STEADY FLUID FLOW INVESTIGATION USING L2F AND PIV IN A MULTI-PASS COOLANT CHANNEL

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ABSTRACT
Fluid flow and pressure loss in a stationary two-pass coolant channel system is investigated experimentally and numerically. One of the main objectives of this paper is to describe the capability of different measuring techniques, i.e. L2F versus PIV. Results of pressure losses are not the objective of this paper. The investigated system has an engine-near lay-out with an 180° turn including a turning vane, and has smooth walls. As a first step, the system is analyzed in non-rotating mode. During future work it will rotate about an axis orthogonal to the center-line of the straight passes. The results shown in this paper demonstrate the effect of rotation with isothermal flow condition excluding any buoyancy. Turbulent channel flow with a Reynolds number of 25,000 and 50,000, derived with the hydraulic diameter of the first pass, was investigated.

At the test rig at DLR several test models were mounted to investigate pressure drop behavior and fluid motion separately. Numerical investigations regarding flow structure and pressure drop have been carried out in order to validate a CFD code against the experimental data. The numerical solution is compared with streamline pictures, obtained from flow visualization of all walls using oil flow technique, and near wall PIV results. Mid-span flow distribution is received from laser light sheet visualization technique with oil fog as indicator and also from PIV.

The results presented in this paper clarify the complex flow situation given by the two pass system with inherent turn. Especially in the bend region and behind the turning vane appear separation regions, vortices and a wake with high local turbulence. These very demanding measuring task represents a benchmark test case for the different used measuring techniques (L2F, PIV and visualization).

INTRODUCTION
The aero-engine industry and the power generation industry operate in a highly competitive market. Therefore high requirements in terms of high technology development as well as cost and development times reduction are constant major objectives. On the other hand, environmental and safety constraints are an increasingly stringent necessity, which enforces the demand for new technologies. Currently the industry relies on expensive and time consuming rig test programs, whereas the existing numerical design tools have a number of deficiencies in accurately describing the complex multi-pass coolant channel flow. Under these conditions the Institute of Propulsion Technology is involved in national and European research programs aimed to providing the industry with high quality experimental data from the flow field for CFD validation.

In past projects the flow behavior in rotating passages was analyzed at DLR using wall pressure measurements to obtain the pressure drop. In addition, Laser-2-Focus velocimetry (L2F) was used to obtain flow velocity components and fluctuations. Although time-consuming, this non-intrusive, single-point
measurement technique worked very well within straight and smooth duct flows, which generally have a moderate degree of turbulence. However, state of the art, serpentine shaped, multi-pass systems are equipped with ribbed walls, in order to improve heat exchange which is typical in realistic configurations. In this case L2F velocimetry was not able to measure accurate flow properties due to the increased turbulence intensities in the vicinity of the ribs as in the bend region and further downstream. The dividing wall separating the two passages forces the flow into a sharp turn which generally results in a flow separation. The flow within the separation bubble itself is very unsteady.

An important work package within these research programs is to provide detailed information of the flow field inside the multi-pass coolant channel using single point measurement techniques such as Laser 2 Focus (L2F) velocimetry [SCHODL, 1977] and planar techniques such as Planar Doppler Velocimetry (PDV) [RÖHLE, 2000] or Particle Image Velocimetry (PIV) [ADRIAN, 1991, WILLERT, GHAHIB, 1991, RAFFEL et al, 1998]. Modern planar measurement techniques such as PIV are capable of obtaining complete maps of flows even at high turbulence. As a first step toward applying this technique, a multi-pass cooling system is investigated in stationary (e.g. non-rotating) mode using two-component PIV. The new results are compared with results from L2F, flow visualization and CFD. The high quality of the obtained new results encourage the application of two-component PIV to the rotating system. As a logical consequence, the application of three-component PIV will be necessary to obtain the complete flow field information within the complex flow passages. This paper’s intention is to report on the status of applicability of PIV in a multi-pass coolant channel.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>dh</td>
<td>Hydraulic diameter</td>
</tr>
<tr>
<td>f</td>
<td>Lens focal length</td>
</tr>
<tr>
<td>f#</td>
<td>Lens f-number</td>
</tr>
<tr>
<td>ν</td>
<td>Kinematic viscosity</td>
</tr>
<tr>
<td>n</td>
<td>Speed</td>
</tr>
<tr>
<td>Re</td>
<td>REYNOLDS number, Re=ρv_d/η</td>
</tr>
<tr>
<td>τ</td>
<td>Pulse delay</td>
</tr>
<tr>
<td>v</td>
<td>Volumetric absolute velocity</td>
</tr>
<tr>
<td>v₀</td>
<td>Intake velocity</td>
</tr>
<tr>
<td>x, y, z</td>
<td>CARTESIAN co-ordinates</td>
</tr>
</tbody>
</table>

