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GT36 TURBINE AERO-THERMAL DEVELOPMENT AND VALIDATION

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ABSTRACT

This paper describes the aero-thermal development and validation of the GT36 heavy duty gas turbine. The turbine which has evolved from the existing and proven GT26 design, consists of an optimised annulus flow path, higher lift aerofoil profiles, optimised aerodynamic matching between the turbine stages and new and improved cooling systems of the turbine vanes and blades. A major design feature of the turbine has been to control and reduce the aerodynamic losses, associated with the aerofoil profiles, trailing edges, blade tips, endwalls and coolant ejection. The advantages of these design changes to the overall gas turbine efficiency have been verified via extensive experimental testing in high-speed cascade test rigs and via the utilisation of high fidelity multi-row computational fluid dynamics design systems.

The thermal design and cooling systems of the turbine vanes, blades have also been improved and optimised. For the first stage vane and blade aerofoils and platforms, multi-row film cooling with new and optimised diffuser cooling holes have been implemented and validated in high speed linear cascades. Additionally, the internal cooling design features of all the blades and vanes were also improved and optimised, which allowed for more homogenous metal temperatures distributions on the aerofoils. The verification and validation of the internal thermal designs of all the turbine components has been confirmed via extensive testing in dedicated Perspex models, where measurements were conducted for local pressure losses, overall flow distributions and local heat transfer coefficients.

The turbine is currently being tested and undergoing validation in the GT36 Test Power Plant in Birr, Switzerland. The gas turbine is heavily instrumented with a wide range of validation instrumentation including thermocouples, pressure sensors, strain gauges and five-hole probes. In addition to performance mapping and operational validation, a dedicated thermal paint validation test will also be performed.

NOMENCLATURE

PO	Performance Optimized mode
XL	eXtended Lifetime mode
PDQ	Product development quality
VIGV	Variable inlet guide vanes
CFD	Computational Fluid Dynamics
TP	Thermal Paint
TLC	Thermo-chromic liquid crystals
SS	Suction side
PS	Pressure side
Eta	Film cooling effectiveness
Ma	Mach number
Nu	Nusselt number
p	Pressure

INTRODUCTION

To reduce the cost of electricity in today’s challenging power generation market and to minimise CO2 emissions, high all-round efficiency at both base-load and part-load operation is one of the key drivers in gas turbine technology development. With the introduction of new gas turbine products and/or upgrades, the market expectation is also to maintain a high level of reliability and availability. In this paper, the aero-thermal design and validation of the GT36 gas turbine, which has essentially evolved from the existing and proven GT26 design, is described. The GT36 gas turbine is shown by Figure 1.

The GT36 operates efficiently over a wide operating range, and it is also able to switch online between two operational modes, namely Performance Optimized (PO) mode, and XL (eXtended Lifetime) mode. This same operational concept is also available on the current fleet of the GT26 gas turbines. The PO Mode produces maximum performance and output, while XL allows service intervals to be increased, thereby reducing maintenance costs. To achieve high all-round turbine efficiencies, all four stages of the turbine consist of aerodynamically optimized aerofoil profiles and efficient cooling schemes. The turbine blade tips of the front stages and the rear stage shrouds have been further aerodynamically optimised to minimise over-tip leakage flows. Further additions include vane part count reduction to reduce the hot gas wetted area and trailing edge losses, which then also enables further optimization of the turbine cooling air consumption. Figure 2 shows the stage 1 and stage 3 vane and blade components.

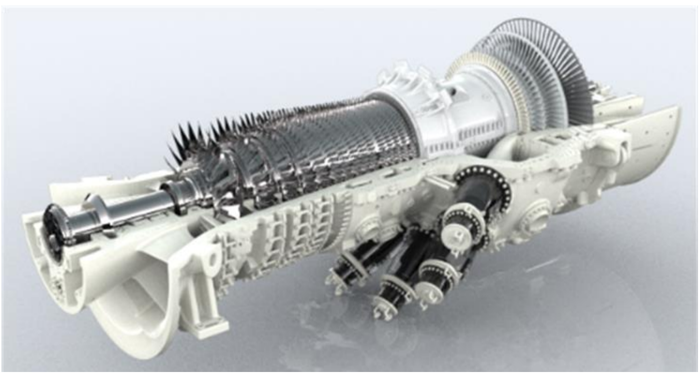
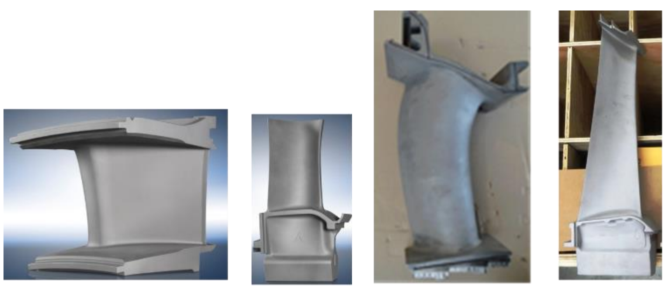


Figure 1 GT36 Gas Turbine



(a) (b) (c) (d)

Figure 2 Turbine components, (a) Vane 1, (b) Blade 1, (c) Vane 3, (d) Blade 3.

