A Comprehensive Multifidelity Design and Analysis Process for Cooled Axial Flow Turbines: From Concept to Component

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ABSTRACT

This paper presents an efficient multifidelity process for the design and analysis of cooled axial flow turbine components. The process is initiated with data from a 0D performance model. First, a 1D meanline method is used to define the general turbine layout and the cooling requirements. Then, the blade profile geometry and the boundary conditions for a cooling design method are generated using 2D through-flow and passage flow simulations. Finally, the 3D blade and internal cooling geometry are analyzed using 3D computational fluid dynamics (CFD) simulations. The process is applied to a nozzle guide vane of a next-generation turbofan engine, and the resulting data is compared and evaluated. This approach provides an efficient and effective means of validating novel engine concepts by refining and assessing turbine components in a timely manner.

NOMENCLATURE

CFD	Computational Fluid Dynamics
HPT	High Pressure Turbine
LPT	Low Pressure Turbine
NGV	Nozzle Guide Vane
UHBR GTF	Ultra-High Bypass Ratio Geared TurboFan

INTRODUCTION

The aero-thermodynamic design of completely new or retrofitted turbine sections of jet engines and stationary gas turbines remains a complex and usually time-consuming process. The use of only high fidelity 3D design and analysis tools such as Computational Fluid Dynamics (CFD) imposes too many free parameters and therefore too many possible designs, to arrive at an optimal design within a reasonable time frame. Thus, low fidelity design tools are still commonly applied to limit the reasonable design space by evaluating multiple design variations in the early design phase. In successive design stages of increasing fidelity levels, the geometries are refined by taking dimensional aspects into account to reduce performance uncertainties. Since many different engineering tools are used in this process, a user-oriented design framework with well-defined tool interfaces is crucial for an efficient design process.

This paper presents DLR's current turbine design and analysis process, spanning all fidelity levels from 1D to 3D, in which state-of-the-art cooling models and design methods have been integrated recently. The main focus of this paper is on the overall process and the interconnection of the tools, rather than on the specific features of the tools. However, references are provided for each tool, where the details are explained. The general multifidelity process is described in many engineering books on turbine design (e. g. [1, 2]). The process begins with very few data inputs such as spool powers, rotation speeds and inlet mass flow from a 0D performance model. The entire turbine section layout, including coolant requirements, stage and annulus design, is defined for the design operating point using a 1D meanline method. Subsequently, a 2D through-flow method is used to analyze the circumferential averaged flow field and the performance characteristics at relevant off-design operating points. Blade profile geometries are optimized for low loss and desired performance using a 2D blade-to-blade flow solver. Knowing the hot gas conditions on the blade surface and the coolant conditions at the blade inlet, a cooling design is defined for each profile section. Finally, the 3D blade geometry, including the complex internal cooling geometry, is generated and evaluated in a high fidelity 3D CFD simulation.

Parts of this process have been presented earlier for uncooled blades, e. g. the multidisciplinary design optimization of a low pressure titanium aluminide turbine blade [3] and the design of a 3 stage turbine propulsion simulator [4]. The extended design process for cooled turbines is now demonstrated for a nozzle guide vane (NGV) located in the high pressure turbine (HPT) of a generic ultra-high bypass ratio geared turbofan (UHBR GTF) jet engine that was conceptualized by DLR [5].

METHODS: TURBINE DESIGN AND ANALYSIS TOOLS

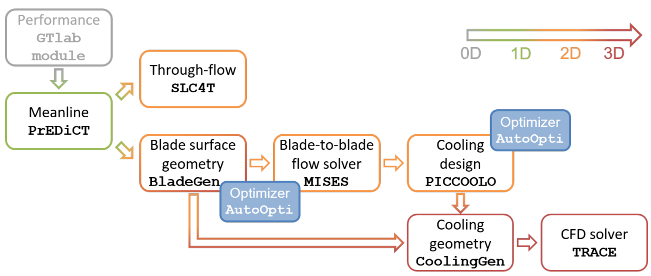

Fig.1 Multifidelity turbine design and analysis process

Figure 1 shows the overall design process at all fidelity levels and for all tools mentioned in this paper. All 0D to 2D low fidelity tools were integrated into the dedicated engine design framework `GTlab` [6], which enhances data transfer and consistency between the tools.

