FULL ANNULAR COMBUSTION RIG TESTING WITH HIGH-PRESSURE TURBINE NOZZLE GUIDE VANES

Carsten Clemen, Jerrit Daehnert, Benno Wurm, Knut Lehmann, Erik Janke
Rolls-Royce Deutschland Ltd. & Co. KG, Eschenweg 11, 15827 Blankenfelde-Mahlow

Abstract

Future aero-engine development programmes are facing significant challenges with demanding development schedules and ambitious technical performance requirements. Hence, it is crucial a) to be capable to design the different subsystems like compressor – combustor – turbine in an integrated way, and b), to enable testing of critical features as early as possible, in realistic environments and ideally upfront of any engine test. In addition development and validation efforts need to be optimized in terms of time and cost.

The hottest interface in the engine core is located between the combustor and the high pressure turbine, where the high temperature flow field at the combustor exit interacts with the nozzle guide vanes. In order to predict combustor and turbine component life and turbine performance correctly, this interface has to be designed interdisciplinary using complex computational fluid dynamics (CFD) models.
Engine thermal paint and type testing are usually used to validate the design of this interface. Both tests only deliver limited data at an advanced stage of a development programme. Hence the decision was taken to establish a new method of validation for a) validation of the CFD modelling capability, and b), to measure more and more accurate data on the interface. Both aspects can be addressed by using full annular combustion rig testing extended by the possibility of having a full ring of nozzle guide vanes downstream the combustor installed into the rig.

Partly funded by the European Framework 7 programme Lemcotec an existing Rolls-Royce full annular combustor rig was improved such that it can carry nozzle guide vanes downstream of the combustor utilizing real engine hardware. This rig upgrade was designed together with FTT Deutschland. It was built, commissioned and tested to engine representative thermal paint test conditions and delivered validation data of very high quality, thereby enabling a direct back to back comparison to engine thermal paint data.

This new rig extends the current capability of Full Annular (FANN) rig testing from the combustor specific elements like aero-thermal performance as well as gaseous and particulate emissions, thermo-acoustic characteristics and combustor temperatures to the understanding of the interaction with the downstream high pressure turbine.

This will enable Rolls-Royce in the future to prove new designs with faster turn-around times and testing of multiple configurations upfront any engine development programmes providing valuable, early test data. The advantage of this approach is to enable early testing and hence down-select e.g. between different nozzle guide vane cooling schemes. This represents a significant step towards a "right-first-time" design into future products.

1. INTRODUCTION

Although significant improvements have been made in the field of combustion modelling capabilities, the development of low emission combustion technologies will require substantial experimental and validation efforts to meet future legislative requirements for gaseous and particulate emissions. In general, new aero-engine technologies have to be validated to TRL6 before they can be introduced into a new product. Since a TRL6 validation at engine level requires a demonstrator engine and thus a significant level of investment, combustion testing to a TRL5 to 6 is preferably done on rig level [1, 2]. For combustion technology development this final demonstration on component level corresponds to full annular (FANN) combustor testing, with combustor hardware being close or possibly identical to engine hardware standard [2]. One key element to validate the combustion subsystem is to understand its interaction with the downstream high pressure turbine. The temperature field downstream the combustor exit at the inlet to the nozzle guide vane is determining the heat load on the turbine vanes and blades which is required to design the turbine cooling to achieve the required turbine life and to ensure a safe turbine operation. Since the turbine nozzle guide vanes have an upstream effect on the combustor flow field, the only test setup to measure the correct temperature pattern is to implement the nozzle guide vanes into the full annular combustor rig or to perform a thermal paint test at engine level. This gives the opportunity to directly measure wall temperatures and pressures on end walls and vane leading edges and to derive the required information to validate and improve the turbine design and the design methods.