In this paper, the salient design features of the GT36 turbine are described, with respect to its aerodynamic and thermal design. The aerodynamic design is based on optimising the annulus flow path, using advanced high lift aerofoil profiles, thinner trailing edges, optimising radial and axial clearances and optimising the aerodynamic matching between the turbine stages. Special attention has been given to minimise aerodynamic and thermodynamic losses at the interfaces between the combustor and turbine and between the turbine and the exhaust diffuser. These design modifications have been achieved via the utilisation of high fidelity 3D multi-row computational fluid dynamics analysis tools, rig tests and engine tests. Similarly, the thermal design of the turbine vanes, blades and heatshields have been developed via the use of high fidelity CFD, semi-empirical experimental methods, rig tests and engine tests. The aero-thermal development of the turbine and the subsequent testing and validation of the complete turbine has been undertaken using the internal company product development quality (PDQ) process as shown by

Figure 3.

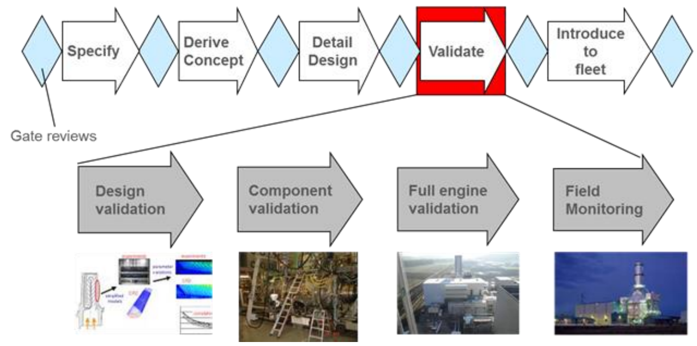


Figure 3 Engine development process and validation steps.

TURBINE AERODYNAMIC DESIGN AND VALIDATION

Based on the proven GT26 design [4] the aerodynamic design of the GT36 turbine has focused on optimising the annulus flow path, using advanced high lift aerofoil profiles, incorporation of thinner trailing edges, optimising radial and axial clearances and optimising the aerodynamic matching between the turbine stages. Special attention has also been given to minimise aerodynamic and thermodynamic losses at the interfaces between the combustor and turbine and between the turbine and the exhaust diffuser.

While the flow path annulus has been optimised to the GT36 operational regime, which includes higher air massflows and increased operating temperatures, the GT36 turbine design also accommodates for future retrofit requirements and upgrade scenarios. These design improvements have been achieved via the utilisation of the full suite of aerodynamic tools from one-dimensional mean-line and axisymmetric through-flow calculation to high fidelity 3D multi-row computational fluid dynamics analysis, which incorporates aerofoil film cooling and gas path leakages, as shown by Figure 4.

As an integral part of the design process, selected aerofoil profile sections were tested in high-speed linear cascade rigs for early feedback. To optimise the losses due to film cooling on the turbine front stages, representative aerofoils have been tested in a high speed linear cascade representing both static and rotating aerofoils. Both vane and blade aerofoils film cooling schemes were tested as individual film rows, in combinations and engine ready configurations. Different film cooling arrangements have also been tested, which allowed for the optimisation of the aerofoil aero-thermal behaviour in terms of both losses and film cooling effectiveness. Loss optimisation was achieved for both the static and rotating blades as shown by Figure 5.

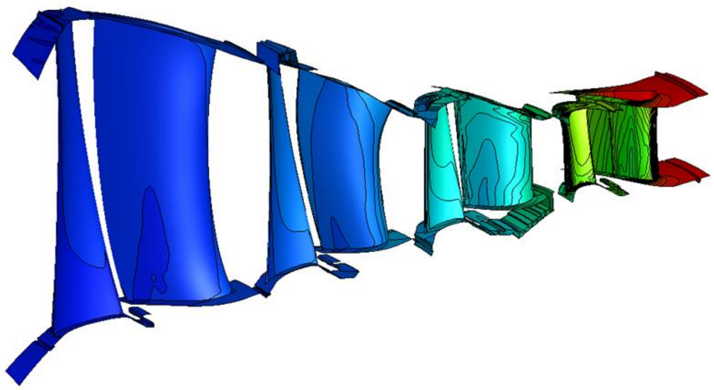


Figure 4 Turbine high fidelity multi row CFD aerothermal design and optimisation (contours of surface pressure – red and blue indicate respectively high and low values).

As part of the turbine aerodynamic optimisation, a smooth surface thermal barrier coating system has also been incorporated in the GT36 turbine. Extensive aerodynamic testing of the effect of the system was tested in a high speed linear cascade under varying operating conditions. As shown by Figure 6, the aerodynamic profile losses were reduced and this behaviour was observed for vane and blade profiles at engine representative Mach and Reynolds numbers. In the early development phase of the GT36, the smooth surface layer coating system was also extensively tested in the GT26 Test Power Plant in Birr, Switzerland [4], under all GT load conditions and for extended operational periods. These engine specific tests provided very positive feedback on the behaviour of the coating system.

Another key part of the GT36 turbine aerodynamic optimisation programme was to also minimise the over tip leakage losses from the shrouded blades of the rear stages and also from the unshrouded blade tips of the front stages. For the shrouded blades, a significant effort was dedicated to the minimisation of the overtip gas path leakage flows over the shroud tips and its interaction with the shroud cooling flows. This has been achieved by optimising the blade profile loading in the tip sections, improving the shroud fin designs, better clearance management at all operational modes and via the tangential ejection of the blade coolant flows through angled outlet ports in the shroud. Figure 7 shows the distribution of gas and coolant flows and velocity vectors on the third stage shrouded blade. The tangential coolant ejection between the shroud fins is indicated by Figure 7a.

