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3D MRV Messungen der Geschwindigkeit und des Reynoldsspannungstensors einer Prallkühlungsströmung als Validierungsdaten für CFD

3D MRV Measurements of the Velocity and Reynolds Stress Tensor of an Impingement Cooling Flow as Validation Data for CFD

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Magnetic resonance velocimetry, Validation, CFD, Turbulence, impingement cooling

Zusammenfassung

Die Strömungsvorgänge in Prallkühlungssystemen stellen eine besondere Herausforderung für die in der Industrie verwendeten Simulationsmethoden dar. Die eingesetzten CFD-Methoden (Computational Fluid Dynamics) müssen in anwendungsorientierten Fällen validiert werden. Die Magnetresonanz-Velocimetrie (MRV) ist ein geeignetes Messverfahren, um strömungsmechanische Validierungsdaten zu erzeugen, da sie Strömungskomponenten im dreidimensionalen Raum erfassen und in vergleichsweise kurzer Zeit Millionen von Datenpunkten produzieren kann. Durch die Möglichkeit, innerhalb optisch unzugänglicher Modelle zu messen, können die Messdaten sogar innerhalb der Bohrlöcher aufgezeichnet werden und stehen somit für die Validierung zur Verfügung.

Ein Modell der Prallkühlung wird mit MRV untersucht, um Validierungsdaten zu produzieren. Dazu wird ein Prallkühlungsfall mit drei Jets in Reihe, einer Jet-Reynoldszahl von 30.000 und einem Querstromverhältnis von 0,1 vermessen. Mit MRV wird das mittlere Geschwindigkeitsfeld sowie der Reynolds-Spannungstensor (RST) im gesamten dreidimensionalen Volumen erfasst. Diese Daten können verwendet werden, um CFD-Verfahren umfassend zu validieren und das am besten passende Turbulenzmodell zu finden oder die verwendeten Simulationsparameter zu optimieren.

Viele Reynolds-gemittelte Navier-Stokes-Turbulenzmodelle stützen sich auf die Wirbelviskositätshypothese. Mit den verfügbaren mittleren Geschwindigkeits- und RST-Daten kann die Wirbelviskosität berechnet werden. Das dreidimensionale Wirbelviskositätsfeld kann als Entscheidungshilfe für die Wahl eines geeigneten Turbulenzmodells verwendet werden. Falls auf Wirbelviskosität basierende Turbulenzmodelle als nicht hinreichend genau eingestuft werden, können komplexere Turbulenzmodelle verwendet und falls umsetzbar, anhand der verfügbaren RST-Daten validiert werden.

Abstract

Flow processes in impingement cooling systems are particularly challenging for simulation methods commonly used in the industry. Computational Fluid Dynamics (CFD) methods have to be validated in application-oriented cases. Magnetic resonance velocimetry (MRV) is a suitable measurement technique to provide fluid mechanic validation data as it can acquire flow components in the three-dimensional space and can yield millions of data points in a comparatively short time. The possibility of measuring within models without optical access means that measurement data can even be recorded within the boreholes and thus be available for validation.

An impingement cooling model is investigated using MRV to provide validation data. Therefore, an impingement cooling case with three jets in line, a jet Reynolds number of 30,000, and a crossflow ratio of 0.1 is measured. With MRV, the mean velocity field as well as the Reynolds Stress Tensor (RST) in the entire three-dimensional volume is captured. These data can be used to comprehensively validate CFD and to identify the most suitable turbulence model or to optimize the parameters of the chosen simulation method.

Many Reynolds-averaged Navier Stokes turbulence models rely on the eddy viscosity. With the available mean velocity and RST data, the eddy viscosity can be calculated. The three-dimensional eddy viscosity field can be used as a decision guidance for the choice of a suitable turbulence model. If eddy viscosity-based turbulence models are classified as not sufficiently accurate, more complex turbulence models can be used and validated by the available RST data if feasible.

Introduction

The focus of the presented study is the flow in the vicinity of and within cooling holes. These may consist of impingement- or film-cooling holes, such as those used in gas turbine combustors, aerofoils or electronics cooling. The simulation of the flow in these holes and the interaction with the surrounding fluid are computationally challenging [1]. CFD is used extensively but is mostly validated using empirical correlations and experiments. With the advances in additive manufacturing and the associated geometrical freedoms, the established correlations are no longer sufficient and the CFD codes need to be improved in the accurate prediction of the flow in randomly shaped and positioned holes. Their verification and validation can only be based on sufficiently accurate experiments that visualize the relevant flow phenomena.