1D Meanline: PrEDiCT

Based on very few data from a 0D engine performance model, the 1D meanline design program PrEDiCT calculates the number of stages, their characteristics and the annulus contour, to deliver the required power at given rotation speed and inlet conditions. The program provides a graphical user interface, to foster an efficient and interactive design process of the turbine by modifying characteristic parameters and evaluating the resulting design simultaneously. Common empirical correlations were implemented, such as the *Zweifel* correlation and a flow coefficient - blade loading correlation [2]. Aerodynamic losses, such as profile loss, secondary flow loss and tip clearance loss, are estimated by the common loss correlations from *Ainley and Mathieson* [7], *Dunham and Came* [8], *Kacker and Okapuu* [9] and *Benner and Sjolander* [10]. In addition to the meanline characterization, the radial flow variations are also described by a variable twist law. More details on the iterative 1D design process are provided in [11].

The turbine design is generally optimized for high efficiency at the aerodynamic operating point, at which the engine is operated most of the time, usually cruise. The required amount of coolant, however, is determined from the operating point of highest thermal loads, usually maximum takeoff. Originally, only an empirical coolant model from *Grieb* [12] was implemented, which is based on jet engines until 1990 and is therefore limited in reliable coolant predictions of future turbine concepts. A new semi-empirical coolant model from *Holland and Thake* [13] has recently been implemented to account for new materials and cooling concepts at an early design stage. More information about the implementation and validation of this model can be found in an accompanying paper [14].

2D Through-flow: SLC4T

SLC4T is a through-flow program based on the streamline curvature method. It calculates the circumferential averaged flow field of a turbine section along the meridional S2m stream surface at various off-design operating points. Thus, it is also used to generate a performance map of the turbine. The S2m plane, defining the hub and tip contour as well as the locations of the blade rows, and the blade profile parameterization, which has to be prescribed at leading edge, trailing edge and throat station, are derived directly from PrEDiCT. The same loss correlation were implemented to improve the consistency of the results. Film cooling and trailing edge cooling are homogeneously distributed over the radius at leading and trailing edge, respectively. Blade tip dust holes and rim seal purge flow are ejected locally at tip and hub endwall, respectively. A detailed description of SLC4T's methodology is given in [15].

2D Blade-to-Blade Flow Solver: MISES

The passage flow on the radially distributed S1 stream surfaces is calculated using the blade-to-blade flow solver MISES [16]. The required blade profile geometries are generated by DLR's turbomachinery blade design program BladeGen [17]. Common profile design parameters, such as blade metal angles, stagger angles, wedge angles, leading and trailing edge thickness are used to generate the profiles. A smooth pressure and suction side is modeled by a B-spline, for which the control points have to be provided. PrEDiCT calculates initial values for these geometric BladeGen parameters as well as boundary conditions for the MISES calculation, such as Reynolds number, inlet and outlet Mach numbers and flow angles. An optimal airfoil design is generated using the multi-objective optimizer AutoOpti [18]. In an evolutionary process, 19 free profile parameters are varied and the passage flow is evaluated for minimum loss and steady flow acceleration, preferably subsonic. Thereby, the prescribed flow angles and Mach numbers must be observed to retain the characteristic of the pre-designed turbine. Positive and negative incidence calculations are also considered, in order to design a robust leading edge that is insensitive to inflow changes, e. g. due to inhomogeneous combustor outflow or spool speed changes, and to reduce turbine losses at off-design.