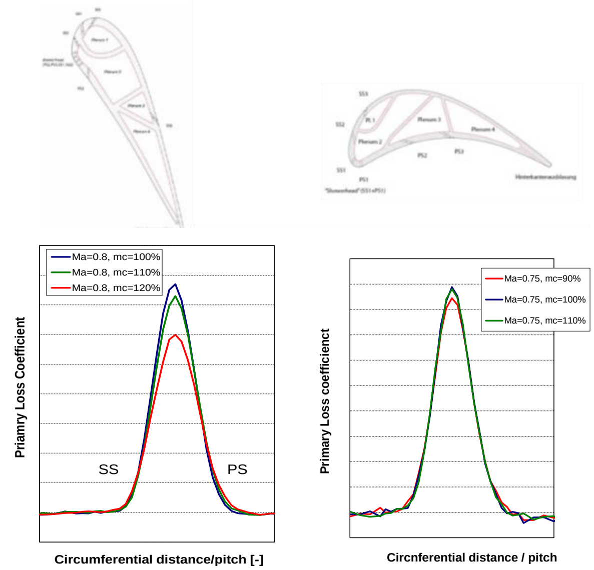
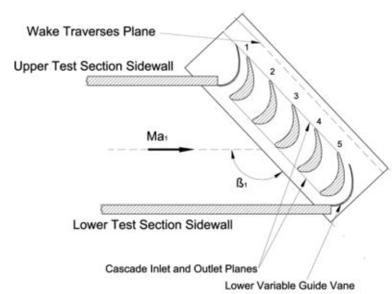
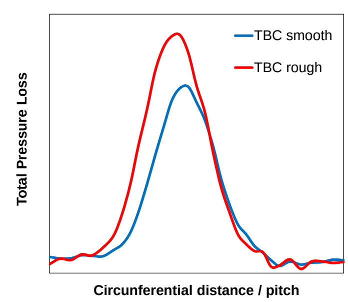


Figure 5 Aerodynamic loss optimisation for film cooled aerofoils.



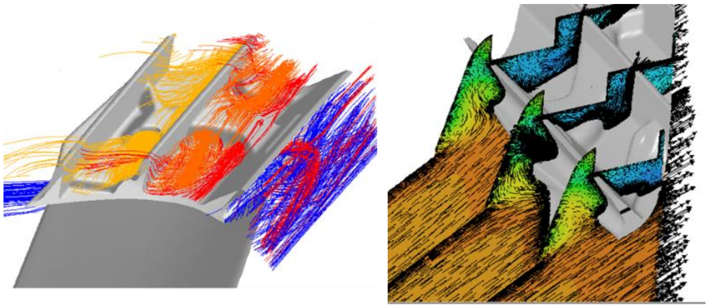
(a)

(b)



(c)

Figure 6 Smooth surface layer thermal barrier coating optimisation for aerodynamic losses. (a) High speed cascade rig, (b) smooth and rough aerofoil, (c) measured aero losses.



(a) (b)

Figure 7 Blade shroud aero thermal design optimisation, (a) streamlines of gas leakage flows (blue) interaction with coolant flows (red-orange), (b) gas path velocity vectors on three tangential planes on the blade shroud.

For the unshrouded front stages, the aerothermal development also focused on overtip leakage minimisation, improved clearance management at all operational conditions and the minimisation of the cooling air losses. For the front stage blade, extensive use was made of a high speed linear cascade, which was operated with engine specific aerofoil geometries and for a range of engine representative Mach and Reynolds number. Figure 8 shows the flow patterns on the blade surface including the tip and platform at engine representative conditions. Such tests allow for optimising and validating of the aerofoil profile characteristics. This is particularly valid for the profile loading near the blade tip sections, which together with the tip clearance and the tip geometry design essentially determine the over tip leakage flows. Figure 8b and c, also show the corresponding predictions of the flow structure around the blade tip with and without tip cooling flows. By using the combined results of numerical predictions and high speed cascade data, aerothermal losses related to blade tips were optimised and reduced through profile and film cooling design modifications.

Another area of aerodynamic optimisation was the interface between the can combustors and the turbine inlet. Due to the differences in the number of combustor cans and turbine vanes, the exit geometry of the combustor can picture frames can create aerodynamic losses at the turbine inlet. To minimise these losses, experimental testing of generic vane and combustor exit picture frame geometries were tested in a linear cascade to determine the aerodynamic characteristics and associated losses [15]. Figure 9 shows the vane and combustor interface, in which a movable picture frame with coolant discharge was arranged to move both circumferentially and axially. Aerodynamic measurement using five hole probes (5HP) and Laser Doppler Anemometry (LDA) systems were conducted for several tangential and axial positions of the picture frame. As shown by Figure 9, the aerodynamic losses vary depending on the combustor-vane arrangement. For the GT36 gas turbine, the combustor – vane interface losses were optimised using a range of experimental and numerical tests similar to that shown by Figure 9.

