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Turbinenschaufelkühlung: Data Matching von MRV und CFD Datensätzen

Turbine blade cooling: data matching of MRV and CFD data sets

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Data Matching, Magnet Resonanz Velocimetrie, Turbinenschaufelkühlung, Turbulenz
data matching, magnetic resonance velocimetry, turbine blade cooling, turbulence

Zusammenfassung

Für die Validierung turbulenter Strömungssimulationen (Computational Fluid Dynamics, CFD) ist es notwendig, experimentelle Daten bereitzustellen. Magnetresonanz-Velocimetrie (MRV) ist eine vielversprechende Methode, um solche Validierungsdaten dreidimensionaler Geschwindigkeitsfelder (3D3C) in komplexen Strömungen zu generieren, ohne dass ein optischer Zugriff erforderlich ist. Um die 3D3C-Datensätze in ihrem vollen Umfang für die CFD-Validierung verwenden zu können, sind jedoch mehrere Schritte erforderlich. Die CFD- und MRV-Datensätze müssen in ein gemeinsames Koordinatensystem transformiert werden. Nach der Interpolation der CFD-Daten auf das äquidistante MRV-Gitter kann ein Punkt-zu-Punkt-Vergleich der gemessenen Strömungsvariablen durchgeführt werden. Zusätzlich zu globalen Fehlern können nun auch lokale Fehlerfelder berechnet und damit zur dreidimensionalen Visualisierung der Abweichungen verwendet werden (Wüstenhagen et al. 2021).
In dieser Studie wird diese *Data Matching* Routine sowie ihre Anwendung auf die turbulente Strömung durch ein Turbinenschaufelkühlsystem vorgestellt. Die globalen und lokalen Fehlergrößen werden am Beispiel des Kühlstroms dargestellt und interpretiert.

Abstract

It is necessary to provide experimental data to validate turbulent flow simulations (computational fluid dynamics, CFD). Magnetic Resonance Velocimetry (MRV) is a promising method to supply such validation data of three-dimensional velocity fields (3D3C) in complex flows without requiring optical access. However, to use the obtained 3D3C data sets in their entirety for CFD validation, several steps are required.
First, the CFD and MRV data sets have to be transformed to a common coordinate system. Then a point-to-point comparison of the measured flow variables can be carried out. In addition to global errors, local error fields can now be calculated and used to visualize the deviations in three dimensions (Wüstenhagen et al. 2021).
In this study, we present the data matching routine as well as its application on the turbulent flow through a turbine blade cooling system. The global and local error quantities are presented and interpreted using the cooling flow model.

Introduction

The turbine inlet temperature of gas turbines is an important operating parameter that affects the performance of the system. However, this is limited by the temperature resistance of the turbine blades. The temperature levels have nonetheless increased considerably in recent years, which has been made possible by advances in materials and turbine blade cooling techniques. Effective cooling strategies for the turbine blades can thus increase the efficiency of gas turbines.

In order to investigate the influence of different cooling systems on the temperature of the turbine blades, numerical simulations (computational fluid dynamics, CFD) are the most commonly used tool in the gas turbine industry. In particular, parameter studies can be carried out quickly (e.g., Amano 2010, Khalil 2019). However, the numerical method and the applied models must be confirmed by validation experiments.

Many validation experiments have been performed using a variety of measurement techniques. Kim et al. (2007) performed an experiment in which they investigated the influence of the rib angle with bleed holes on the heat transfer in a rotating system using thermo couples. Wang et al. (2018) used PIV measurements to investigate the flow characteristics of an entire internal cooling system. Biegger et al. (2018) combined the PIV measurements with thermochromic liquid crystals (TLC) and compared their results to a detached eddy simulation investigating swirl tubes. Whereas Shiau et al. (2020) used TLC to study a realistic turbine blade internal cooling design including both pin-fins and ribs. Baek et al. (2019) used magnetic resonance velocimetry (MRV) to validate a large eddy simulation of triangular cooling channels and Benson et al. (2019) even combined MRV measurements with magnetic resonance thermometry and compared them to a CFD simulation using the k-ε turbulence model.