2D Cooling Design: PICCOOLO

PICCOOLO is a preliminary cooling design tool that is used to create and evaluate a cooling concept at an early design stage. Typical cooling methods such as film cooling, impingement cooling or convective cooling, optionally supplemented by ribs or pin-fins, can be modeled. The calculation method is based on the 1D form of Fourier's law of heat conduction. External / internal heat convection and conduction through the external walls are modeled as a series of thermal resistances. The method is applied to the discretized pressure and suction side profile contours at specified radial cuts of the turbine blade or vane. The heat flux into the blade is dependent on the driving temperature gradient between hot gas and cooling air. While the hot gas temperature is assumed to be constant, the temperature of the cooling air changes based on the absorbed heat, hence it's iterated until energy conservation is achieved. The pressure loss is approximated by loss correlations and the ratio of internal to external pressure. The coolant mass flow rate is iterated until mass conservation is satisfied. The resulting temperature distribution along the blade surface is used in conjunction with the coolant mass flow rate to evaluate the cooling design. Additional information can be found in [19].

3D Geometry: BladeGen and CoolingGen

With BladeGen, the 2D blade profiles are radially stacked to obtain the final 3D blade surface. Blade bow, lean and sweep designs are possible by describing shifting and rotation parameters of the stacking line. Based on the 3D design of the blade surface from BladeGen and the 2D cooling design from PICCOOLO, the internal 3D cooling geometry is generated using CoolingGen [19]. Additional parameters, in particular the radial distribution of cooling geometries like film cooling holes, which can only be estimated at the preliminary design stage, can be specified in more detail.

3D CFD Solver: TRACE

For the high fidelity 3D simulations, the flow volume inside and around the final blade geometry is discretized with an unstructured mesh generated by CENTAUR [20] to allow node-to-node connectivity between cooling and main flow domain. DLR's turbomachinery CFD code for incompressible flows TRACE [21] is used to solve the steady-state Reynolds-averaged Navier-Stokes equations. With a spatial discretization of second order accuracy the turbulence is calculated with the two-equation k-ω SST turbulence model [22]. Inflow direction, stagnation pressure and temperature from the preliminary design are prescribed as cross-section averaged inlet boundary conditions to the flow domain, and the meanline static pressure is set as outlet boundary condition.

RESULTS AND DISCUSSION: HPT AND NGV DESIGN

The multifidelity turbine design process is demonstrated with an NGV of the HPT of a next-generation UHBR GTF, from 1D meanline to the 3D blade and cooling layout.

Table 1 Input data for PrEDiCT from performance model

Cruise OP:Efficient performance design	
HPT / LPT power	11.6 MW / 11.8 MW
HPT / LPT spool speed	16550 rpm / 7804 rpm
HPT inlet temperature	1516.5 K
HPT inlet pressure	1.59 MPa
HPT inlet Mach number	0.09
HPT inlet mean radius	0.241 m

End-of-field OP: Efficient cooling design	
HPT inlet temperature	1893.6 K
HPT inlet pressure	4.54 MPa
Coolant temperature	971.5 K
Coolant pressure	4.76 MPa

The input data for the meanline method PrEDiCT, coming from the performance model, are listed in Table 1 (cf. [5]). The cruise operating point defines the turbine's efficient performance design, while the end-of-field operating point, having slightly higher thermal loads than the maximum takeoff operating point, defines the efficient coolant design.

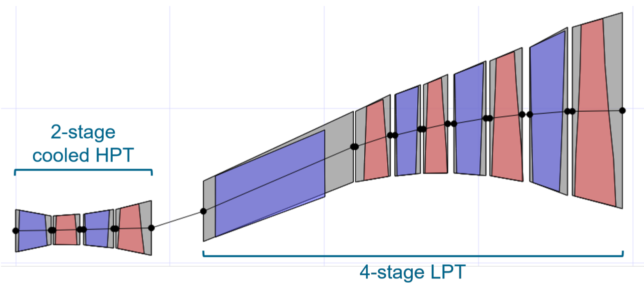

Fig.2 1D turbine design of the entire UHBR GTF from PrEDiCT

Figure 2 shows the resulting turbine sections: A cooled, two-stage high pressure turbine and an uncooled, four-stage low pressure turbine. The HPT efficiency is 90.41 % and the stage loading and reaction of the first stage is 1.44 and 0.43, respectively. The NGV's coolant-to-inlet mass flow ratio is estimated to 10.5 %, of which 74 % is ejected through the airfoil. The 27 NGV experience a total pressure loss coefficient of 0.1156 (profile loss 0.0311).