A common approach to study turbulent flows is the numerical simulation of time-averaged differential equations, which are referred to as RANS (Reynolds-averaged Navier-Stokes) equations. Using RANS methods, highly turbulent flows in complex machines can be simulated with reasonable effort. Due to the low computing power required, these methods are widely used in industry.

The challenge with RANS-CFD lies in the accuracy of the simulation results. The Reynolds-averaging leads to additional correlation terms, the so-called Reynolds stresses, which require additional transport equations or empirical models to solve this closure problem. An elementary modeling approach is the eddy viscosity hypothesis to model the Reynolds stresses as a function of the mean flow. The validity of this model assumption is generally limited. However, RANS methods are still highly relevant in industrial applications due to their simplicity and computational efficiency. Especially for small and medium-sized enterprises, RANS-CFD is often the only way to perform CFD studies economically.

The accuracy of the RANS-CFD can be improved by calibrating the coefficients of the turbulence models used for the respective application. For this purpose, a validation experiment must be carried out that has a similar geometry and similar dimensionless flow parameters as the real application [2]. Based on this experiment, the turbulence models can be calibrated and validated, which ensures the accuracy of the RANS-CFD for the original component. The success of the validation depends directly on the accuracy and completeness of the experimental data sets.

Fluid mechanical validation data in the field of impingement cooling is mainly generated using the laser-optical measurement methods Laser Doppler Velocimetry (LDV) and Particle Image Velocimetry (PIV). These methods require that the flow system is transparent and that the refractive indices of the liquid and model material match. Such experiments are therefore technically complex and cost-intensive. In the case of impingement cooling, laser-optical measurements inside the borehole are especially challenging and usually omitted, although this region is highly relevant for CFD validation.

In this study, magnetic resonance velocimetry (MRV) is used as a flow measurement technique to acquire more complete experimental data sets for these cooling applications. Therefore, an impingement cooling case with three jets in line is presented to investigate the interaction of the cooling flows. The quantities measured by MRV in this study are the three-dimensional velocity field and the three-dimensional Reynolds Stress Tensor (RST). The results of these measurements enable the calculation of the eddy viscosity. With this, statements can be made about the presumed suitability of different turbulence models.

Materials and Methods

MRV Measurements

MRV is a non-optical imaging method used in medical applications that enables fluid mechanic measurements in areas that cannot be captured using optical measurement methods. It is non-invasive and based on the electromagnetic properties of the atomic nuclei (nuclear spins) in the magnetic field of the MRV scanner. MRV measurement technology has been continuously developed over the last few decades and enables, among other things, the 3D recording of velocities, temperature fields, mixing processes, and turbulence quantities in fluid flows.

MRV is relatively new in the field of fluid mechanics and mechanical engineering. However, there are sufficient case studies in the literature that demonstrate the high accuracy and diverse applications of MRV [3]. Further examples can be found in the field of turbomachinery [4-8] and power plants [9,10]. The feasibility of the MRI measurement for the intended application has been demonstrated several times in previous studies [11,12].

The test rig for the MRV measurements is designed to realize an array of three impinging jets in combination with crossflow. A schematic overview of the setup can be seen in Figure 1. The flow circuit is composed of a tank, connected to a pump, leading to a manometer. Then the flow divides into four streams, supplying the main channel and the three impingement holes. The flow into the crossflow channel is guided through a diffusor with several grids to homogenize the flow. The flow through the three impinging holes is straightened using a porous medium. The channel and impinging flow rates are adjusted by manually operated valves and monitored using magnetic inductive sensors (SM6020 and SM7020, ifm electronics GmbH, Germany). These sensors also measure the fluid temperature.