2. COMBUSTOR-TURBINE INTERACTION

The interface between combustor and HP turbine is essential for both performance and life of the entire HPT module. Whilst the optimisation of the HPT aerodynamics and cooling configuration for a well understood combustor exit flow field is already a complex topic, designing a robust HPT for a not yet fully verified combustor exit flow field is one of the major challenges in modern aero-engine designs.
In order to address the interaction aspects of the combustor and the downstream HP turbine, significant efforts have been directed towards improved understanding, modelling, designing, measuring and testing of parameters affecting this interface in the recent years within Rolls-Royce. A series of state of the art experimental facilities has been established, ranging from low TRL rigs to rigs capable of delivering aerodynamic aspects of the Combustor-Turbine Interaction (CTI) up to TRL6. For example, the TRL4 capable Large Scale Turbine Rig (LSTR) at Darmstadt University, features a combustor simulator that delivers realistic inlet swirl conditions [3, 4]. Moreover, the adoption of an existing high TRL rig for determining HPT vane capacity with metal temperature measurement capability in a first step and with a combustor exit flow simulator in a second step [5] is a significant step towards quick assessments and modifications of HPT vanes to simulated traverse effects. Lastly, the tests planned in the new high TRL rig facility described in [6] will aid designing more robust HPTs due to the capability of testing at different HPT inlet conditions and varying relative positions of Combustor exit flow simulator and HPT vane leading edges.
The experimental knowledge captured in these low and high TRL rig tests as well as numerical tools developed are continuously incorporated into the industrial design processes towards new aero engines.

3. DESIGN OF A FANN RIG WITH NGV

To measure the interaction of combustor and downstream turbine components the task was to design and make a full annular rig build which features the nozzle guide vane downstream the combustion chamber in such a way that a) the NGV and combustor can be operated in engine representative conditions with regards to temperature and pressure, b) the NGV and combustor in hot operating condition are positioned to each other as in the engine, c) combustor and NGV engine hardware can be implemented and d) that the flow field downstream the NGV is engine representative although no rotor is installed downstream but a big rig exhaust ducting.
An existing full annular combustor rig representative for the current standard of Business Jet Engines developed by Rolls-Royce Deutschland was chosen and its structure was extended such that it can be equipped with nozzle guide vanes in a modular way.
To achieve this, a full blown mechanical and thermal design study had to be undertaken including extensive CFD of the flow field downstream the NGV including the exhaust duct geometry and the exhaust duct water cooling (Figure 1).

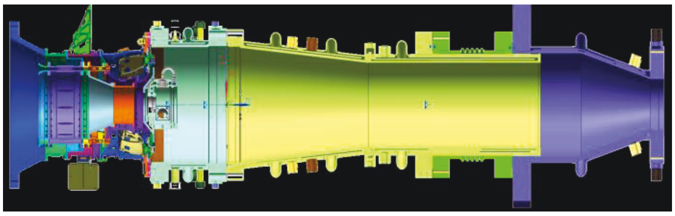

Figure 1: CFD domain of FANN rig with NGV installed in facility duct

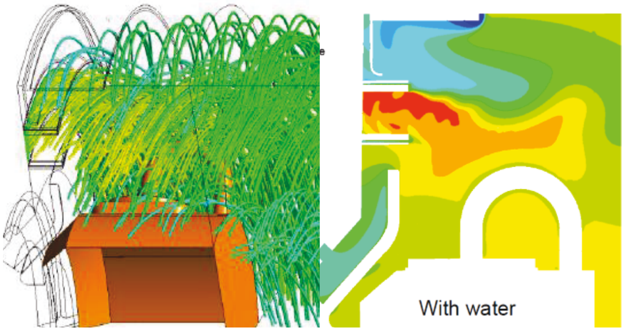

Figure 2: Flow stream lines and temperature in water cooled exhaust duct downstream the NGV

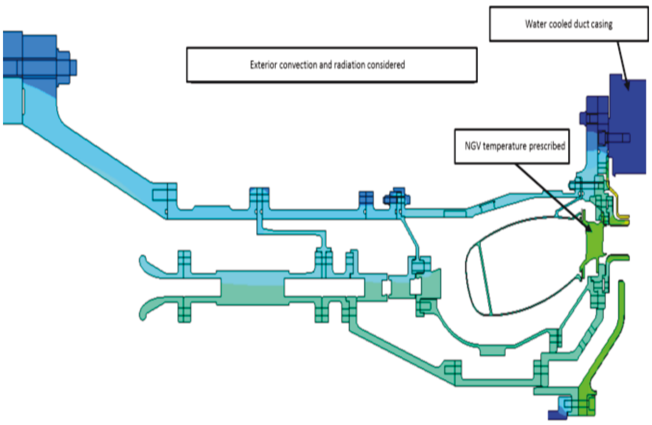

Figure 3: Thermal field

The result of the CFD and thermo-mechanical analysis was:

- Implementation of a dedicated geometry downstream the NGV to de-couple the NGV

flow field from the high swirling flow in the exhaust duct dump (Figure 2)
- Implementation of according cooling and heat shielding of the rig parts based on a thermal calculation (Figure 3)
- Implementation of adjustable devices to calibrate the cooling flow to the requirements of the turbine secondary air system
- Re-work of NGV fixation to enable an outer mounting of the NGV to transfer the torque load into the rig facility structure caused by the absence of a downstream rotor (Figure 4)
- Re-design of inner rig structure to carry huge pressure loads introduced by dumping the flow downstream into a facility exhaust duct
- Assembly sequence to achieve a modular built (Figure 5)

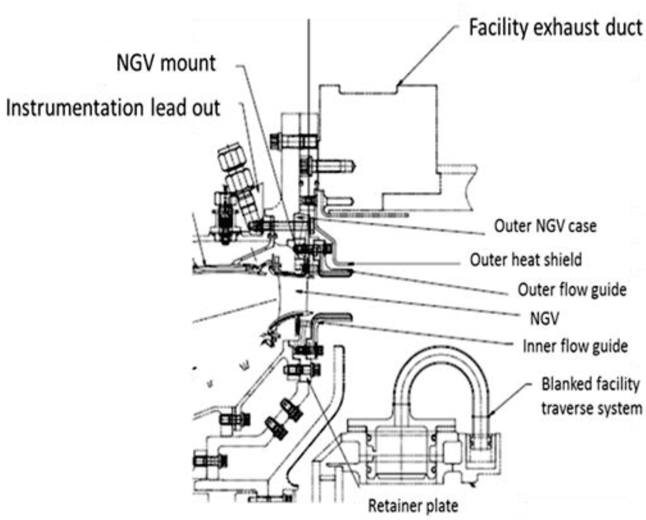

Figure 4: NGV build general arrangement

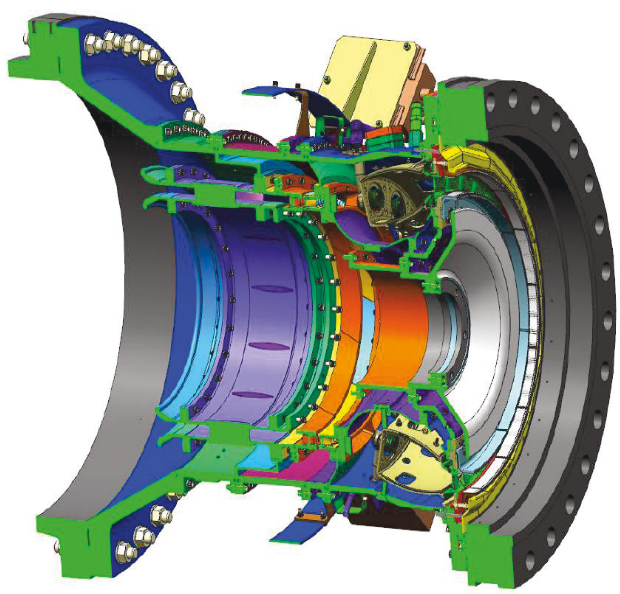

Figure 5: 3D model of FANN rig with NGV

4. INSTRUMENTATION AND BUILDS

4.1. Instrumentation

The rig featured specific instrumentation for the measurement with NGV in addition to the standard rig instrumentation for the operation of the rig (inlet temperature, inlet and outlet pressures):

- 24 static pressure tappings and 2 pressure rakes in combustion section.
- 18 pressure tappings on vanes.
- 4x3 pressure rakes at pre-diffusor exit.
- 6-off dynamic pressure traducers on the combustor outer casings and on the combustor liner to detect any vibrations during operation
- 17 thermocouples on combustor walls

Figure 6: Instrumented NGV

4.2. Calibration Build

Before testing the rig with NGV with combustion a calibration had to be carried out to ensure that the secondary air system is feeding the NGV with the intended cooling mass flow.