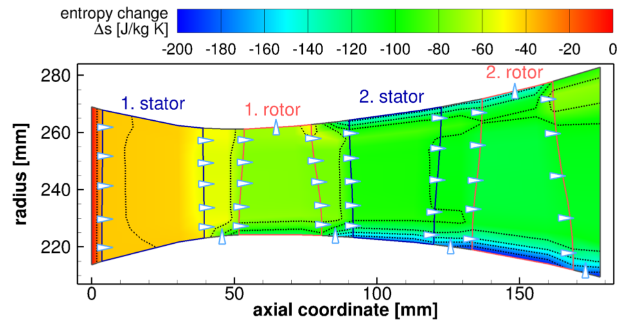

Fig.3 2D S2m entropy field of the cooled HPT from SLC4T

Figure 3 shows the entropy distribution across the HPT from the through-flow calculation. The coolant ejections are marked by hollow triangles. Because of the low entropy carrying cooling flows, the averaged entropy of the main flow is decreasing in downstream direction. Yet, the entropy increasing loss zones of the rotor blade tip vortices and the secondary flows are perceptible. Calibrating for the same power, the HPT efficiency is predicted to 92.13 % and the NGV total pressure loss coefficient to 0.0982 (profile loss 0.0249).

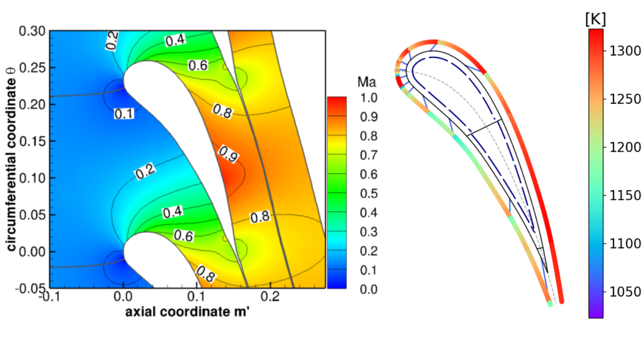

Fig.4 left: 2D S1 NGV Mach number field from MISES, right: cooling design and NGV surface temperatures from PICCOOLO

The NGV profile was optimized for low aerodynamic losses while retaining inlet and outlet Mach numbers and flow angles. Large incidence angles of $\pm 30^\circ$ were considered to give respect to the high swirl combustor outflow. Figure 4, left, shows the optimized midspan profile and the Mach number field with a steady accelerated subsonic passage flow. The profile loss coefficient is assessed to 0.0490.

Figure 4, right, shows the resulting cooling design and the external metal surface temperatures at the end-of-field operating point. Cooling techniques include impingement cooling, showerhead film cooling at the leading edge, laidback fan-shaped film cooling holes on pressure and suction side and slots for convective cooling of the trailing edge. The maximum surface temperature of the metallic blade material was limited to 1323 K. As a result, an airfoil coolant mass flow rate, which is 13 % higher than predicted from the early 1D meanline model, and an averaged external metal temperature of 1218 K was calculated.