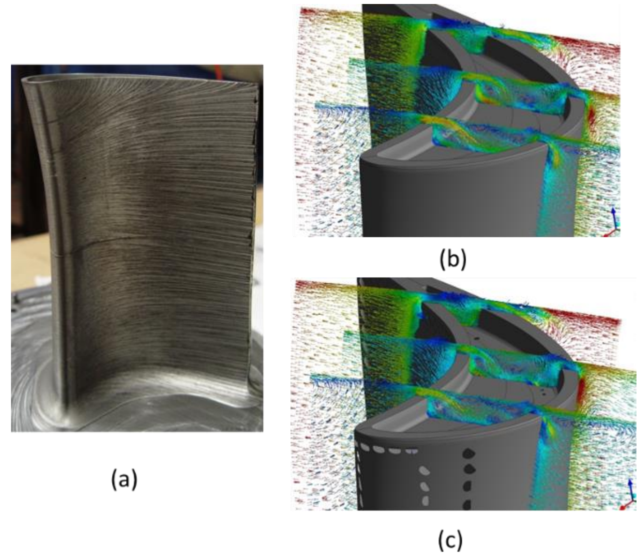


Figure 8 Blade tip aerothermal design, (a) high speed cascade oil flow visualisation, (b) predicted uncooled blade tip streamline and velocities, and (c) predicted cooled blade tip streamlines and velocities.

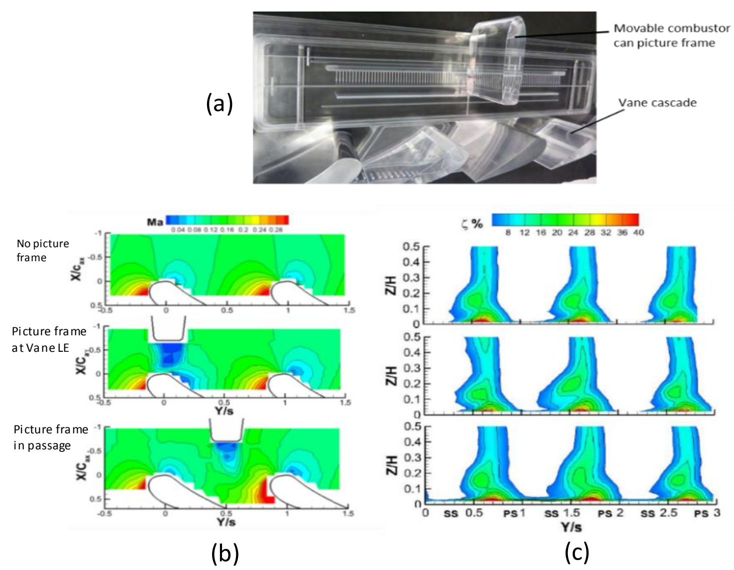


Figure 9 Optimisation of combustor exit picture frame axial and circumferential position (a) cascade test rig, (b) vane midspan measured Mach numbers, and (b) aerodynamic losses at vane exit.

TURBINE THERMAL DESIGN AND VALIDATION

For the turbine aerofoil designs, one of the major focus was on improving the blade and vane film cooling technology, and adapting them to the optimised high lift aerodynamic profiles. Additionally, all aerofoil internal cooling systems were developed with advanced and optimised internal cooling features. The latter included advanced pedestals combined with turbulators, 3D internal flow turbulators, optimised impingement cooling of leading edges and mid-chord aerofoil sections and the optimization of cooling air pressure ratios for all operational conditions. The thermal designs were also optimised to minimise temperature gradients and to provide more uniform surface temperature distributions on the aerofoil and platforms. Through this combination of both external and internal heat load management, the turbine cooling and leakage was substantially improved and minimized. Additionally, the vanes and blades thermal-mechanical designs were also optimised with respect to coolant consumption and lifetime for a wide range of ambient operational conditions, part-load and full-load operational regimes.

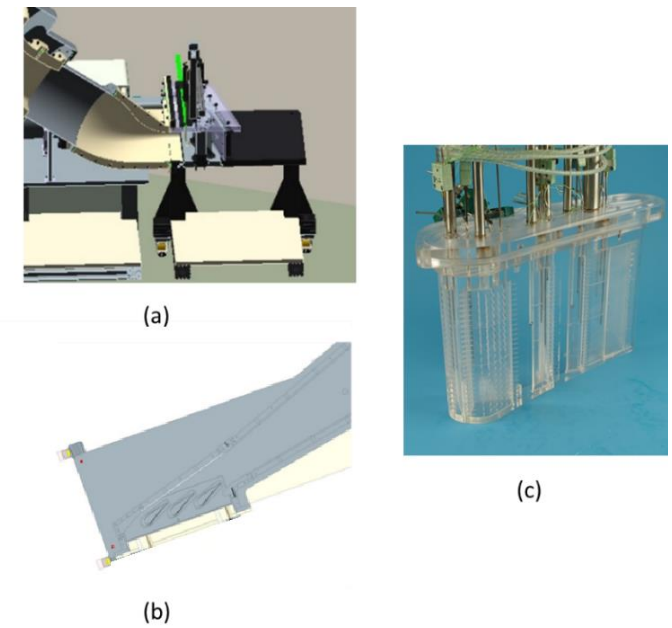


Figure 10 Aerodynamic and film cooling validation for first stage vane and combustor interface; (a) cascade side view with can combustor liner, (b) cascade and combustor liner sectional view, (c) vane film cooled Perspex test model.