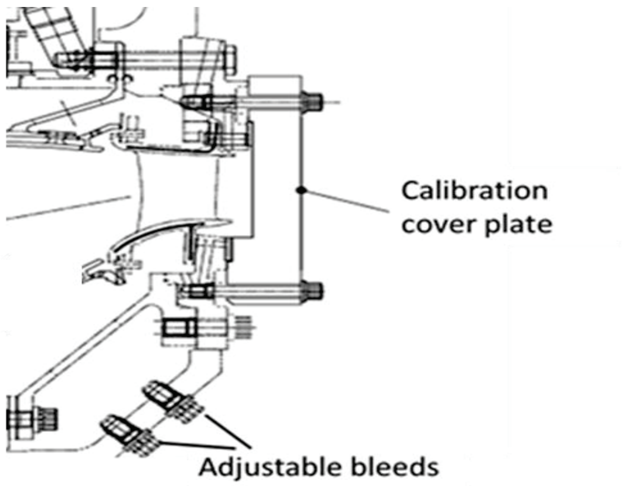

Figure 7: Calibration build general arrangement

To check this, the rig has been delivered in a calibration build assembly as shown in Figure 7 and Figure 8.

This build has a cover plate downstream the NGV which closes the exit flow area of the NGV to measure the flows through the combustor bleeds. The bleeds itself can be adjusted with individual bolts to fix the correct NGV cooling flows.

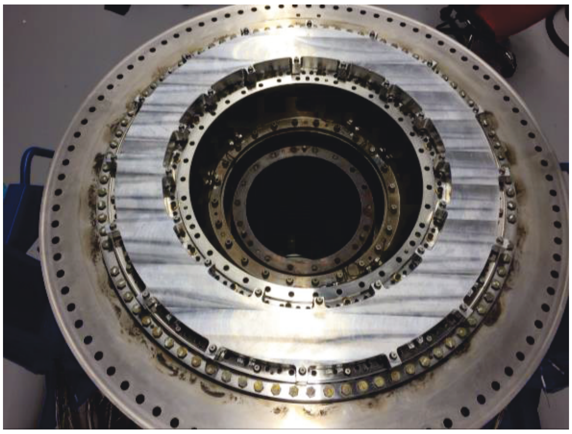

Figure 8: Calibration build – Looking from the rear onto cover plate

4.3. Thermal paint build

For the thermal paint build the calibration plates are removed and downstream the NGV internally cooled flow guides (Figure 9), which have been made out of the material C263 using Direct Laser Depositioning, are installed to realize a flow field downstream the NGV which has no back effect on the NGV flow and temperature field.
The general arrangement is shown in Figure 4.

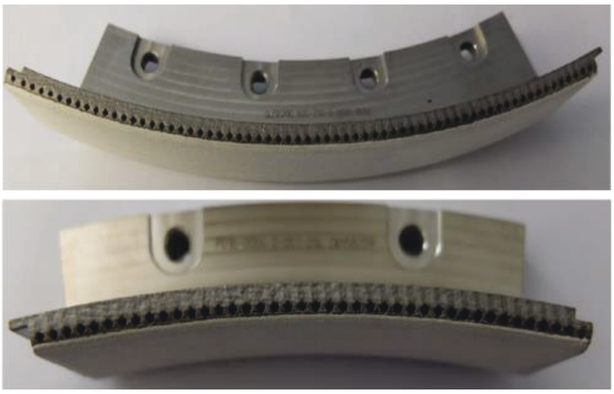

Figure 9: Flow guides

5. FULL ANNULAR TESTING

5.1. Calibration test

The calibration test (see Figure 10) was performed in November 2016 at the altitude test facility of the Institut für Luftfahrtantriebe (ILA) at the University of Stuttgart (Figure 11).