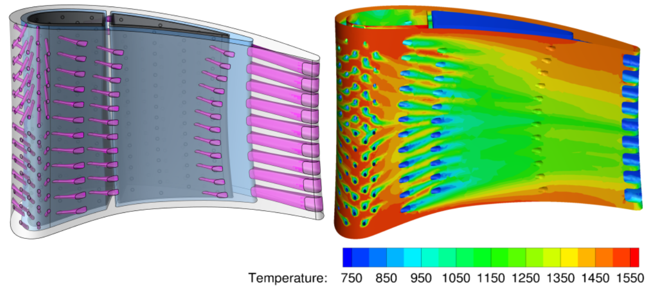

Fig.5 left: 3D NGV cooling design from CoolingGen, right: wall temperature from 3D TRACE CFD

Based on the optimized blade profiles and the cooling design, the final 3D NGV surface and internal cooling geometry was generated (Figure 5, left). The investigated NGV was intentionally designed as prismatic vane, such that the midspan profile is representative for all span positions. A 3D CFD simulation was carried out on an unstructured mesh with about 14 million elements. The solid walls are modeled as adiabatic walls, so no heat transfer is simulated. Figure 5, right, shows the simulated temperature on the vane surface. The maximum surface temperature of 1516 K occurs at the leading edge stagnation point, where the showerhead film cooling seems to be ineffective. A conjugated heat transfer simulation would be required to model the heat conduction inside the solid. Yet, such a simulation is outside the scope of this paper, which is focusing on the aerodynamic performance of the vane. The NGV total pressure loss coefficient is 0.1038, which is in the range of the values from the low fidelity predictions.

CONCLUSION

A multifidelity process chain has been developed to design and analyze turbine sections and cooled blades rows. Starting from limited performance data, a 1D meanline method defines an efficient turbine layout for the design operating point and already proposes blade geometry parameterizations and cooling requirements. A 2D through-flow method calculates the circumferential averaged flow and performance characteristics at off-design operating points. A blade-to-blade flow solver is used to optimize the blade profile geometry for low losses, and a cooling design method describes an efficient cooling concept. The results lead to a 3D geometry of the blade surface and internal cooling that is meshed and evaluated in a high fidelity CFD simulation.

The process was applied to an NGV of a HPT. The results at different fidelity levels show that some properties, e. g. the total pressure loss coefficient, are predicted with sufficient confidence already at low fidelity levels, while others, such as the cooling mass flow rate, need to be refined with caution in later design stages.

The current design process runs in a straightforward manner from lower to higher fidelity levels. But some designs clearly require adjustments, such as the film cooling distribution as seen in the high fidelity CFD simulation. These adjustments need to be made not only at the current fidelity level, but also at upstream fidelity levels to ensure that the design changes are represented in the overall turbine characteristic. Ongoing work involves iterating over the entire process chain to incorporate adjustments from high fidelity tools also in low fidelity tools, and extending the process to cooled rotor blades.

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REFERENCES

[1] Moustapha, H. et al. *Axial and Radial Turbines*. Concepts NREC, White River Junction, VT, 2003.

[2] Aungier, R. H. *Turbine Aerodynamics: Axial-Flow and Radial-Flow Turbine Design and Analysis*. ASME PRESS, New York, 2005.

[3] Buske, C. et al. "Distributed Multidisciplinary Optimization of a Turbine Blade Regarding Performance, Reliability and Castability". In: *Proceedings of ASME Turbo Expo 2016*. Seoul, South Korea: ASME, June 2016, V02CT45A002. DOI: 10.1115/GT2016-56079.

[4] Krumme, A., Hegen, S., and Nahuis, R. "Design of a Multi-Stage Axial Turbine within the Scope of Complete System Design, Manufacturing and Operation of a New Turbine Propulsion Simulator (TPS)". In: *33rd AIAA Applied Aerodynamics Conference*. AIAA, 2015.

[5] Vieweg, M. et al. "Collaborative Aircraft Engine Preliminary Design Using a Virtual Engine Platform, Part B: Application". In: *AIAA Scitech 2020 Forum*. Orlando, FL, USA: AIAA, Jan. 2020. DOI: 10.2514/6.2020-0124.