This article aims to present a data matching method that contains a geometry alignment and an evaluation step. With this method, two different 3D3C (three dimensions, three components) data sets are compared, in this case, CFD and MRV. Therefore, an internal cooling system of a turbine blade is presented. A CFD simulation, as well as an MRV measurement, is performed. Finally, the validation method, including geometry matching and an evaluation step, is presented and carried out on the two data sets.

Materials and Methods

MRV Experiment

The actual flow through a turbine blade cooling system is a turbulent compressible gas flow, there are high temperature gradients, and in the case of a rotor blade, the flow system is subject to coriolis forces.

A CFD setup must consider all these effects. However, the most challenging aspect among the calculation of the flow field inside gas turbine blades and vanes is the modelling of turbulence. As the local Mach number of internal flows is typically below 0.3 and temperature gradients have only minor impact on the flow field, ~~is~~ validation experiments to calibrate the turbulence models of the CFD code, are typically conducted with incompressible, isothermal, stationary flow. According to dimensional analysis the Reynolds number is the only dimensionless quantity that has to maintained to provide similar turbulent flow conditions.

MRV experiments require that the flow medium has a measureable nuclear spin. Also, the material of the measurement section must be made of non-metallic materials. Commonly, water is used as the flow medium and the test rig is made of plastic. The dimensions of the flow system are further adjusted to provide convenient measurement parameters.

In this study, the model is scaled 3.15-fold compared to the original geometry to assure a sufficiently high spatial resolution with low measurement uncertainty. Note that the measurement uncertainty in MRV is inverse proportional to the size of the volume elements, which are known as voxels.

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The model shown in Fig. 1 was manufactured by laser sintering of polyamide powder. It consists of the internal turbine blade cooling system, which is connected to a plenum at the inlet as well as the outlet. The surface roughness is approximate $0.01\ mm$, which is considered hydraulically smooth and therefore negligible. Flexible hoses connect the MRV model to a pump system.
A solution of water and copper sulfate is admitted to the turbine blade cooling system: $1g/l$ copper sulfate was added as a contrast agent, which led to a kinematic viscosity of $\nu_{MRV} = 1.003 \cdot 10^{-6}\ m^2/s$. The temperature of the fluid was controlled at $T = 20°C$ by a cooling unit.
The flow conditions were calculated to reach a Reynolds number of approximately 7000 at the inlet to assure turbulent flow and to validate the turbulence model used in CFD. This resulted in a calculated flow rate of $10.0\ l/min$. However, the measured flow rate of the MRV measurement was $9.68\ l/min$. This equals a mass flow rate of $161\ g/s$.
The experiment was performed on a Siemens 3T Magnetom Tim TRIO (Siemens, Erlangen, Germany). The scanner has a maximum gradient amplitude of $40mTm^{-1}$ and a maximum gradient slew rate of $200\ Tm^{-1}s^{-1}$.
The parameters of the 4D Flow MRI measurement are shown in Tab. 1.

Tab. 1: Parameters of the MRV measurement

Parameter	**Value**
Matrix size	512 x 256 x 120
Isotropic resolution	0.75 mm
Echo time	4.91 ms
Repetition time	9 ms
RF Flip angle	20°
Receiver bandwidth	440 Hz Pixel^{-1}
VENC	1.0 m/s
Number of acquisitions	4 (Flow on) + 1 (Flow off)
Total acquisition time	95 min