External heat transfer

The thermal design and validation for the external heat transfer and film cooling effectiveness of the turbine first stage was conducted via both experimental testing and extensive numerical studies. For the first stage vane, a new high speed linear cascade was developed which also included the upstream combustor sequential liner as shown by Figure 10. With this arrangement, the inlet velocity and inlet swirl profile from the combustor to the turbine vane was simulated to engine representative conditions. Figure 10c also shows the Perspex model of the film cooled vane that was used for testing. The experimental testing in the cascade consisted of performing measurements of static pressures and conducting oil flow visualisation studies on the airfoil surfaces and platform surfaces. Measurements were conducted at design and off-design conditions. These pressure measurements were generally converted to isentropic Mach numbers for easy comparisons with CFD models. In addition to the aerodynamic measurements, the film cooling performances of the vane and blade were also conducted. The TLC measurement technique was used for all the film cooling measurements.

The measured Mach numbers, from the cascade test rig, of the vane midspan is shown by Figure 11. This shows that the agreement between the measurements and the predictions is excellent. The vane profile assessed in Figure 11 is similar to that indicated by [6], which was evaluated in a different cascade. The good agreements in the profile Mach numbers between measurements from two different cascade rigs and the predictions was a important validation step of the CFD models and methods used for the vane aerodynamics.

The vane midspan measured film cooling effectiveness is shown in Figure 12. The optimized first vane film cooling scheme shows a good coverage and provides sufficient cooling to the vane while maintaining a moderate consumption.

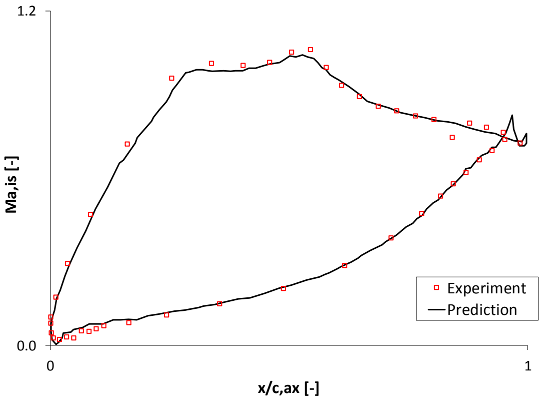


Figure 11 Vane oil flow visualisation on aerofoil and platform, and measured and predicted vane Mach numbers.

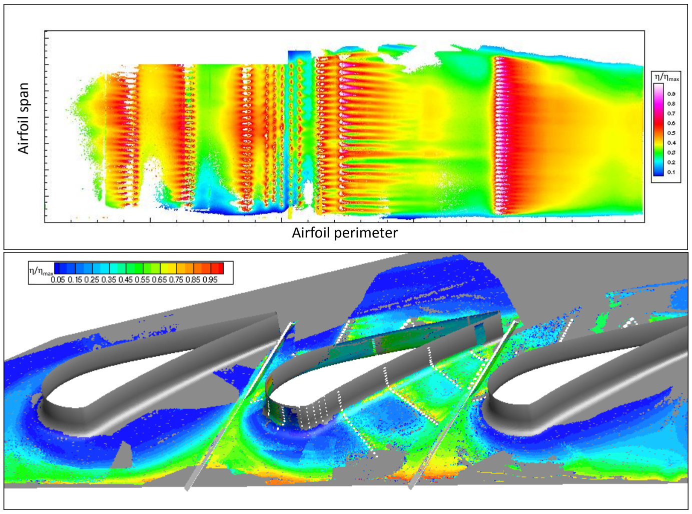


Figure 12 Measured film cooling effectiveness of vane aerofoil (top) and platform surfaces (bottom).

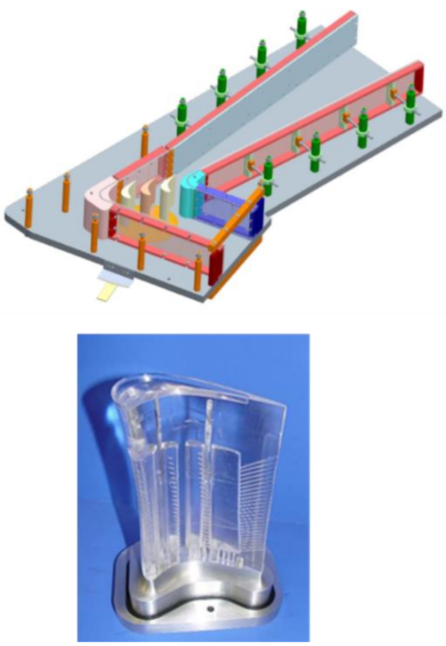


Figure 13 High speed blade linear cascade and blade film cooling test model.

In addition to the vane airfoil thermal design, the vane platform thermal design was also extensively developed. Figure 12 shows the film cooling layout on the vane platform and the measured film cooling effectiveness under nominal design conditions. The thermal design and validation of the blade shown by Figure 13, was also conducted in a similar way to the vane. A new cascade test facility was extensively utilised for the aerodynamic and film cooling design and validation of the blade. Oil flow visualisation studies were initially conducted at design operating condition in order to ensure key aerodynamic flow features were within expectations, as indicated by Figure 14.