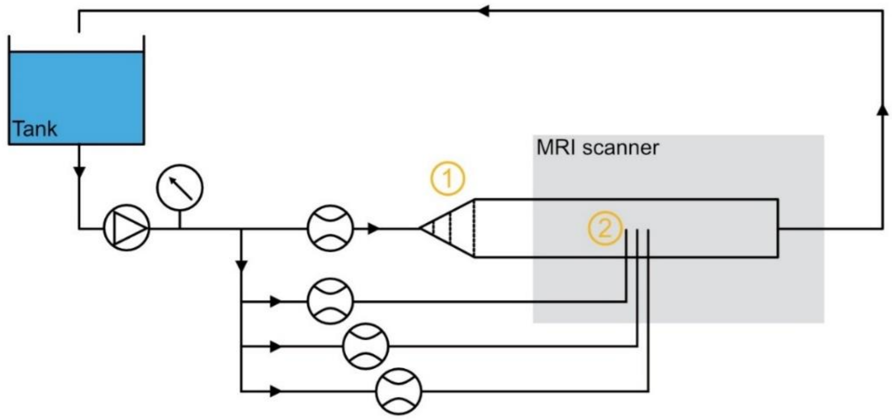

Figure 1: Schematic illustration of the test stand for the investigation of impinging jets with crossflow. (1) Diffusor with nets; (2) Exchangeable impinging plate.

The test section is shown in Figure 2. The crossflow channel features a removable insert to realize different impingement plate configurations. The channel has a height of 150 mm, a width of 40 mm, and a length of 1000 mm. Since one of the channel walls acts as the target plate, the distance between the impingement and the target plate cannot be changed.

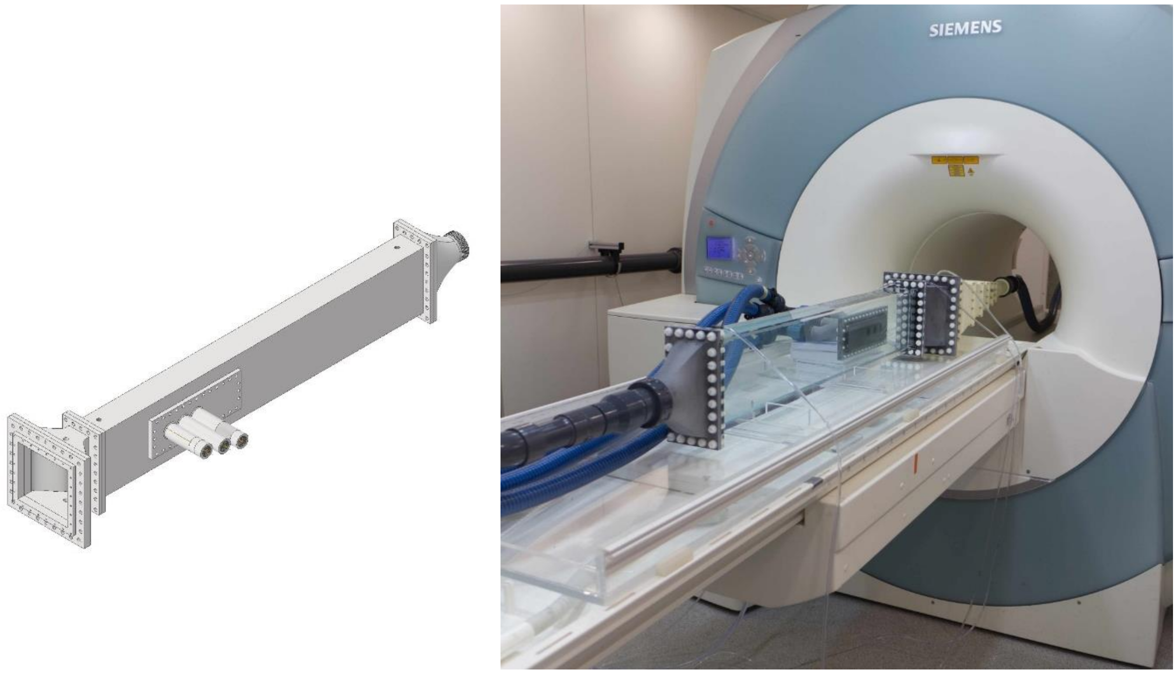

Figure 2: Left: CAD model of the impingement cooling system with crossflow; Right: MRI model for the investigation of impinging jets with crossflow.

The nozzle diameter D and the distance between the impingement and target plate H were set to 20 mm and 40 mm, respectively. The distance between the jet center lines S is 40 mm, the jet Reynolds number Re_{jet} is set to 30,000, and the crossflow ratio o is 0.1.