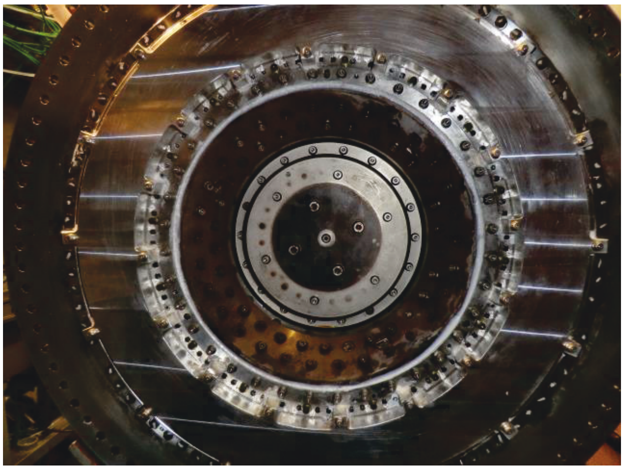

Figure 10: Calibration build installed in ILA facility

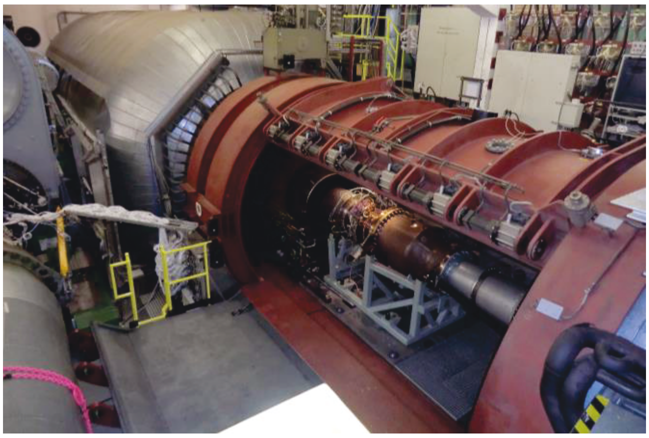

Figure 11: Full annular combustor rig in sub-atmospheric test facility at ILA Stuttgart
The calculated flows were achieved, so the rig was released fit for purpose for the thermal paint test.

5.2. NGV / Thermal Paint test

5.2.1. Thermal paint background information

The measurement of gas turbine component surface temperatures is restricted to a very few specialist methods, all of which having their own advantages and disadvantages. Currently, Thermal Paints are the only method available which allows a permanent record of temperatures to be made over the entire surface of a component when operated in a realistic engine environment.
The basic technique is very straightforward and entails the spray application of Thermal Paint onto the surface of a component, which can then be tested under engine or rig conditions. The resulting exposure to elevated temperature causes a chemical reaction in the paint to occur, resulting in a colour or texture change to the paint, which is permanent, and can be interpreted and allocated a temperature value.
Different types of Thermal Paint are available, with the “TP” family, typically measuring temperatures

higher than about 400°C up to a current maximum of 1300°C, with each paint type able to change colour or texture relating to seven temperature steps.
This technique, widely practised in Rolls-Royce in support of gas turbine development, requires a high degree of specialist capability, both in the paint application and particularly in the interpretation of resulting paint colour changes.
Without the requisite level of skill and experience, it is very easy to misinterpret the paint colour changes, or to lose the paint from the component during the test run and for these reasons, only a small number of people throughout Rolls-Royce carry out this task on a permanent, day-to-day basis.
The interpretation of Thermal Paint colour changes is made particularly difficult when a video scope inspection is made, as some colour changes are not so clear and the possibility to detect texture changes of the paint is of course impossible. This shortfall, coupled with areas of component, which are not visible by video scope, e.g. blade shrouds or shanks, should be taken into account when deciding between an engine full strip or a video scope read.
The Thermal Paints themselves are manufactured and calibrated by Rolls-Royce Derby, ensuring a high degree of quality control and a consistent product.

