard et al. [18] studied the aero-thermodynamics of an ITD vane, while changing its pitch-wise relative position to the upstream HPT NGV to four different positions. The change in relative position altered the inlet conditions to the ITD significantly, due to a change in relative position of the pitchwise variation in total pressure and the potential field coupled to the static pressure of the ITD vane, which affects the ITD inlet Ma. The main effects on the vane due to clocking were found to be within the leading edge. It was also shown that the thermal load was noticeably reduced for one of the clocking positions. In Lavagnoli et al. [19] and Solano et al. [20], a multi-splitter concept was integrated in the ITD and investigated for three operating conditions. It was equipped with large structural vanes with three smaller aero vanes in between. It was introduced as a way of achieving increased uniformity at the exit of the ITD, as well as integrating the first stator of the downstream turbine stage with the ITD. The structural vane was shown to distort the flow into the aero vanes, with larger circumferential non-uniformities. However, the pressure levels at the rear of the vanes is shown to be similar, also for off-design conditions, providing a uniform outlet flow field. When operating the facility at an off-design condition with an ITD inlet flow angle far off the nominal, a large separation appears along the pressure side of the structural vane and the whole vane passage is shown to be affected.

At Ohio State University, the Turbine Test Facility was equipped with a 1.5 stage turbine. Haldeman et al. [21] studied the aerodynamics and heat flux of this configuration, operating at different modes. The findings showed for example that the normalised pressure data was insensitive to the operation of the facility and the Reynolds number, thus enabling combinations of data taken when operating the facility in both shock-tube mode and blowdown. In Haldeman et al. [22] the clocking effect between the upstream HPT NGV and the ITD vane was studied by rotating the ITD configuration circumferentially between experiments, to five different positions. Multiple measurement techniques were used, and a notable and consistent change in efficiency for the different clocking positions was reported. The maximum efficiency was obtained when the static pressure was the highest on the ITD vane surface, with the least amount of variation in both the time and frequency domain. A small effect on the upstream NGV was shown to be caused by the ITD vane, and the interaction between the two changed the inlet conditions to the ITD significantly.

3 Experimental facilities

This section gives a brief overview of different experimental set-ups used when studying the flow through aero engine components, discussing advantages and disadvantages. It also describes the facilities used in the investigations presented in this thesis, the Chalmers LSLS Turbine Facility and the OTRF.

3.1 Different kinds of turbine facilities

In general, facilities used in aero engine research are divided into rotating vs. non-rotating, low-speed vs. high-speed, cold vs. hot and continuous vs. transient facilities. All these variations come with general advantages and disadvantages, and depending on the desired targets and constraints within a project, the most suitable combination of these attributes varies.

A major consideration when designing a new facility is the total cost of building and running it. This is highly affected by what attributes are chosen, for example a rotating facility is more complicated to design and more costly to run compared with a non-rotating facility. Rotating facilities offer a more engine realistic flow with complex flow structures, especially when realistic rotational speeds are investigated. However, this introduces issues such as large forces within the facility that needs handling and potentially complex instrumentation paths. Facilities such as the TTTF at Graz University of Technology (Göttlich et al. [13]), the Oxford Rotor Facility at University of Oxford (Ainsworth et al. [23]) and the Chalmers LSLS Turbine Facility (Arroyo et al. [24]) are included in this category. Linear and annular cascades (non-rotational) on the other hand, targets more novel research, where a specific issue is isolated. This could for example. include measurements of capacity, vane cooling or detailed vane aerodynamics and heat transfer, see for example Hjärne et al. [25], Norris [6] and Hu et al. [7].

When focusing on the heat transfer of an aero engine component, a temperature gradient of some sort is necessary. This could imply either having a hot gas flowing over a cold surface, or a cold gas flowing over a heated surface. In transient high-speed facilities, such as the OTRF at University of Oxford (Chana et al. [26]), the Compression Tube Facility at Von Karman Institute (Paniagua et al. [27]), the Turbine Research Facility at the Air Force Research Laboratory (Anthony et al. [28]) and the Turbine Test Facility at the Ohio State University (Dunn et al. [29]), this is typically solved by introducing a temperature step at the start of a run. It is somewhat more complicated in a continuous facility, where either the surface of interest needs to be heated as used by Arroyo [10], or a temperature step to be introduced to the test gas when stable conditions are established.

3.2 Chalmers LSLS Turbine Facility

The Chalmers LSLS Turbine Facility is a low-speed large-scale 1.5 stage turbine facility, offering possibilities to study the flow through an ITD. A schematic of the facility is found in Figure 3.2.1. It was designed within the previous EU programmes AIDA and AITEB-2, where it was utilized for aerodynamic (Axelsson [9]) and heat transfer (Arroyo [10]) measurements in two different ITD configurations, both including a structural and aerodynamically unloaded vane. The facility was designed to meet the Reynolds number of the corresponding part in a real aero engine, for the results to be associated to what can be expected in a real aero engine. The nominal operating conditions of the facility is found in Table 3.2.1. The facility is powered by a 110 kW centrifugal fan. The test gas (air) is then passing through several flow conditioning devices before reaching the nose cone that splits the flow to annular. The turbine stage, designed within AIDA by Rolls Royce Deutschland (RRD), is designed to be simple, robust and corresponding to a second stage of an unshrouded two-stage HPT, providing a realistic ITD inlet flow. The turbine is kept at constant speed with the aid of a hydraulic brake, which converts the mechanical power of the turbine to hydraulic work. The brake load to the turbine is governed by the adjustment of two valves that restricts the oil flow through the hydraulic pump. By this, the facility is tuned to the desired operating point. It can also be used to set off-design conditions by allowing the turbine to spin at a higher or lower speed and hence delivering a different ITD inlet condition, mainly in terms of flow angle variations.