A three-dimensional three-component (3D3C) velocity measurement was performed with a spatial resolution of 1 mm³. The overall field of view (FOV) is 320 x 160 x 64 mm³ and the measurement volume is shown in Figure 3. In addition, a three-dimensional six-component (3D6C) RST measurement was performed on the same three-dimensional volume but with a

spatial resolution of 2 mm in each direction leading to the turbulence statistics in the whole volume.
Additionally, a two-dimensional three-component (2D3C) velocity measurement of the inlet slice 100 mm stream up of the first jet was performed to obtain a suitable inlet boundary condition for CFD simulations.

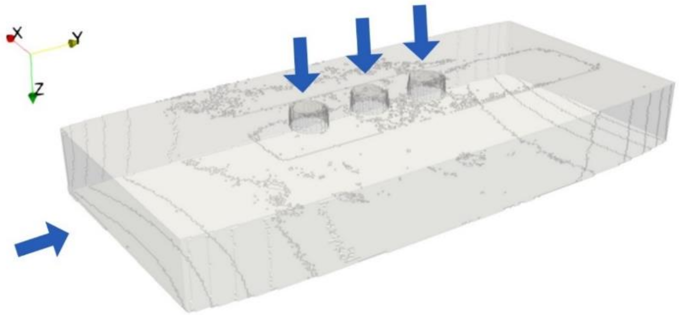

Figure 3: Three-dimensional measurement volume for impinging jets with crossflow.

Results and Discussion

The result of the 3D3C velocity measurement of three impinging jets with a crossflow ratio of 0.1 is shown in Figure 4. It can be seen that there is almost no deflection of the upstream jet by the crossflow. The effect of the crossflow is substantially stronger for the middle and downstream jets.

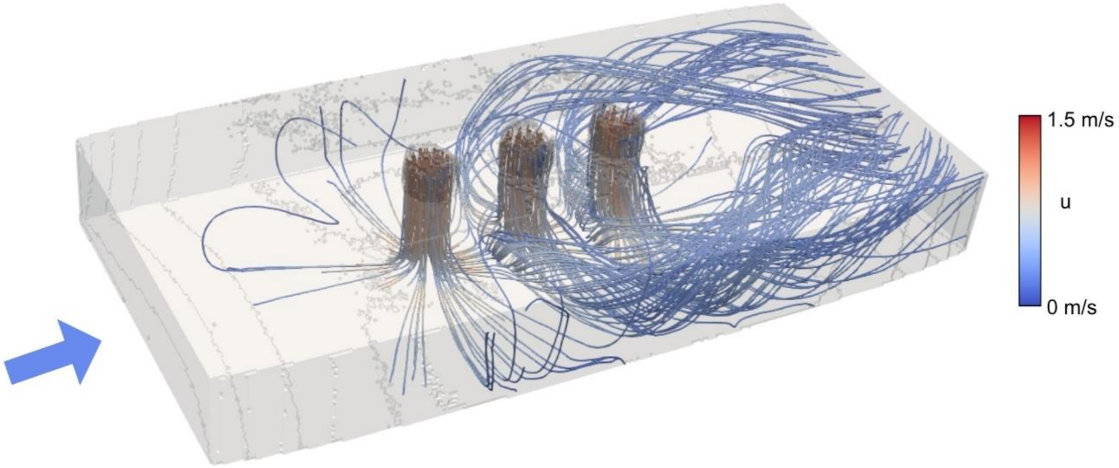

Figure 4: Results of the 3D3C velocity measurement depicted in streamlines.

The velocity field in the symmetry plane, depicted in Figure 5, shows more details of these flow characteristics. It can be seen that the two stagnation points between the jets are moved downstream. Also, the position and intensity of the upwash is affected significantly by the crossflow.