[6] Reitenbach, S. et al. "Collaborative Aircraft Engine Preliminary Design Using a Virtual Engine Platform, Part A: Architecture and Methodology". In: *AIAA Scitech 2020 Forum*. Orlando, FL, USA: AIAA, Jan. 2020. DOI: 10.2514/6.2020-0867.

[7] Ainley, D. G. and Mathieson, G. C. R. "A Method of Performance Estimation for Axial-Flow Turbines". In: *R. & M.* 2974 (1957).

[8] Dunham, J. and Came, P. M. "Improvements to the Ainley-Mathieson Method of Turbine Performance Prediction". In: *J. Eng. P.* 92.3 (July 1970), pp. 252–256. DOI: 10.1115/1.3445349.

[9] Kacker, S. C. and Okapuu, U. "A Mean Line Prediction Method for Axial Flow Turbine Efficiency". In: *J. Eng. P.* 104.1 (Jan. 1982), pp. 111–119. DOI: 10.1115/1.3227240.

[10] Benner, M. W., Sjolander, S. A., and Moustapha, S. H. "An Empirical Prediction Method for Secondary Losses In Turbines - Part II: A New Secondary Loss Correlation". In: *J. Turbomach.* 128.2 (Apr. 2006), pp. 281–291. DOI: 10.1115/1.2162594.

[11] Krumme, A. "Performance Prediction and Early Design Code for Axial Turbines and Its Application in Research and Predesign". In: *Proceedings of ASME Turbo Expo 2016*. Seoul, South Korea: ASME, June 2016, V02CT39A003. DOI: 10.1115/GT2016-56082.

[12] Grieb, H. *Projektierung von Turboflugtriebwerken*. Technik der Turboflugtriebwerke. Springer Basel AG, 2004.

[13] Holland, M. J. and Thake, T. F. "Rotor Blade Cooling in High Pressure Turbines". In: *Journal of Aircraft* 17.6 (June 1980), pp. 412–418. DOI: 10.2514/3.44668.

[14] Carvalho, F. et al. "Cooling Model Calibration in a Collaborative Turbine Preliminary Design Process Using the NASA Energy Efficient Engine Part II: 1D Turbine Modeling". In: *Proceedings of IGTC 2023*. Kyoto, Japan: GTSJ, Nov. 2023.

[15] Kost, F. *Ein Verfahren zur Berechnung der Meridionalströmung von Axialturbinen*. Internal Report DLR-IB 225 - 2014 A 01. Göttingen, Germany: DLR AT-TUR, 2014, p. 61.

[16] Drela, M. and Youngren, H. *Mises 2.63 Doku*. Tech. rep. 2008.

[17] Voß, C. and Nicke, E. *Automatische Optimierung von Verdichterstufen*. Research Report 0327713 B. Cologne, Germany: DLR AT-FUV, 2008, p. 71.

[18] Voß, C. et al. "Automated Multiobjective Optimisation in Axial Compressor Blade Design". In: *Proceedings of ASME Turbo Expo 2006*. Barcelona, Spain: ASME, 2006, pp. 1289–1297. DOI: 10.1115/GT2006-90420.

[19] Schöffler, R. et al. "Development of a Multistage Turbine Vane Cooling Design and Optimization Process". In: *Proceedings of IGTC 2023*. Kyoto, Japan: GTSJ, Nov. 2023.

[20] CentaurSoft. *CENTAUR*. https://www.centaursoft.com/, 2022.

[21] Geiser, G. et al. "On the Simulation and Spectral Analysis of Unsteady Turbulence and Transition Effects in a Multistage Low Pressure Turbine". In: *J. Turbomach.* 141.5 (May 2019), p. 051012. DOI: 10.1115/1.4041820.

[22] Menter, F., Kuntz, M., and Langtry, R. "Ten Years of Industrial Experience with the SST Turbulence Model". In: *Proceedings of the 4th Symposium of Turbulence, Heat and Mass Transfer*. Antalya, Turkey: THMT, Oct. 2003, pp. 625–632.