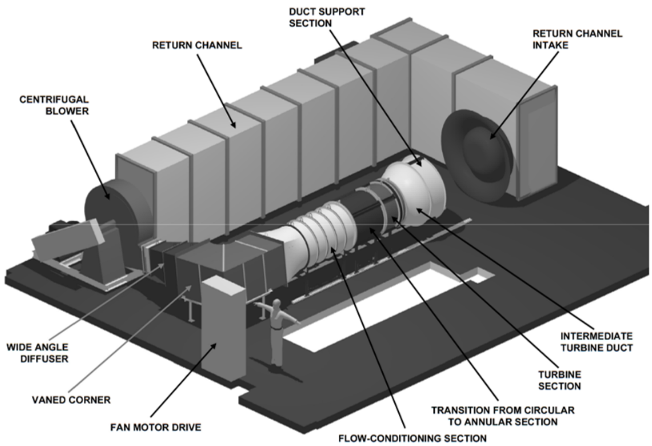


Figure 3.2.1: *Chalmers LSLS Turbine Facility.*

3.2.1 The NFFP5 ITD design

The ITD with vane design evaluated in the Chalmers LSLS Turbine Facility was performed at Volvo Aero Corporation (today GKN Aerospace). The same turbine stage as used within AIDA and AITEB-2 was reused, setting the inlet conditions to the ITD. It also, to some extent, gave geometric restrictions to the design. The design was targeted to be robust to off-design conditions and engine representative, with low pressure losses and without separations in the ITD. The vane was chosen to be typical for a counter rotating engine system design and hence low turning. The design was performed in the Volvo Aero

Table 3.2.1: Chalmers LSLS Turbine Facility nominal conditions.

Parameter	Value
Re based on ITD inlet height	160000
Speed [rpm]	1060.0
Power [kW]	110.0
Max turbine pressure ratio	1.06
$\dot{m}$ [kg/s]	10.0

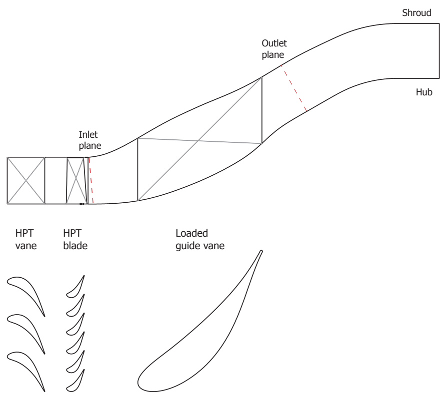


Figure 3.2.2: *Cross-sectional view of the Chalmers Turbine Facility.*

in-house tool VolVane and evaluated in Ansys CFX. A meridional view of the turbine stage and the new ITD configuration is shown in Figure 3.2.2.

3.3 Oxford Turbine Research Facility

The OTRF is a short duration wind tunnel, enabling engine sized turbines to be tested at the correct non-dimensional parameters, see Table 3.3.1, relevant for aerodynamic and heat transfer measurements. It was firstly used as an annular cascade, investigating flows through HP NGVs. Later, a HP rotor was installed (Hilditch et al. [30]), and the facility was used in several research programmes. In year 2000 a second vane was introduced and a 1.5 stage HPT was investigated with different inlet conditions, see Povey et al. [31] and Chana et al. [32]. A schematic of the facility is shown in Figure 3.3.1. The ITD has been isolated from downstream components by introducing a choked throat and a novel deswirl vane, of similar type as described by Povey et al. [33]. By this, the radial static pressure distribution at the ITD exit is maintained. The deswirl vane also turns the flow back to axial, to meet the downstream turbobrake's design inlet condition. The turbobrake is mounted on the same shaft as the turbine, and matches the turbine power when running at design speed. Thus, its purpose of maintaining constant turbine speed through a run can be achieved, see Goodisman et al. [34].

A typical run consists of accelerating the turbine to design speed, while the test gas is being isentropically compressed to the desired pressure and temperature by a light piston, driven by a higher pressure upstream. When the desired conditions are obtained, the gas is released into the working section, by means of a fast acting plug valve. A typical test results in about 500 ms with steady conditions.

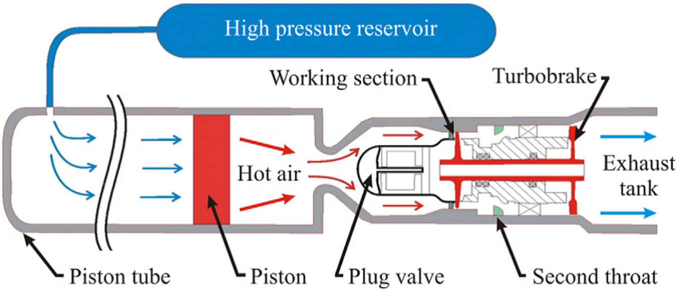


Figure 3.3.1: *Schematic of the OTRF.*

Table 3.3.1: OTRF nominal conditions.