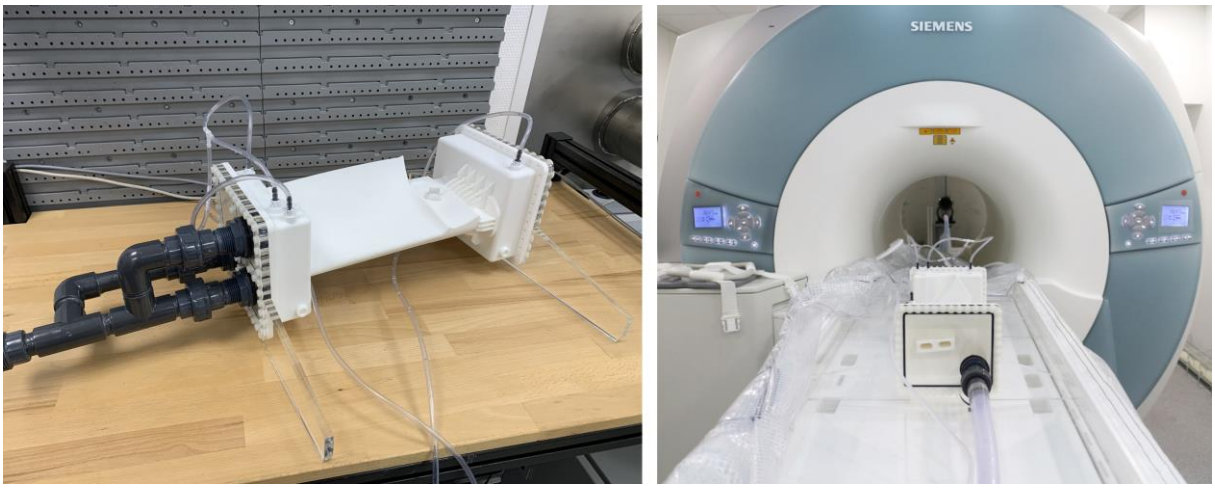

Fig. 1: MRV model of the turbine blade cooling and test stand.

CFD Simulation

The boundary conditions of the CFD simulation were derived from the measurement results of the MRV experiment to assure the consistency of Reynolds number. It should be noted that the CFD was performed on a model of the blade at the original scale and with air. With a

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calculated Reynolds number of 7000, a kinematic viscosity of $\nu_{CFD} = 1.53 \cdot 10^{-5}\, m^2/s$ and a density of $\rho = 2.59 kg/m^3$, a mass flow of $1.89 g/s$ is set as boundary condition.
The turbine blade cooling system was numerically simulated using the commercial software ANSYS CFX 19.2 (ANSYS Inc., Canonsburg, PA, USA). The steady state solution was carried out with the high resolution scheme, which allows second order accuracy in the majority of the regions of the computational domain as given in Fig. 2. No slip condition is assumed at the walls which are considered to be hydraulically smooth. At the inlet (A) a total pressure boundary condition was set. By setting individual mass flow boundary conditions at the outlets (B) and (C) an outflow distribution similar to the experiment was obtained. 10% of the mass flow passes through the outlet at position B.
The computational domain is discretized by an unstructured grid consisting of 44 million elements. The element size and the grid quality criteria are according to MAN best practice guidelines based on previous studies on similar geometries. The boundary layer is resolved by 15 layers of prismatic elements.
The modeling of the turbulence was carried out with the eddy-viscosity based k-ω-SST turbulence model by Menter (1997). Fig. 3 shows that the non-dimensional height y+ of the first layer is below 0.5 and hence sufficiently low for this model.

Fig.2: Computational domain

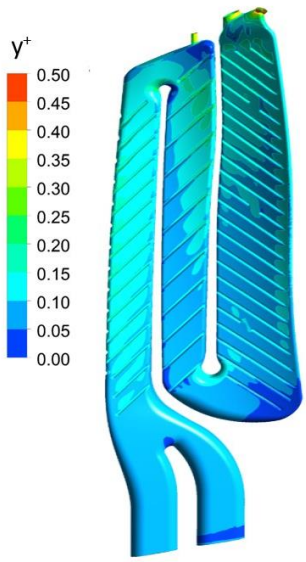

Fig. 3: Distribution of the non-dimensional wall distance y+

Evaluation Routine

To match the MRV geometry to the CFD geometry, the surfaces of the geometries are represented as point clouds and are aligned using the coherent point drift algorithm. The geometry matching accuracy is then described by the percentage of successfully interpolated points relative to all MRV grid points. After interpolating the CFD velocity data onto the MRV grid, point to point comparison is possible (Wüstenhagen et al. 2021).
For error quantification, global errors and local error fields will be evaluated. Therefore, a normalized velocity vector