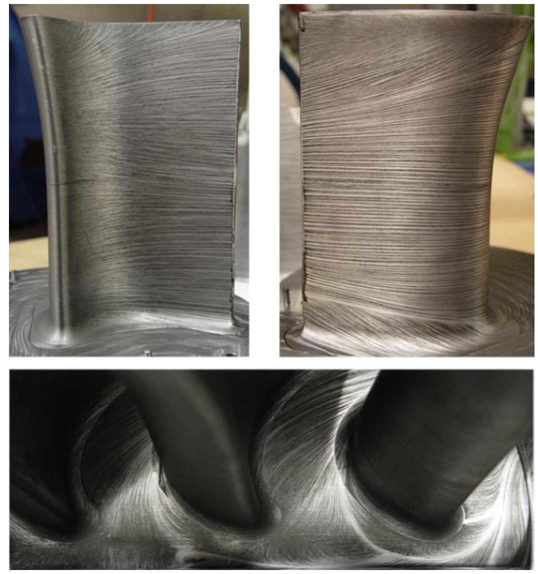


Figure 14 Blade aerodynamic and leakage interaction oil flow visualisation.

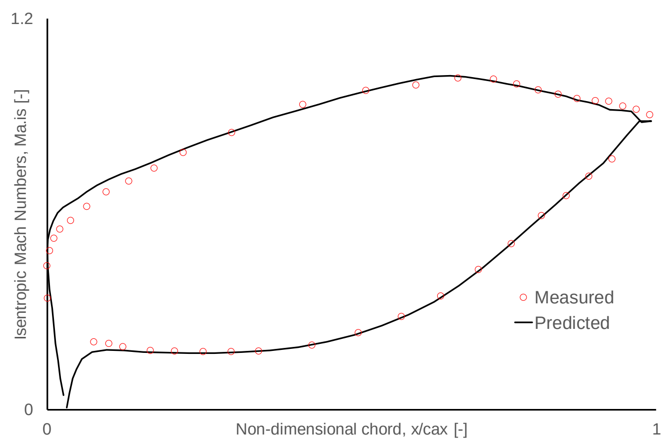


Figure 15 Blade midspan Mach numbers for design conditions.

The blade midspan Mach numbers for the design conditions, which are derived from measured static pressures around the blade profile, are shown by Figure 15. This shows that the agreement between the measurements and the predictions is excellent. In addition to the measurements of the pressure distribution on the blade airfoil, platform and tip, the film cooling effectiveness was also measured on the blade airfoil, platform and the entire blade tip. Measured film cooling effectiveness results compared well with design predictions on all areas of the blade.

Internal Heat Transfer

The thermal design of the vanes and blades has been further optimised starting from the proven design of the GT26. At a first generic level specific cooling features (turbulators, pedestals, impingement configuration) were numerically and experimentally investigated. Figure 16 shows a generic passage turbulator test rig which allows various turbulators and passages to be tested for internal heat transfer and pressure losses. Figure 17 shows the internal flow heat transfer for different turbulator designs in a very large aspect ratio cooling channel, which are described in more detail in [13].

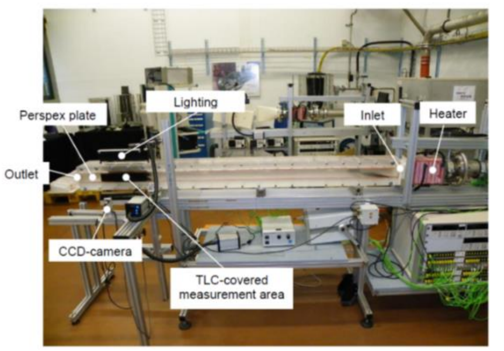


Figure 16 Internal flow test validation of heat transfer enhancement turbulators.

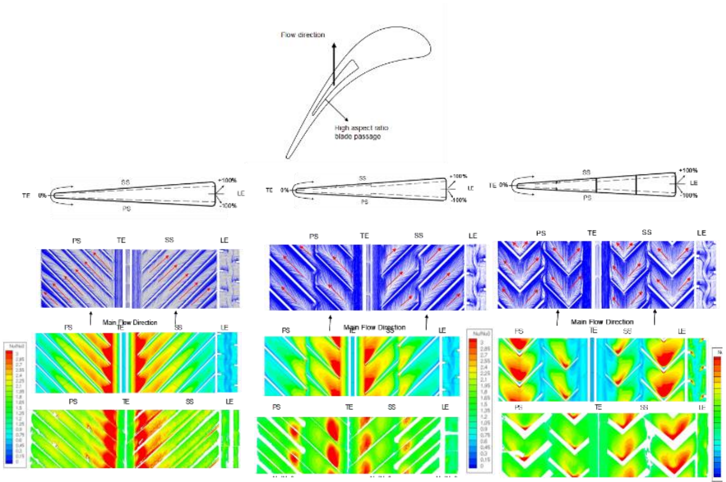


Figure 17 Internal flow heat transfer turbulator comparisons and validation with measurements and predictions [13].

The test facility for testing various aerofoil trailing edges pedestal designs is shown in Figure 18, which allowed measurement of both internal heat transfer and pressure losses. Figure 19 shows three different vane trailing edge designs which were tested and compared to CFD predictions, [14]. These feature tests were used to identify the most efficient cooling schemes that were at a second level integrated into the specific components.