Parameter	Value
Re based on NGV axial chord	1.61×10^6
Ma at NGV exit	0.879
Speed [rpm]	9500
Mean inlet T_0 [K]	444
Mean inlet p_0 (bar)	4.6
Gas to wall temperature T_g/T_w	1.52
$\dot{m}$ [kg/s]	17.4

3.3.1 The FACTOR ITD design

The new ITD configuration has been designed using the GKN Aerospace Engine Systems in-house design tool, VolVane, which contains a 3D Euler solver. To determine the targeted aerodynamic exit condition of the ITD, a throughflow analysis was performed at Rolls-Royce Plc using their Q263 code, ahead of designing the ITD with vane. The throughflow analysis provided ITD exit profiles in terms of radial distributions of flow angles, static pressure and Mach number. These, along with geometric constraints, were used as targets in the design process. The geometric constraints were put together so that the final design would be representative for an engine component, although still

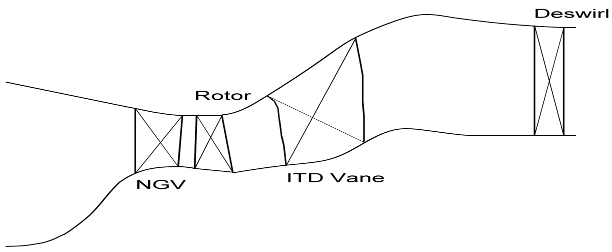


Figure 3.3.2: *Meridional view of the MT1 stage and ITD.*

being robust to off-design conditions, without flow separation, shocks and with low total pressure losses. This included measures such as inlet to outlet area ratio, ITD length to inlet height ratio, radial offset to ITD length ratio. Also, there was a desire to keep a few key parts in the facility to reduce the cost of this re-build, which introduced some minor constraints to the final design. The proposed designs (from VolVane) were evaluated using 3D CFD in ANSYS CFX version 12.1, with a fully resolved mesh in the order of 2.2×10^6 number of nodes, the $k - \omega$ SST turbulence model and assuming a fully turbulent flow. Radial profiles based on previously measured and published data from Beard et al. [35], were used as the inlet boundary conditions, to set the flow angle, total temperature and total pressure distributions. A radial static pressure profile was used at the outlet. The design aimed to meet the set ITD exit targets from the throughflow analysis, while also reducing the risk of separation, peak Mach numbers and total pressure loss. A meridional view of the new configuration, including deswirl, and the MT1 turbine stage is found in Figure 3.3.2. The final design was also evaluated at off-design conditions, to prove its robustness, by varying the radial profile of the ITD inlet swirl angle with ± 10 degrees. The results showed no flow separation within the ITD and the flow was turned to the desired ITD exit swirl angle distribution.

With this new ITD a new deswirl vane design was necessary. Two different designs were evaluated using 3D CFD in ANSYS CFX with different vane counts and chord length. Both performed in accordance with set targets, delivering an axial flow downstream and choking the flow within its passage when introducing a plate at the trailing edge. To increase the axial distance between the ITD vane trailing edge and deswirl vane leading edge, the shorter design with a higher vane count was chosen. This introduces a larger flexibility in accessing the area downstream of the ITD vane to for example traverse a probe.

4 Instrumentation

This section includes a description of the instrumentation used in both facilities, and the calibration of said instrumentation.

4.1 Chalmers LSLS Turbine Facility

While running the facility, several measurements are continuously being conducted to monitor the current operating point and surrounding conditions. This includes measures such as turbine speed and torque, hydraulic brake oil temperature, NGV inlet total temperature and pressure, static pressures across the 1.5 stage etc. The measurements are recorded every 2 s and used to determine whether the facility is performing in accordance with its design conditions and when the flow can be considered as steady. The latter is mainly determined by monitoring the change in the hydraulic brake oil temperature, when considered stable so is also the flow.

The flow measurements reported in the first paper attached to this thesis were conducted with static pressure tappings along the surface of the ITD vane and by the traversing of a seven-hole probe. The static pressure tappings were distributed along five heights of the vane (5, 25, 50, 75 and 95%), with more tappings where larger gradients are expected, such as around the leading edge. The instrumented vane was manufactured with stereolithography (SLA), with the pressure tappings built in. Plastic tubes were attached to each tapping and the recording was carried out with a Scanivalve mechanical multiplexer, connected to a 16-channel PSI 9116 digital pressure scanner with a measuring range of ±2500 Pa. The mean pressures were evaluated by averaging across 1000 samples acquired at a sampling rate of 500 Hz. The seven-hole probe is of an L-type shape, with a 2 mm head and individual distances between the holes of 0.5 mm and a tip half-cone angle of 30 degrees. The calibration of the probe was performed in an open jet flow at a velocity of 25 m/s. The probe is traversed by a three-axis traversing system (cylindrical coordinates), which is powered by three stepper motors, one in each axis direction. The traversing was performed across a two dimensional area covering an ITD vane pitch, i.e. 30 degrees, upstream and downstream of the ITD vane. The location of the measurement planes are indicated as dashed lines in Figure 3.2.2. Measurements were performed with a denser distribution close to the hub and shroud, to better resolve the larger gradients associated with these areas, especially close to the shroud. The data is acquired by the same digital pressure scanner as for the static pressure tapping measurements.