$$u_{MRV/CFD}(r) = \sqrt{{u_x}^2 + {u_y}^2 + {u_z}^2} / U_{in,MRV/CFD} \qquad (1)$$

is defined for both, MRV and CFD. Note that because of the different viscosities of air and water and the scaling in size it is necessary to compare normalized flow quantities such as the velocity normalized with the respective bulk velocities, despite retaining the Reynolds number.

As global error quantities, a mean absolute (MAE), as well as a corrected root mean square error (cRMSE), will be investigated:

$$\text{MAE} = \left|\frac{\frac{1}{N}\sum(u_{CFD}(\boldsymbol{r})-u_{MRV}(\boldsymbol{r}))}{U_{in}}\right| \cdot 100\% \tag{2}$$

$$\text{cRMSE} = \frac{\sqrt{\frac{1}{N}\sum(u_{CFD}(\boldsymbol{r})-u_{MRV}(\boldsymbol{r}))^2 \ -\sigma_u^2}}{U_{in}} \cdot 100\% \tag{3}$$

with U_{in} being the bulk velocity and σ_u^2 being the measurement uncertainty calculated using the difference method from Bruschewski et al. (2016). Note that the global error quantities are unbiased to the measurement uncertainty.

The local error fields will be presented using an absolute as well as an arctangent percentage error:

$$\text{AE}(\boldsymbol{r}) = \left|\frac{u_{CFD}(\boldsymbol{r})-u_{MRV}(\boldsymbol{r})}{U_{in}}\right| \cdot 100\% \tag{4}$$

$$\text{AAPE}(\boldsymbol{r}) = \frac{4}{\pi} arctan\left(\left|\frac{u_{CFD}(\boldsymbol{r})-u_{MRV}(\boldsymbol{r})}{u_{MRV}(\boldsymbol{r})}\right|\right) \cdot 100\% \tag{5}$$

Errors that are in the range of 100% to infinity will be displayed in an error range of 100%-200% by using a scaling of the percentage error with the arctangent function. The errors in the range of 0%-100% are displayed in the same range, but with a slight overestimation. The advantage of this method is that the whole dynamic range of the error can be visualized in a single color-coded figure.

Results

The geometry matching routine reached an accuracy of 99.24%, which is considered sufficient. Fig. 4A shows streamlines of both the MRV experiment and the CFD simulation. The normalized velocity distributions in selected slices are presented in Fig. 4B. It can be seen that the velocity distributions seem to be in good agreement. Note that the streamlines near the turbine blade wall are less visible in the MRV data due to the lower resolution of the near-wall region. A mere visual agreement would be insufficient for an extensive validation in the field of technical applications, though.

Therefore, the evaluation of global errors MAE and $cRMSE$ is performed. The measurement uncertainty of the MRV measurement is calculated using the difference method and results in $\sigma = 0.022\frac{m}{s}$. This leads to $MAE = 1.42\%$ and $cRMSE = 27.45\%$. The low MAE value and the high cRMSE value indicate local velocity errors whereas a high MAE and low cRMSE errors would indicate a global bias.

