PDA AND PIV MEASUREMENTS IN A TWO-PHASE-FLOW TRANSONIC CASCADE WIND-TUNNEL

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ABSTRACT

The investigations concern the velocity distribution in an axial-compressor cascade in the 2-phase-flow wind-tunnel at the Helmut-Schmidt-University in Hamburg, Germany. The test facility and the measurement techniques are described briefly in this paper.

Results of LDA measurements and CFD-simulations complement each other. Results of PIV measurements show the same velocity distribution but not as obvious as the LDA measurements. A comparison between the LDA results and measurements with a five-hole-probe shows a good qualitative agreement.

INTRODUCTION

Inlet fogging and high fogging systems for gas turbine power augmentation are drawing increasing attention to recent research. In both systems a fine mist of water is injected into the intake of a gas turbine. While the water evaporates in the intake of the gas turbine when using inlet fogging, at the high fogging system some water is carried into the compressor of the gas turbine where it evaporates. Both methods lead to lower temperature of the process-air and thus to a reduction in the work of compression which results in a higher power output of the gas turbine. Similar effects occur if a plane flies through clouds or rain for example.

This is why two-phase-flow in turbo-machines, especially air as the gaseous phase and water as the liquid phase, has become the topic of research projects in recent years. Most of these projects deal with the evaporation process and the effects on the work of compression. Mathematical models have been derived to describe the effects of 2-phase-flow in turbo-machines and their performance.

Only very few research projects deal with the actual flow of the two phases around the compressor blades and the influence of the liquid phase on the airflow in the compressor. At the Helmut-Schmidt-University in Hamburg the existing cascade wind-tunnel was extended so that it is possible to inject water into the air flow before passing the compressor cascade.

Typically the performance of the compressor cascade, i.e. the Mach number distribution, the stagnation pressure loss and the air deflection are measured by pressure probes like three- or five-hole-probes. In a two-phase-flow it is difficult to apply these probes due to droplets clogging the pressure holes. Therefore alternative non-intrusive measurement techniques for a typical droplet loaded compressor flow have to be investigated.

Both Particle Doppler Analysis (PDA) and Particle Image Velocimetry (PIV) as well as five-hole-probe measurements are the main measurement techniques to observe the flow in the compressor cascade. Before the experiments with water injection are accomplished, the wind-tunnel has to be prepared and the PDA and PIV have to be implemented. The PDA measurements are compared with the pressure-probe measurements.

NOMENCLATURE

d	[mm]	Distance between fringes
d_p	[µm]	Droplet diameter
D_h	[m]	Hydraulic Diameter
Ma	[-]	Mach Number
Re	[-]	Reynolds Number
T_u	[-]	Turbulence Level
$\Delta\Phi_{12}$	[]	Phase shift
β	[°]	Disperse angle
β_{12}	[-]	Diameter conversion factor
λ	[nm]	Laser-beam wavelength
θ	[°]	Angel between laser-beams

THE TEST FACILITY

The existing cascade wind-tunnel at the Laboratory of Turbomachiery of the Helmut-Schmidt-University was extended, so that it allows the injection of tracer particles or water for optical measurement techniques.

The wind-tunnel is driven by a radial compressor with a shaft power of 2 MW followed by a heat exchanger to cool down the compressed air in a wide temperature range. After passing the plenum chamber where tracer particles or water are injected the air flows through a 1800 mm long branch towards the measurement section. Both the branch and the measurement section have a height of 300 mm and a width 100 mm. Due to this long intake a CFD simulation was performed to investigate the development of the boundary layer at the walls. The results show a boundary layer at the side walls that is not negligible, since compressor blades are very vulnerable to side wall effects (see [1]). Therefore the compressor cascade consisting of seven blades is mounted between two Plexiglas plates (see Figure 1) so that the boundary

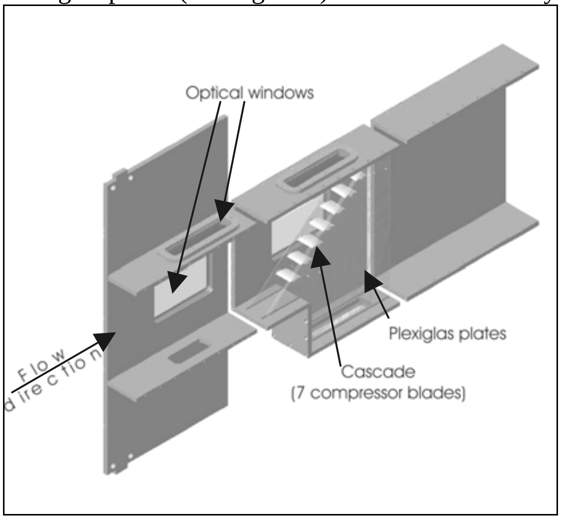

Figure 1: The Measurement Section

layer is cut of and the blades are passed by an almost undisturbed airflow. Hence the blades have a height of 50 mm and a chord length of approximately 40 mm. To adjust the stagger angle the Plexiglas plates have to be replaced.

BK7 optical glass-windows are mounted on the top, the bottom and on the side walls of the measurement section and 400 mm upstream to assure optical accessibility.