4.2 Oxford Turbine Research Facility

To monitor the performance of the OTRF while running, a set of standard instrumentation is installed and data is acquired for every run, to determine the quality of the run. This includes measures such as turbine speed, NGV inlet total temperature and pressure, NGV static pressure distribution along 50% height and endwall static pressures across the 1.5 stage. A tolerance is set for every individual measure, which the measurement

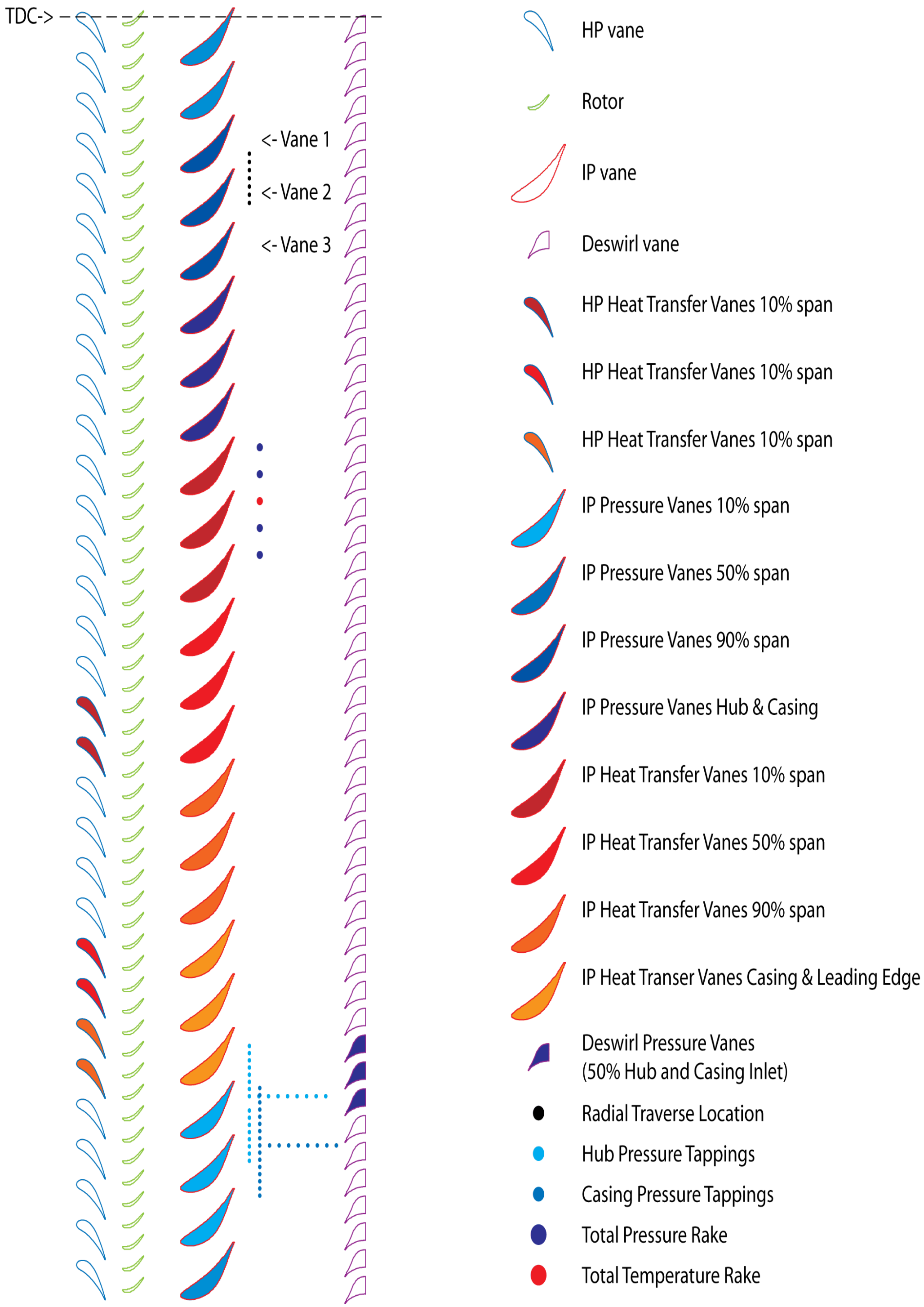


Figure 4.2.1: *Instrumentation plan within FACTOR.*

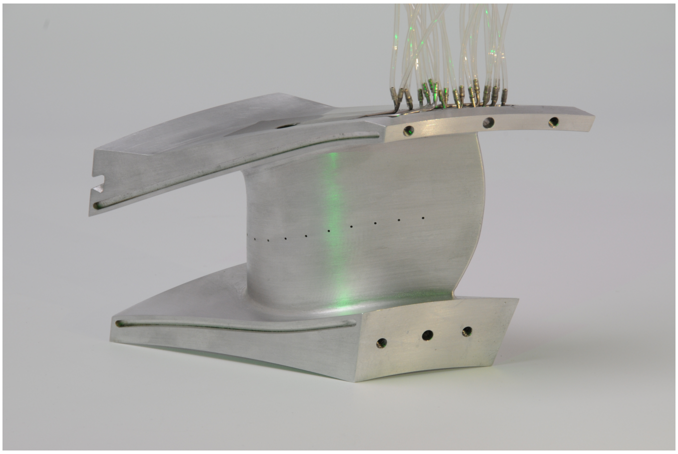


Figure 4.2.2: *ITD vane instrumented with static pressure tappings at 50% height.*

needs to meet for the run to be considered successful. Most of these measures have been set as standard in multiple research projects within the OTRF, and are considered a standardised way to determine the success of a specific run in the OTRF. A few measures, such as ITD endwall static pressures, are however added specifically for this project and their nominal condition are determined during commissioning of the new configuration.

Ahead of instrumenting the new configuration, an unsteady 1.5 stage CFD prediction was performed to guide the instrumentation. The prediction showed a significant dependence on the circumferential position of the ITD vane, due to a difference in vane counts between the ITD vane (24) and the upstream NGV (32). With this in mind, the same instrumentation was applied to three neighbouring ITD vanes to investigate the predicted clocking effect within the facility. A schematic of all the instrumentation installed in the facility for this measurement campaign is presented in Figure 4.2.1, although not all have yet been measured and analysed.