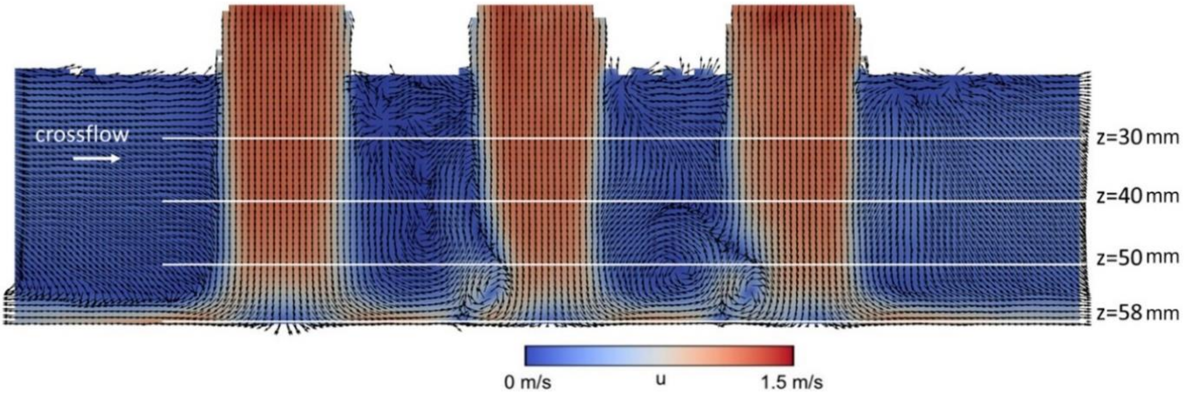

Figure 5: Velocity field in a side view with velocity vectors.

The velocity distribution in planes along the z-axes depicted in Figure 5 is shown in Figure 6. The interactions between jets and crossflow become stronger closer to the target plate. At z=30 mm which is located at 1/4th of the jet length, the cross-section of the jets shows little to no deflection, whereas the deformation of the jets increases closer to the target plate. The jet cores of the second and third jets in line take on a deformed oval shape.

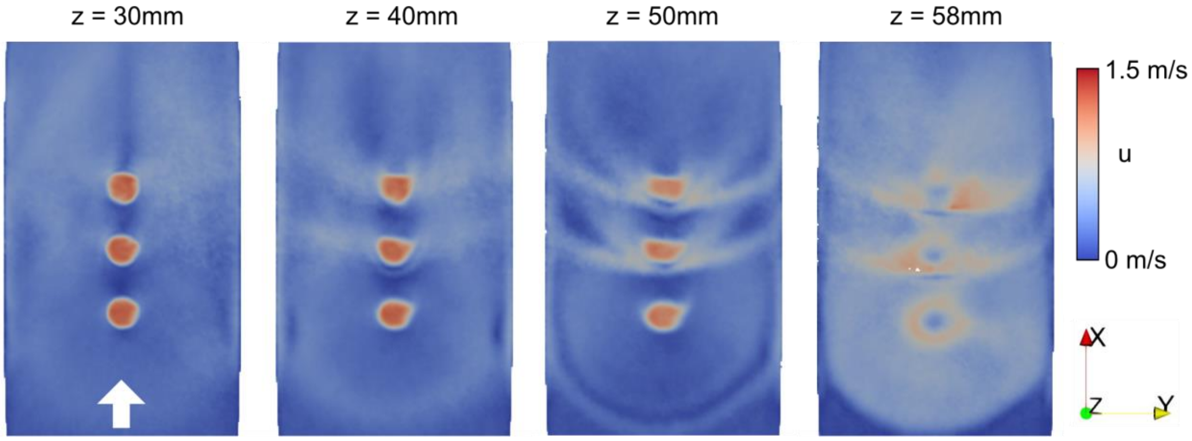

Figure 6: Mean velocity field along the z-axes.

The results of the 3D6C RST measurements are shown in Figure 7 by means of the turbulent kinetic energy (TKE), calculated from the components of the measured RST. The strongest TKE is observed near the stagnation points between the jets.