5.2.2. Method

All Thermal Paints were applied to the components listed below. The paint application for all combustor components was carried out in the Rolls-Royce Thermal Paint Laboratory in The following list gives an overview of all painted components, including their built-in positions:

Component	Thermal Paint	Intention
NGVs / 16off	On all annulus (hot-gas washed) surfaces On all annulus (cold-gas washed) surfaces	Measure metal surface temperatures
Outer Flow Guides / 16off	On all TBC coated surfaces	Measure gas surface temperature
Inner Flow Guides / 8off	On all TBC coated surfaces	Measure gas surface temperature

5.2.3. Test

Following Thermal Paint application and build process, the rig underwent a dedicated Thermal Paint test run at the RRUK Combustion Test Centre in Derby (UK) which was conducted in order to see the difference in NGV wall temperatures between this test and a comparable engine test in order to prove the feasibility of the FANN-Rig method including NGVs.
The thermal paint test was performed in February 2017 at the C06 facility in Derby, see Figure 12. The test was performed such that the rig was run to a typical engine steady state thermal paint condition (as also tested during engine development testing), and on this condition the rig was stabilized for a specified period of time to “record” the thermal footprint on the NGV vanes, the platforms and the flow guides. The test was carried out for a simulated high power operating point. The test was successfully run without any issues, and thermal paint results are of very good quality, see Figure 13.

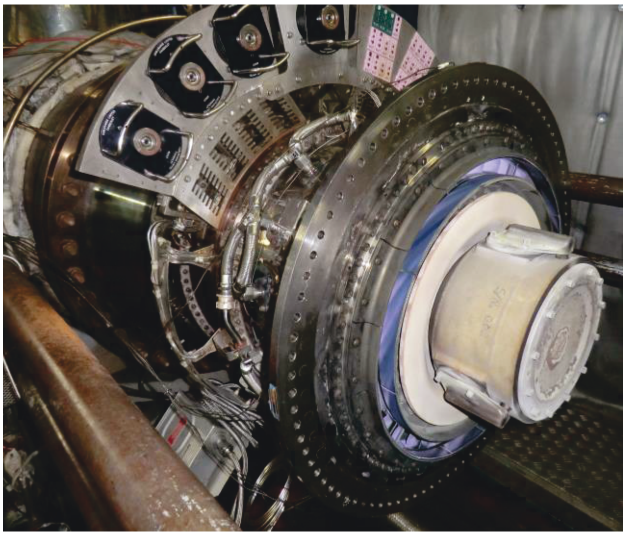

Figure 12: NGV rig installed into C06 facility

Figure 13: Thermal paint snapshot after test

5.2.4. Results

After the test run and subsequent cool down, the internal surfaces of the combustor were inspected and recorded by video scope, following which all painted components were disassembled from the rig and sent to the Thermal Paint Laboratory in Dahlewitz, where all Thermal Paint colours changes were interpreted and recorded. The NGV Build after removal from the rig is shown in Figure 14.

A visual inspection of the NGVs revealed a very good agreement of the thermal paint readings with (1) Rolls-Royce Engine Experience and (2) the predictive 3D Thermal models, which have been used to predict the surface metal temperatures of the vanes and platforms.

Figure 14: Thermal paint results NGV

An exemplary photograph of a painted and analysed pair of NGVs can be seen in Figure 15 and Figure 16. The markings made by the specialist are visible.

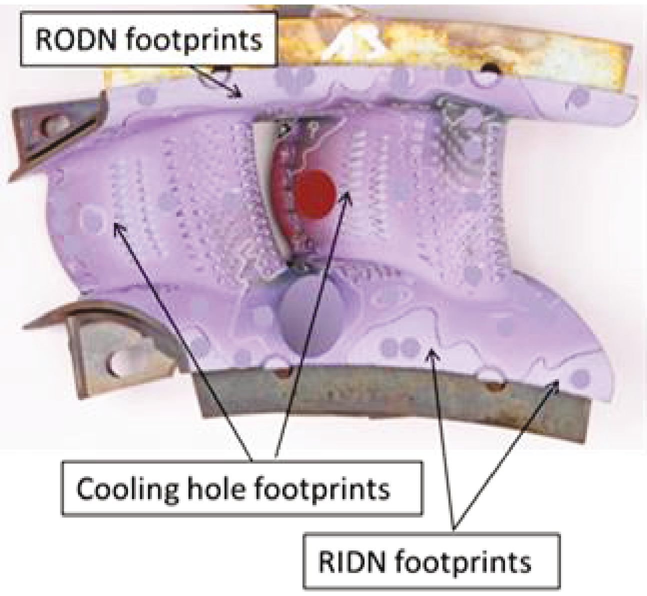

Figure 15: Thermal paint results NGV1 – Pressure side

The lines mark isothermal lines. Classified information had to be masked out. The following features could be identified from the Thermal paint analysis:

- Footprints of the RIDN/RODN cooling air jets on the NGV platforms.
- Hot spot locations and wall temperatures.
- Cooling air footprints from the wall cooling holes on the pressure and suction side of the vanes.
- Absolute wall temperatures within a definite uncertainty range.

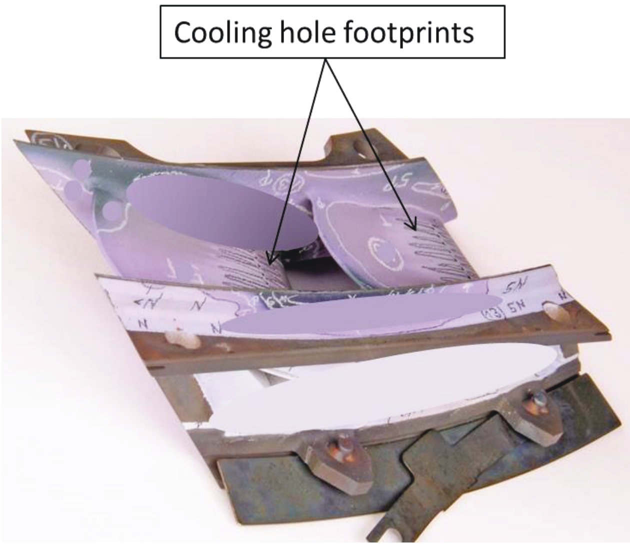

Figure 16: Thermal paint results NGV1 – Suction side

6. SUMMARY AND CONCLUSIONS

Some differences between the FANN-Rig NGV Build thermal paint readings and RRD engine experience can be found at the both rear platform overhangs (inner and outer). These regions are strongly affected by cooling air which had to be realised in different ways compared to an engine.

- The inner platform overhang in an engine is cooled by swirling rim seal flow where as in the FANN-Rig NGV Build this cooling air is missing the tangential velocity component. Hence, the heat transfer coefficients must be different between Rig and engine leading to higher metal temperatures in the FANN-Rig than in an engine.

- Usually the outer platform overhang in an engine is cooled largely by the seal segment cooling flow. This feature could also not be realized during the FANN-Rig test leading to the observation of higher metal temperatures in the rig compared to an engine run.

However, those differences could be reproduced with very good agreement utilising the 3D Thermal model by accounting for the different cooling of the rear platform overhangs applied.

The FANN-Rig NGV Build results are very promising. As intended the FANN-Rig NGV Build appears to give similar results as an engine test of the combustor – turbine interface. Localized features such as the Combustor Hot-Spot, RIDN and RODN jets thermal footprint are in same locations for FANN-Rig and Engine. The results are encouraging with regards to future use of this FANN-Rig method to substitute full scale engine test, such as a dedicated Engine Thermal Paint Tests, to investigate the combustor turbine interface.

7. ACKNOWLEDGMENTS

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8. NOMENCLATURE

3D	Three-dimensional
CFD	Computational Fluid Dynamics
CTI	Combustor-Turbine Interaction
DLD	Direct Laser Depositioning
FANN	Full Annular Combustor
HP(T)	High pressure (Turbine)
ILA	Institut für Luftfahrtantriebe
LSTR	Large Scale Turbine Rig
NGV	Nozzle guide vane
R&T	Research and Technology
RIDN	Rear inner discharge nozzle
RODN	Rear outer discharge nozzle
RRD	Rolls-Royce Deutschland
RRUK	Rolls-Royce plc
TBC	Thermal Barrier Coating
TP	Thermal Paint
TRL	Technology Readiness Level
UK	United Kingdom

9. LITERATURE

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