4.2.1 Static pressure tappings

To measure the static pressure across the surfaces within the ITD, a large number of static pressure tappings were drilled into the endwalls and vane. The tappings have a diameter of 1 mm and a pipe is glued to the outlet of the hole and their connection sealed. A plastic tube is then attached to the pipe and taken out of the facility to the acquisition system. Figure 4.2.2 shows a typical ITD vane with static pressure tappings at 50% height. In total, twelve vanes are instrumented with tappings, in four different set-ups, giving that three neighbouring vanes are instrumented in the same way. There are tappings at three heights (10, 50 and 90%) and circumferentially both on hub and shroud; upstream, in the passage and downstream of the ITD vane. There are approximately 20 tappings on each vane and about 40 on each vane pitch platform, giving in total 312 tappings, with a spacing between tappings of about 5 mm, measured as surface distance. There are also

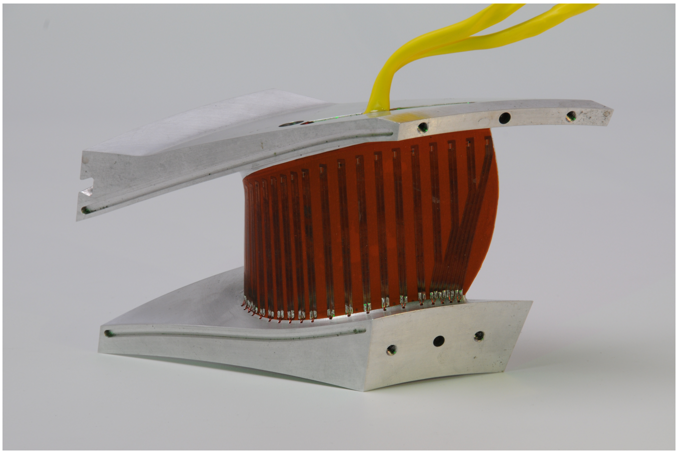


Figure 4.2.3: *ITD vane instrumented with TFHTGs at 90% height.*

a number of tappings installed further downstream of the ITD vane, at the exit of the duct, both circumferentially and axially. To make sure the deswirl vane is performing in accordance with what is expected, a deswirl vane has been fitted with tappings at 50% height as well as upstream of the vane, circumferentially on both hub and shroud.

4.2.2 Thin film heat transfer gauges

To measure the heat transfer along the surfaces of the ITD with vane, TFHTGs have been manufactured, annealed, calibrated and installed. This technique has previously been extensively used within the OTRF and has been developed over the years to its current standard, both in terms of manufacturing, data acquisition and post-processing. Doorly et al. [36] describes the theory behind TFHTGs, while Oldfield [37] describes the impulse response method used to derive the heat transfer signal from a measurement. The main benefit with this technique is the fast response time, allowing high frequency measurements to investigate the unsteady flow over a surface in a high-speed turbine facility.

A sketch of a TFHTG is shown in Figure 4.2.4 and an ITD vane instrumented with TFHTGs is shown in Figure 4.2.3. The design in this campaign consists of the aluminium of the ITD with vane, to which a 50 μm thick sheet of a polyimide (Kapton) is glued, giving the insulating layer a total thickness of 115 μm. The TFHTG and copper tracks is then deposited onto this. The TFHTG works by connecting it to a constant current power supply with copper tracks and wires. It is then fed a constant current and the voltage signal over time is recorded. By choosing a suitable material for the TFHTG, the measured voltage can be correlated to surface temperature, by a calibration coefficient. In this campaign, platinum is used as material of the TFHTG, since it has a linear change in voltage with temperature in the temperature range expected. Eq. 4.2.1 shows the relation between temperature and resistance within a material.

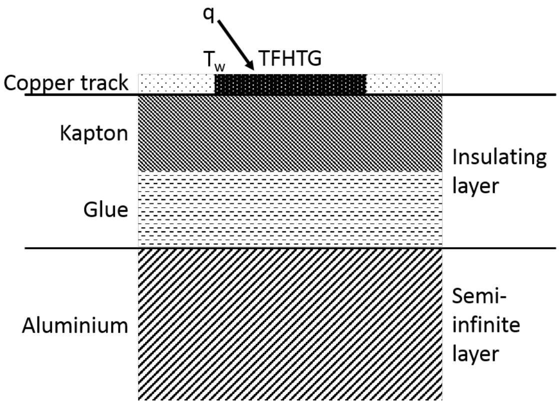


Figure 4.2.4: *Sketch of a TFHTG.*

$$R = R_{in}\left(1 + \alpha_{R/T}\left(T_w - T_{in}\right)\right) \tag{4.2.1}$$

If T_{in}= 0 °C, then R_{in} is the resistance at 0 °C, giving

$$R = \alpha_{R/T} R_{in} T_w + R_{in} \tag{4.2.2}$$

from which the temperature coefficient of resistivity, $\alpha_{R/T}$, can be determined through calibration.