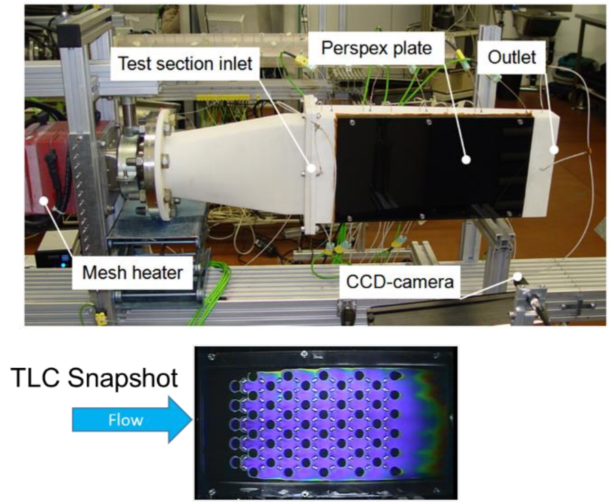


Figure 18 Internal flow test validation for pins and pedestal banks for aerofoil trailing edges.

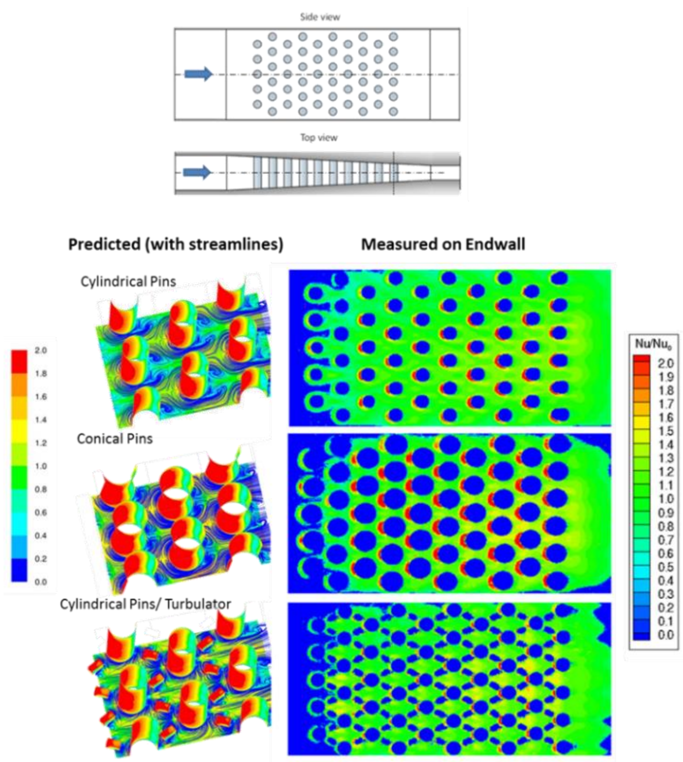


Figure 19 Measured and predicted heat transfer Nusselt number distributions for various designs of trailing edge pedestals, [14].

As part of the overall turbine validation, the heat transfer characteristics of the blade and vane internal cooling designs were also tested and validated with scaled Perspex models using thermo-chromic liquid crystals. This provided detailed distribution of the internal heat transfer coefficients and also allowed very quick flow visualisation of the air flow within the complex cooling passages of the blades and vanes. Figure 20 shows the turbine stage 3 blade and vane Perspex models which were extensively used for the part internal cooling design development and validation.

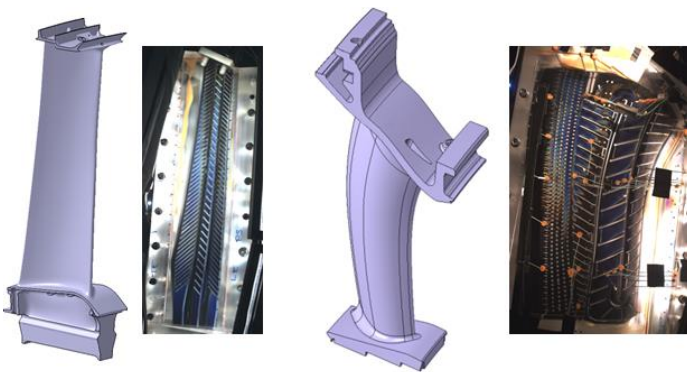


Figure 20 Stage 3 blade and vane perspex models for the measurement of the internal heat transfer coefficient using thermo-chromic liquid crystals.

The engine ready vanes and blades are finally tested in a flow bench to confirm design predictions for mass flow and pressure distribution for the internal flow passages. In addition to this validation, qualitative heat transfer tests were performed on the blades and vanes to provide additional evidence for well-balanced cooling schemes. Figure 21 shows the external surface temperature distribution resulting from a temperature step in the coolant supply for a Stage 3 blade captured with an IR-camera.

ENGINE TESTING AND VALIDATION

In order to ensure fully validated and highly reliable products, Ansaldo is using a Product Development Quality (PDQ) process as shown by Figure 3. This process defines at an early stage during the design phase for each component, the appropriate validation measure to reduce risk to a minimum level. The advanced turbine described in this paper was implemented in the GT36 Test Power Plant in Birr, Switzerland for a full validation test campaign that is currently ongoing.

Divided into three main steps the overall test campaign consists of the performance validation, a dedicated thermal paint test run and an extended test campaign to cover all specific operating conditions. Figure 22 shows the Birr Test Power Plant that is connected to the Swiss grid and dedicated for upfront testing of upgrades in all kinds of operating regimes, i.e. from base-load to extreme off-design conditions, before products are released to the market.