**Abbreviations**

t.v. | turning vane
s.s. | suction side
t.e. | trailing edge

**TEST FACILITY AND INSTRUMENTATION**

**Test Facility**

A large-scale coolant multipass-system rotating spanwise was investigated during the experiments. Air is supplied in the rig through a rotary sealing assembly, a second one is used for venting after the air has passed through the test section. Both are mounted to the end of the double hollow shaft. A schematic of the test rig is given in Figure 1. More detailed information about the test facility are presented in [RATHJEN et al, 1999]. Reynolds number and rotation number can be adjusted appropriately to the models inserted.

**Test Model Geometry**

Figure 2 shows a schematic draw of the model. The test section consists of a leading edge duct (first pass) with trapezoidal cross-section extending radially outward, a 180° bend with a 90° turning vane and a second pass with different trapezoidal cross-section extending radially inward. The ratio between the hydraulic diameter of the second pass and the hydraulic diameter of the first pass is 1.5. The length of each pass is 9.975 dh, where dh denotes the hydraulic diameter of the first passage.

In the bend region the flow is not only directed through the 180° u-bend but also perpendicular to that following the turbine airfoil shape. The test section is 12 dh long. The distance between the tip plate and the divider wall is about 1.875 dh.

The turning vane is mounted in the circumferential mid-plane of the bend and is 0.12 dh thick. The divider wall has a thickness of 0.3 dh.

The model has a small plenum chamber and an inlet and outlet length, both are 3 dh long.

**Measuring Techniques**

**L2F – Laser-Two-Focus Velocimetry**

For the non-intrusive measurement of flow velocities, angles and fluctuations inside the rotating duct the Laser-2-Focus (L2F) technique [BEVERSDFORFF, HEIN, SCHODL, 1992] has been applied using a newly developed optical unit to direct the laser beams into the rotating frame of reference. The optical device mounted in front of the rotor enables the system to stationary non-triggered signal processing. Figure 3
shows a schematic drawing of the optical set-up used in this kind of application. Following the beam path from the laser to the probe volume, the laser light is emitted by an Ar⁺ ion laser of 4 Watt power output which is connected to the launching unit mounted to the test rig by an optical fiber for vibration decoupling purpose. In this unit, the laser beam is split into two beams. The rotation prism co-rotating with half the speed of the rotor focuses the two beams in the rotating frame of reference, saving invariable orientation of the light barrier in relation to the rotating duct. From the turning axis the beams are guided by several mirrors to the measuring point inside the duct finally passing a plane optical window in the duct wall. Adjustment of the mirrors enables flow measurements at different lateral and axial duct locations. The two beams are highly focused in two foci (measuring volume) by means of a traversable focus lens mounted to the rotor. Traversing of the lens, which is also possible during rotation, moves the probe volume within the test section along a line (Figure 4). The L2F method is based on time of flight measurements of co-flowing particles. Small oil droplets with a size less than 0.5 µm were added to the flow before entering the shaft. The flow-following behavior of these particles even at high accelerations has been successfully demonstrated and thereby a correlation between particle and flow velocity is assured [SCHODL, 1977]. The passing of a particle conveyed by the flow through the light barrier (i.e. the 2 foci) produces two consecutive light pulses. The time interval between the signals and the known distance of the foci give the flow velocity. The light pulses received by the same optic in back scattering in the outer area - the inner part is used for launching the laser beams - are imaged at two photo multipliers.