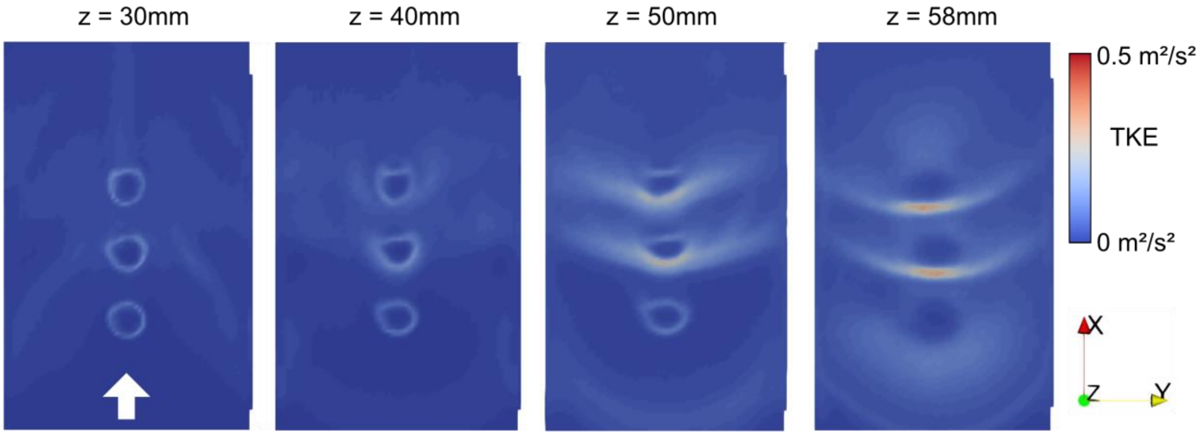

Figure 7: Turbulent kinetic energy (TKE), calculated from the RST components, along the z-axes.

The 3D measurements of the mean velocity field and the components of the RST on the same field of view together with the 2D velocity measurement of the inlet plane form a solid basis for validating CFD simulations of impingement cooling systems.
In addition, the eddy viscosity can be calculated from the measurements of the three-dimensional velocity field and the turbulence statistics. The component of the eddy viscosity in the direction of the jet flow and the crossflow is calculated using

$$\nu_{t_{xz}} = \frac{-\overline{u_x' u_z'}}{\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right)}$$

with $\overline{u_x' u_z'}$ being the RST component and u being the mean velocity.

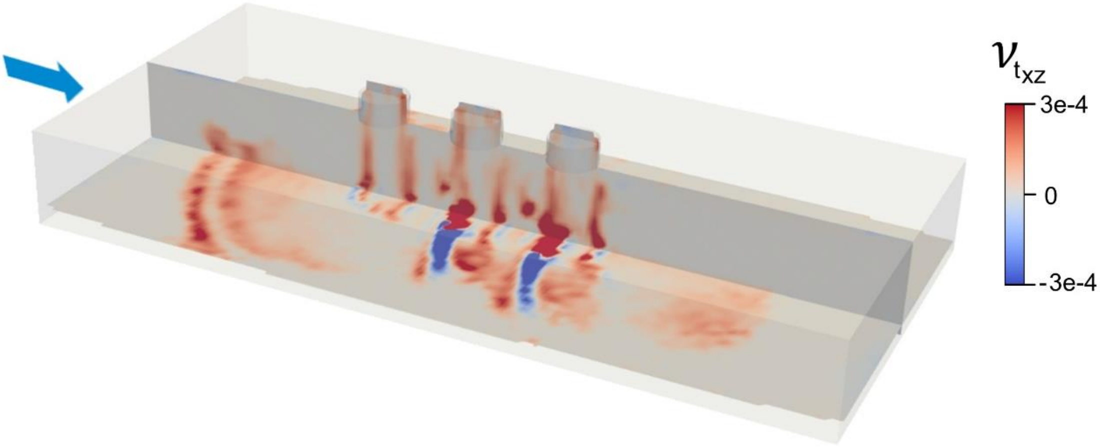

Figure 8: Eddy viscosity calculated from the measured mean velocity field and the measured Reynolds Stress Tensor (RST) data.

Figure 8 shows the eddy viscosity component $\nu_{t_{xz}}$ in the three-dimensional FOV. Regions where the eddy viscosity is below zero are the regions where the eddy viscosity hypothesis is invalid. This three-dimensional eddy viscosity field can be used as a decision guidance for the choice of a suitable turbulence model. If eddy viscosity-based turbulence models are classified as not sufficiently accurate, more complex models can be used and validated by the available RST data if feasible.

Conclusion

This paper presents a comprehensive measurement campaign to study the interactions of impinging jets with crossflow. The three-dimensional measurement technique MRV was used to acquire the mean velocity field and the RST in the entire flow field. These data sets can be used to validate and calibrate turbulence models for RANS simulations used in impingement cooling design. In addition, the eddy viscosity can be calculated and used to choose a suitable turbulence model with the measured quantities.
This generation of extensive and complete experimental data for validation purposes is not limited to impingement cooling cases but can be used for various complex flow structures.

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