To calculate the temperature signal based on the recorded voltage signal, Eq. 4.2.1 is rewritten with Ohms law, Eq. 4.2.3, which with a constant current is defined as Eq. 4.2.4. This gives Eq. 4.2.5 - 4.2.6, which when solved for the wall temperature gives Eq. 4.2.7. I.e., by recording the initial voltage over a gauge and temperature at the start of a run, along with the voltage signal over a run, the wall temperature history can be derived.

$$V = IR \tag{4.2.3}$$

$$V = I_{in} R \tag{4.2.4}$$

$$V = I_{in} R_{in}\left(1 + \alpha_{R/T}\left(T_w - T_{in}\right)\right) \tag{4.2.5}$$

$$V = V_{in}\left(1 + \alpha_{R/T}\left(T_w - T_{in}\right)\right) \tag{4.2.6}$$

$$T_w = \frac{V - V_{in}}{\alpha_{R/T} V_{in}} + T_{in} \tag{4.2.7}$$

To retrieve a heat transfer signal from the temperature signal, it is assumed that the penetration of the thermal pulse during a test is small, due to the short runtime.

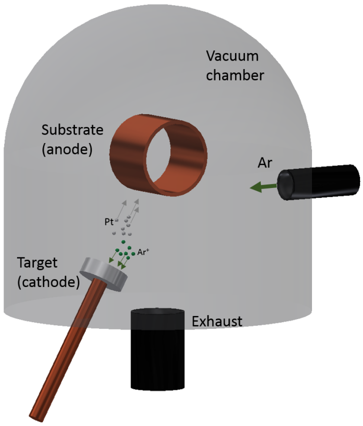


Figure 4.2.5: *Schematic of the method of sputter decomposition.*

The aluminium piece can therefore be assumed as semi-infinite, and the one dimensional heat conduction equation, Eq. 4.2.8, is used to derive the heat transfer signal from the temperature signal. An impulse response filter is created with the same length as the sampled temperature signal. By using a known heat transfer signal (for example a step function) and its corresponding temperature signal, an impulse response function can be found by deconvolving Eq. 4.2.9. This function, $h[n]$, is then used to derive the heat transfer signal by convolving the calculated temperature signal as in Eq. 4.2.9. The impulse response filtering technique is in more detail described by Oldfield [37], who also compared it with previous techniques with great success.

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{4.2.8}$$

$$q[n] = h[n] * T[n] = \sum_{i=0}^{N-1} h[i]T[n-i] \tag{4.2.9}$$

Manufacture

The TFHTGs are manufactured in-house. Two individual black/transparent masks are designed and printed, with the copper tracks (transparent) on one and the platinum gauges (black) on the other. Figure. 4.2.6 shows an inverted mask of the copper tracks to TFHTGs at 10% height. The former mask is used to etch out the spacing between copper tracks from a copper clad polyimide sheet with the desired

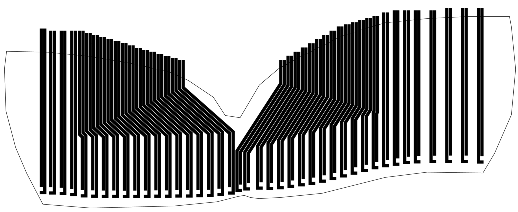
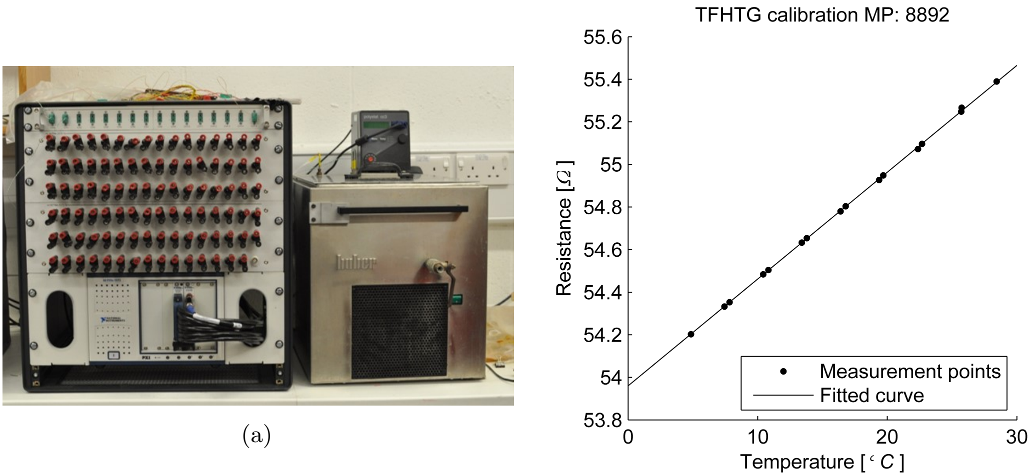


Figure 4.2.6: *Mask of the copper tracks for TFHTGs at 10% height.*



(a)

(b)

Figure 4.2.7: *The water bath and a typical calibration of a TFHTG.*

thickness of polyimide. The second mask is etched so that holes appear where the gauges are located. This is put on top of the copper tracks and platinum is deposited onto it, in the area where the gauges are to be located. When the second mask is removed, platinum is left only where desired.

The deposition of platinum is carried out with the sputter deposition technique. The polyimide sheet with copper tracks and the second mask on top is fixed onto a revolving wheel (anode) situated inside a vacuum chamber. The air inside the chamber is evacuated and a magnetron is used to create a plasma of charged argon particles close to a target of platinum (cathode). Positively charged argon particles are attracted to the negatively biased platinum target at a very high velocity. The collision between the argon particles and platinum target creates a momentum transfer and ejects atomic sized platinum particles that travels to the revolving wheel with the polyimide sheet. A sketch covering the technique is see in Figure 4.2.5.

Annealing

With this manufacturing technique, where platinum is deposited onto the copper clad polyimide at low temperatures, the TFHTGs are unstable before going through an annealing process. Meaning that the TFHTG is not showing a desired relation between resistance and temperature, due to a variation in R_{in} over time. By cycling the TFHTG between an oven at 80 °C and a freezer at −20 °C over a period of 3 days, its microstructure settles and the TFHTG is giving more accurate calibration.