PIV – Particle Image Velocimetry

Now, the flow field is measured first in steady mode by means of PIV. This modern technique is a scientific tool for qualitative and quantitative investigations of flow fields. The principle of the PIV with laser, light sheet optic, laser light sheet and test section is shown in Figure 5 and the existing test set-up is shown in Figure 6. PIV is based on the principle to capture the image of the flow field two times (pulse delay in the range of 5 µs). In the flow there are tracer particles (aerosol) with an average size of 0.1 µm. These particles reflect in the laser light sheet, which is formed with a light sheet optic consisting of a system of one spherical and two cylindrical lenses. It generates a light sheet with a thickness of 1 mm and a divergent angle of 24°. The laser light sheet is adjustable and visualizes the front channel as well as the back channel, due to a mirror. Illumination was provided by a standard, frequency-doubled, double-cavity Nd:YAG laser (NewWave, Gemini PIV) with a pulse energy of up to 120 mJ per pulse at 532 nm. On the recording side, a thermo-electrically cooled, interline transfer CCD camera (PCO, 1280 x 1024 pixel resolution) with a f = 55 mm, f # 2.8 lens (Nikon) was used. A bandpass filter with central frequency 532 nm and width 5 nm (FWHM) placed in front of the lens rejected most of the unwanted radiation. The pulse delay between the laser pulses varied between τ = 6 µs (investigation of mean flow) and τ = 12 µs (investigation of secondary flow). The high resolution CCD camera takes two pictures, depending on the pulsing laser. Each picture has a size of 2.5 MB. The CCD camera, perpendicularly positioned to the light sheet, is a so-called cross correlation camera having double-frame single-exposure evaluation. Now it is possible to calculate the value, direction and orientation of the absolute velocities with the Cross Correlation Function (CCF). 50 pictures at each camera position are taken to calculate the mean value of the absolute velocity. For the secondary flow investigations (cut 1...6) into the first pass from the multi-pass coolant channel one camera positions is adjusted (Figure 7a) and for the investigations of the mean flow (cut 1 & 2) into the second pass of the multi-pass coolant channel five camera positions are necessary (Figure 7b).

OFV – Oil Flow Visualization (Wall Flow)

To analyze the flow phenomena, several kinds of flow visualization techniques have been applied. Using the oil flow visualization method, wall streamline patterns could be achieved within the duct. It is possible to show and localize the boundary layer separation, the reverse flow and vortex regions next to the surface. To some extent it is possible to draw conclusions from the two-dimensional method for application to the strongly three-dimensional character of the flow field. The duct wall has been previously painted with a mixture consisting of oil of appropriate viscosity, oil acid and for contrast purpose Titanium dioxide (TiO₂) and has been then exposed to the flow for a time period long enough to dry the oil paint. The duct is dividable in two halves and is opened after the test run for viewing. A detailed description of the range of application is given in [MALTBY, KEATING, 1962].

LFV – Laser Light Sheet Flow Visualization (Flow)

To obtain more information about the flow around the turning vane and the separation zone, a camera system has been installed to the Perspex duct observ-
One capture from the video of the laser light sheet visualization is shown in Figure 13. Also this tech-
nique confirms the already recognized flow phenomena.

SUMMARY

This paper describes experimental investigations of a typical two-pass cooling channel system of a turbine blade with respect to fluid flow phenomena affected by geometry effects and flow turning supported by a turning vane. A complex flow situation is present showing several kind of separation and vortices:

(i) At the upper surface of the t.v. due to negative incidence off the incoming flow,
(ii) further downstream at the s.s. of the t.v. due to too strong curvature,
(iii) at the dividing wall due to the sharp edge where the flow is incapable to follow.

The jet region under the t.v. and the wake from the t.v. are leading to high velocity gradients and corresponding high shear stresses at the contact layer producing very high turbulence levels there. Higher turbulence levels than 30% leads to uncertainties in L2F results. With supposed levels of 50% and more the PIV technique has not a problems. But to give an accurate value of the turbulence level you will need about 2000 PIV pictures which need high storage capacity.

The performed flow visualization and simulation are very helpful in that case to understand the interaction of all apparent effects. The presented experiments were mainly intended to assess the feasibility of applying PIV in a multi-pass cooling channel used for applied cooling research. The results have shown that it is possible to apply PIV in a multi-pass cooling channel. The application of PIV is approved and will be adopted to the rotating system in the near future.

REFERENCES


FIGURES

Figure 1. Schematics of the test rig at DLR-Cologne

Figure 2. Schematic of test model geometry

Figure 3. Optical set-up for the L2F-measurements

Figure 4. Measuring lines for the L2F-measurements

Figure 5. Principle of Particle-Image Velocimetry

Figure 6. Test set-up for stationary PIV-measurements
Figure 7. Camera and cut positions. a. Secondary flow investigations into first pass (cut 1...6); b. Mean flow investigation into second pass (cut 1 & 2)

Figure 8. Comparison of the axial velocity component between L2F and PIV measurement in the second pass at the position \( z = 193 \text{ mm} \). a cut 1; b cut 2; (according Figure 7b)
Figure 9. Secondary flow velocity distribution in six cross cuts of the first pass measured with PIV (Re=25.000)
Figure 10. Mean flow velocity distribution in two longitudinal cuts of the second pass measured with PIV (Re=25,000)
Figure 11. Comparison between calculated and visualized wall velocities and streamlines on pressure side (left) and suction side (right), non-rotating (Re=50,000)

Figure 12. Numerical simulation at cut 3 in first pass

Figure 13. Pattern of laser light sheet visualization (bend)