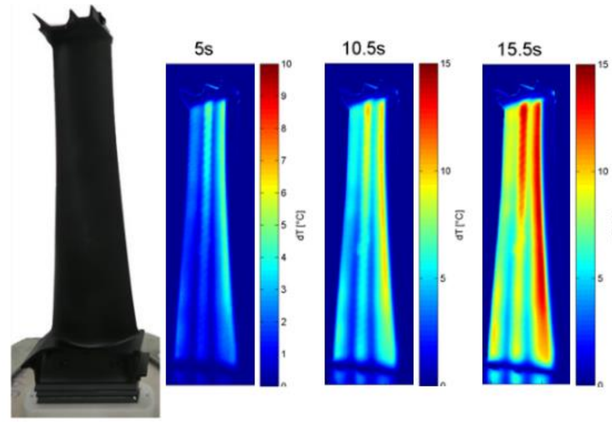


Figure 21 Qualitative heat transfer and flow testing using transient thermography on engine ready Stage 3 blade.

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In addition to thermal paint testing, special additional instrumentation was applied, as shown by Figure 23. For this test and validation campaign, Ansaldo installed more than 4,000 additional test instrumentation on top of the standard instrumentation in order to ensure maximum performance monitoring under all operating conditions.

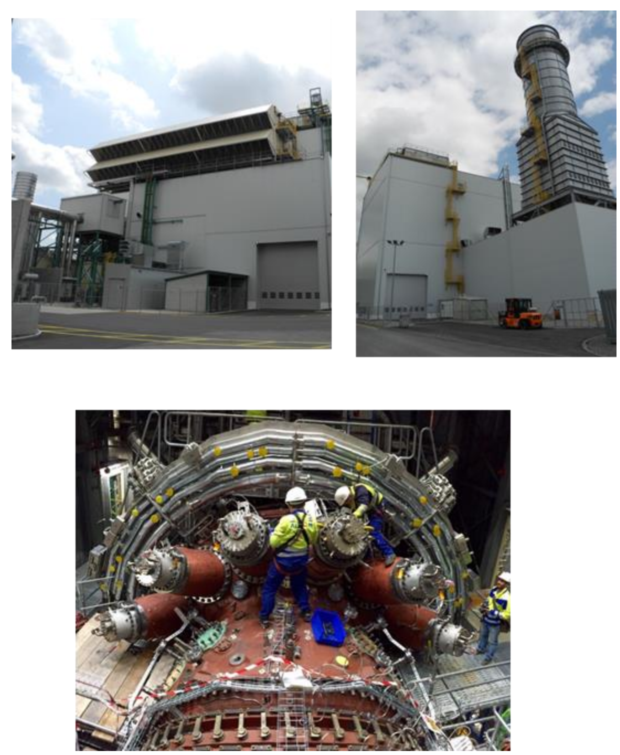

Figure 22 GT36 Test Power Plant at Birr, Switzerland [3].

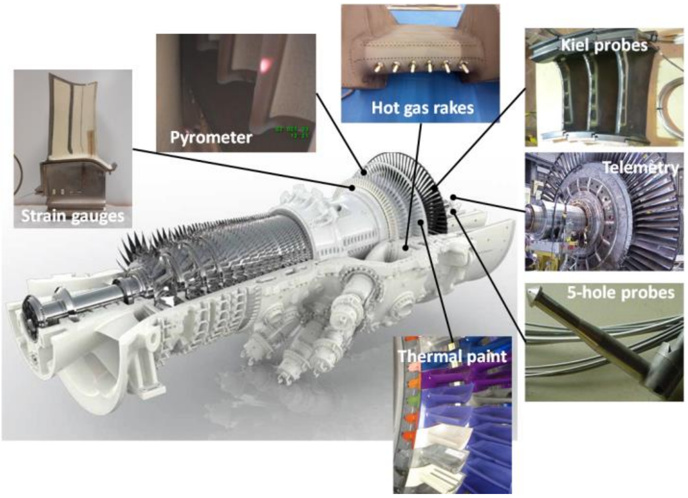

Figure 23 GT36 test power plant – special instrumentation and thermal paint for turbine validation and measurement.

A major aspect of the validation is the confirmation that the expansion, stage matching and vortex design intent was met. These are key drivers for both the aerodynamic efficiency and, via local hot gas temperatures, the thermal design. Pressure taps on vane airfoils and platforms were introduced into the test engine for the purpose of aerodynamic validation. The final thermal validation of all turbine components will be performed via the dedicated thermal paint test run providing full surface metal temperature distribution for the hot gas path as well as the internal surfaces for designated components. This thermal paint test also allows investigating specific part design variants enabling for potential future turbine upgrades.

CONCLUSIONS

The aero-thermal design and validation of an advanced low-pressure axial flow turbine which has evolved from the existing and proven GT26 design has been outlined in this paper. The validation of the turbine has been extensively conducted under controlled laboratory conditions using high speed linear cascades and via extensive use of state-of-the-art computational fluid dynamics tools. Comparisons of the measured and predicted profile Mach number distribution showed excellent agreement under controlled laboratory conditions. For the thermal validation of the turbine components extensive use was made of linear cascades and Perspex model for confirming the film cooling performances. Very good agreement was achieved between the measured and predicted film cooling effectiveness on the first stage vane and blade. For the internal cooling schemes optimized cooling features have been successfully implemented into the part design. For the final part design Perspex models have been used to confirm the internal coolant heat transfer characteristics.

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