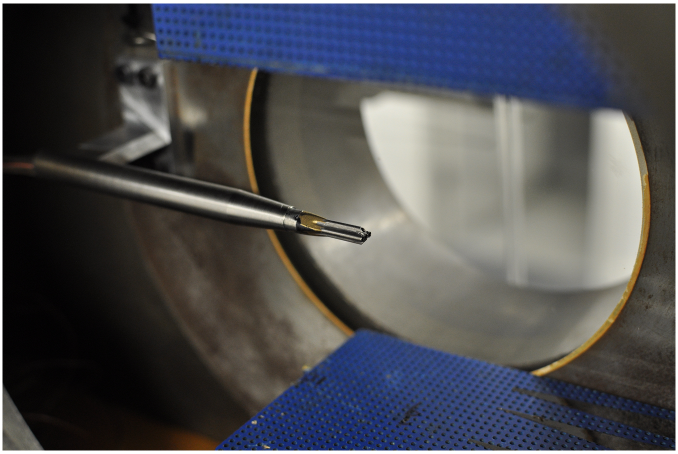


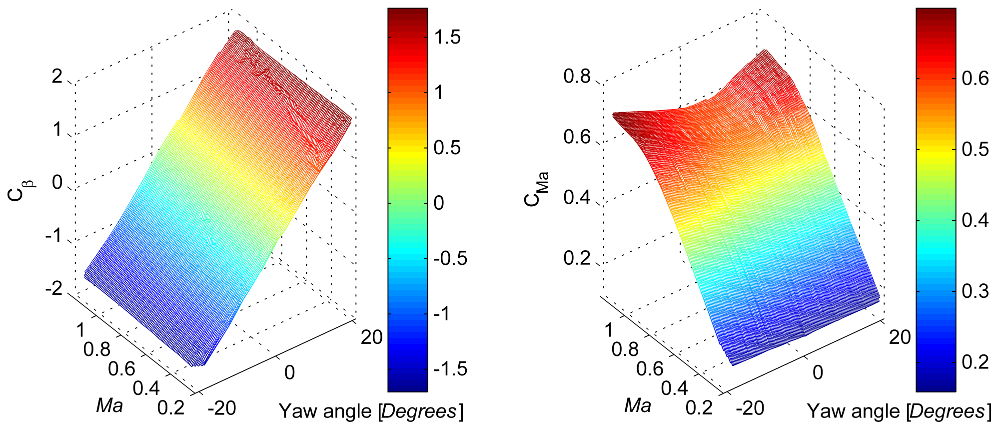
Figure 4.2.8: *Three-hole probe with two thermocouples mounted in the calibration tunnel.*

Calibration

The TFHTGs are calibrated in a fully automated water bath, see Figure 4.2.7a. Each TFHTG's resistance is measured at various temperatures, established by altering the temperature in the water bath. The temperature is measured both in the water and on the surface of the ITD vane, close to the TFHTGs, and a convergence criteria is set to determine when both the water and the gauge is seeing the pre-set temperature. The result of calibration is multiple data points to which a line is fitted and the temperature coefficient of resistivity, $\alpha_{R/T}$, is determined. An example of the results from calibrating one of the TFHTGs is shown in Figure 4.2.7b.

4.2.3 Probe

A three-hole probe with two thermocouples has been designed, manufactured and calibrated, to be traversed at the exit of the ITD. When used in the OTRF, the probe will be sitting in a carriage controlled by a Linear Variable Differential Transformer (LVDT) and traversed 1.5 ITD vane pitches. For each run, a single height will be traversed, travelling in the same direction as the rotor. Figure 4.2.8 shows a photo of the probe when mounted in the calibration tunnel. The probe consists of five steel pipes (⌀1.6 mm), out of which three make up the pressure probe and the remaining two include a 0.001 in k-type thermocouple each. Different mounts have been manufactured, to hold the probe in the calibration tunnel and OTRF. Plastic tubes are attached to the back of the probe to carry the pressure measurements outside of the facility to acquisition systems, along with the wires from the thermocouples.



(a) (b)

Figure 4.2.9: *Results from calibrating the three-hole probe. Distribution of C_β (a) and C_{Ma} (b) over the ranges of yaw angles and Ma calibrated within.*

Calibration

The three-hole probe was calibrated in the in-house 9" $-$ *by* $-$ 3" facility, which has been used for similar calibrations before. It is a partially-closed-loop ejector driven transonic wind tunnel. The facility's name stems from the simple fact that the test section is 9 in by 3 in large. The height of the test section is however variable, and a two dimensional perforated nozzle was used in this calibration. The total pressure within the facility is measured with a Pitot probe upstream of the inlet contraction. Static pressure measurements were taken on the sidewall at the axial position of the probe tip, as well as 10 mm up- and downstream. The probe was calibrated in the range of ± 20 degrees, with steps of 0.5 degrees, in the yawing plane and Ma between $0.2 - 1.2$. Since it is a three-hole probe it was only calibrated for a single pitch angle, 0 degrees, although spot checks were performed at other angles to determine its sensitivity. The yaw angle was changed in between runs by manually turning the probe in situ. The Ma was altered during a run, by partially closing a valve regulating the mass flow through the tunnel. For a run to be considered acceptable, enough time must be left in between closing the valve for the Ma to become steady.