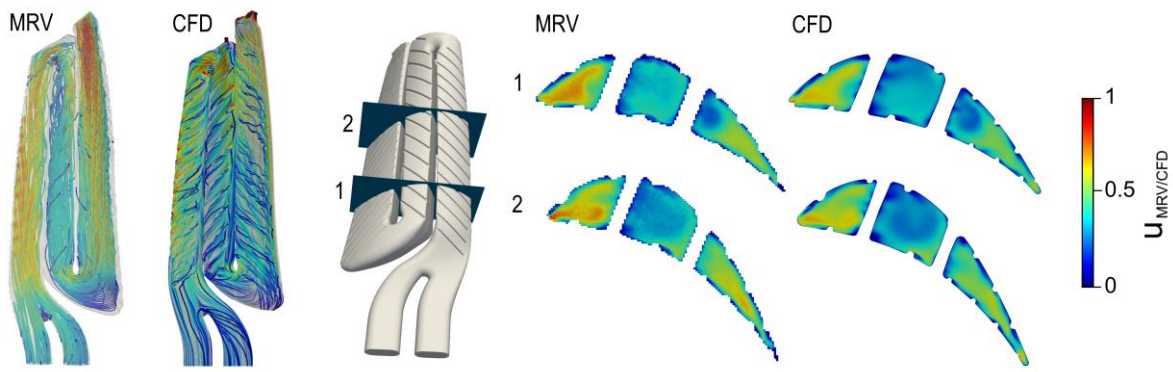

Fig. 4: A) Streamlines of the MRV and CFD experiments; B) velocity distribution of the MRV and CFD experiments at selected slices.

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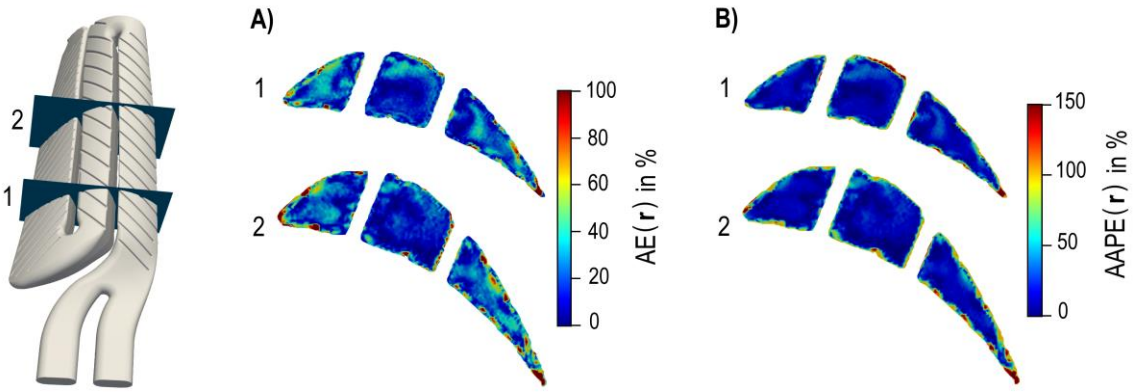

Fig. 5: Local error quantities A) AE(r) and B) AAPE(r) at selected slices.

The local errors $AE(\boldsymbol{r})$ and $AAPE(\boldsymbol{r})$ are shown at selected slices in Fig. 5A respectively Fig. 5B. It can be seen that high absolute as well as relative errors occur near the ribs of the turbine blade cooling system as well as at the walls in general.

Discussion & Conclusion

In this paper, a data matching method for 3D3C data sets was presented. The routine was successfully applied to a numerically simulated and experimentally measured turbulent internal turbine blade cooling flow. The evaluation of the global errors leads to the finding that the overall accordance of CFD and MRV is sufficient, but we encounter local differences. These local differences can be visualized in three-dimensional error fields. Here, high absolute as well as relative errors can be seen in the near-wall region. This could be due to the fact that the velocities of the less well-resolved MRV are compared with the very highly resolved near-wall, near zero velocity area of the CFD.
Nonetheless, the agreement of the velocity distribution within the cooling flow is acceptable.
Improvements to the experiment are possible by controlling the flow rates of all outlets to match the original load case. Temperature measurements and simulations can also be included to investigate the heat transfer. The presented data matching routine can be applied to all measured flow variables such as temperature.
All in all, the presented global and local error quantities are suitable for the detailed investigation of differences in the flow fields of different experimental or numerical data fields. This data matching routine can be used for validating CFD simulations and identifying the most suitable turbulence model for specific applications.

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