To analyse the calibration data acquired, it is transformed into the non-dimensional parameters defined in Eq. 4.2.10 - Eq. 4.2.13, stated in Povey et al. [38] and Main et al. [39]. The fact that the parameters are non-dimensional gives that the calibration is independent on the total pressure, p_0, in the facility, which is necessary since it is significantly lower in the 9" $-$ *by* $-$ 3" than in the OTRF. The acquired data is gathered in a calibration matrix, that simply works as a look-up table, to which measurements will be compared to determine the measured Ma and flow angle. Figure 4.2.9a shows the distribution of C_β within the range of Ma and yaw angles the probe is calibrated. The calibration is shown to be fairly smooth, except for an area at low Ma and high positive yaw angles where a sudden drop is visible, from the otherwise smooth plane. A number of repeat runs have been conducted for these points with unchanged results, giving that it is likely to be due to a slight asymmetry of the probe.

$$C_\beta = \frac{p_a - p_c}{p_b - 0.5\,(p_a + p_c)} \tag{4.2.10}$$

$$C_{p_0} = \frac{p_0 - p_b}{p_b - p_{avg}} \tag{4.2.11}$$

$$C_{Ma} = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{p_{avg}}{p_b}\right)^{\frac{1-\gamma}{\gamma}} - 1\right]} \tag{4.2.12}$$

$$p_{avg} = \frac{p_a + p_c}{2} \tag{4.2.13}$$

4.2.4 Other Instrumentation

Other than the instrumentation mentioned above, this configuration has also been fitted with Pitot probes at the leading edge of one ITD vane at five different heights (15, 25, 50, 75 and 90%) to measure the total pressure into the ITD. There are also total pressure/temperature rakes positioned at the exit of the duct at five circumferential locations covering two ITD vane pitches (30 degrees). Each rake consists of eleven Pitot probes/thermocouples equidistant between the hub and shroud.

4.2.5 Acquisition System

To record the measured data, the following acquisition set-up has been used:

- Pressure measurements: Low speed dedicated A/D converter from National Instruments with Sensym pressure transducers, calibrated using a dead-weight pressure calibration system. Calibration being very close to the nominal value supplied by the manufacturer.

- Low speed TFHTG: HTA3 electronics manufactured by Monitron and low speed A/D system from National Instruments.

- High speed TFHTG: HTA3 electronics manufactured by Monitron and high speed A/D system from National Instruments.

- Thermocouples: Thermocouple cold junctions' standalone within A/D converters.

- Traverse movement: Voltage signal from LVDT.

5 Concluding remarks

This thesis presents two experimental investigations in two different facilities. A numerical comparison is included for both.

A new ITD configuration with a low turning vane was installed in the Chalmers LSLS Turbine Facility and aerodynamic measurements, including surface static pressure distributions on the vane and area mappings of flow angles, total pressure and velocity upstream and downstream of the vane. The experiments were conducted with three different ITD inlet conditions, with varying swirl angle. The results proved the design to be robust in terms of delivering a similar flow at the outlet of the ITD, no matter the variation in inlet flow angle. Loss regions and difficulties in predicting the tip gap flow is discussed. A fairly good agreement was found with the CFD predictions with areas of misalignment discussed.

A new ITD configuration with a low turning vane was also installed in the OTRF. An extensive amount of instrumentation has been designed, manufactured and installed to establish a well-defined test case, to which CFD predictions can be validated. The facility is commissioned to its operating point and first measurements are presented, including surface static pressure and Nusselt number distributions along the ITD vane surface. The results included show a clear dependence on the circumferential position of the ITD vane relative to the NGV, as predicted in the pre-test unsteady 1.5 stage CFD. A comparison with CFD predictions is included and the difference with the experimental results discussed, which is partly believed to be due to the pre-test nature of the predictions, i.e. not having the same boundary conditions as in the experiment.

5.1 Future work

The continuation of this project includes further measurements within the OTRF. The data already collected will also be further investigated, such as the unsteady heat transfer measurements conducted on the ITD vane surface, to further understand the phase averaged flow structures entering the ITD and its effect on the surface heat transfer. Future measurements will include three additional inlet conditions, i.e. temperature distortion, swirl and clocked swirl (relative to the NGV). The temperature distorted inlet condition includes circumferential and radial variation in temperature, developed and described by Povey et al. [40, 41]. The swirl will be provided by a combustor-representative swirl simulator, developed and described by Qureshi et al. [42]. This can also be rotated with respect to the NGV, to provide the clocked swirl inlet condition.

6 My contributions

6.1 Paper 1

In the first appended paper I participated in the experimental measurements and analysis of the experimental results. I was also the main contributor to writing the paper.

6.2 Paper 2

In the second appended paper I participated from the beginning, as stated below:

- Design of new ITD configuration and deswirl vane
  - 3D CFD evaluation of each individual design.
- Instrumentation
  - Design and calibration (when necessary) of TFHTGs, pressure tappings, three-hole probe, rakes.
- Commissioning
  - Evaluation of measurements to determine the operating point.
- Measurements
  - Evaluation of measurements.

The manufacture of hardware and instrumentation has been performed by technicians at University of Oxford and externally. The running of the OTRF and data acquisition is performed by test engineers. I was also the main contributor to writing the paper.

6.3 Additional work

Some time has also been spent to the work included in Rojo et al. [43], where my contribution included the CFD work and part of the experimental set-up ahead of measurements.

6.4 Division of time

The time spent on research during this period time has roughly been divided as follows:

- Paper 1: Chalmers activities – 20%
- Paper 2: Oxford activities – 70%
- Additional work: Chalmers activities – 10%

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