At the beginning of the cascade the height of the wind-tunnel is expanded to 450 mm so that the redirected airflow is not constrained by the walls. Due to vibrations of the Plexiglas plates various reinforcements are mounted in the measurement section which make it possible to realize a maximum Mach number of Ma = 0.7 upstream of the cascade. With the hydraulic diameter D_h = 0.15 m the Reynolds number at the Mach number mentioned above is Re = $2.4 \cdot 10^6$. The turbulence level is approximately T_u = 0.025 in the main flow direction upstream of the cascade.

PHASE DOPPLER ANALYSIS

Before the principle of the Phase Doppler Analysis (PDA) is explained the principle of the Laser Doppler Anemometry (LDA) has to be known. The LDA is an non-intrusive, absolute measurement technique with very high accuracy and high spatial and temporal resolution.

Figure 2 shows the principle of the LDA in backscatter mode. Two monochrome, coherent laser-beams of the same

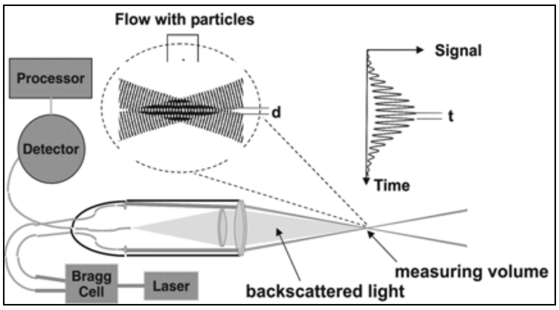

Figure 2: Principle of LDA

wavelength λ are crossing each other with an angle θ. The measuring plane is located in the cross-section of the laser-beams and consists of destructive and constructive fringes with the distance d. A seeding particle in the flow scatters the light of the constructive fringes which is intercepted by the detector. The measured Doppler-frequency f_D of the scattered light is directly proportional to the velocity component of the particle perpendicular to the fringes

$$f_D = \frac{2}{\lambda} v \sin\frac{\theta}{2}. \qquad (1)$$

Since one of the laser-beams is shifted in frequency by 40 MHz by the so-called bragg-cell the fringes are moving in one direction in the measuring volume. This movement makes it possible to determine the flow direction of the particle.

To measure 2D velocity vectors another two laser-beams span a second measuring plane perpendicular to the first one at the same point.

In a PDA system two detectors exist in a known position relative to each other. Hence, both receive the scattered light of the particle with a change in phase of the Doppler-burst (see Figure 3). From this change in phase it is possible to obtain the size of the particle assuming the particle

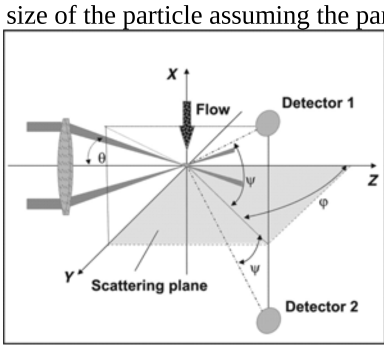

Figure 3: Principle of PDA

has a spherical shape. The phase shift $\Delta\Phi_{12}$ is proportional to the droplet diameter d_p

$$\Delta\Phi_{12} = d_p \cdot \beta_{12}. \qquad (2)$$

Here β_{12} is a diameter conversion factor which depends on the scattering mode used by the geometrical set-up of the system. Further information about LDA and PDA can be found in [2].

For the experiments described here the PDA system is set up as follows. The system consists of an Ar-Ion-Laser. The two laser-beams with a wavelength of 514.5 nm are used to measure the main velocity component (horizontal) and the particle size. The other two beams with a wavelength of 488 nm measure the velocity component perpendicular to the main component (vertical). The sending probe has a focal length of 160 mm and the receiving probe with three detectors has a focal length of 310 mm.

The first order refraction of the scattered light is used to measure the particle size so that the receiving optic is located at an angle of 30° relative to the sending optic in the scattering plane. Therefore the sending and receiving probes are mounted at different sides of the measurement section (see Figure 4). The two probes are mounted to a traverse system so that a simultaneous movement of both optics is possible.

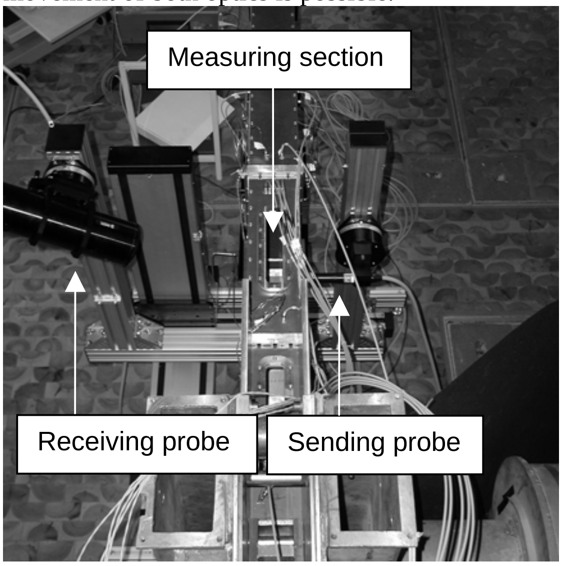

Figure 4: Experimental setup

PARTICLE IMAGE VELOCIMETRY

The second measuring technique used at the test facility is the Particle Image Velocimetry (PIV). This technique is also a non-intrusive system which is capable of measuring instantaneous flow fields. Figure 5 shows the principle of the PIV.

A pulsed laser provides a laser-beam which is spanned to a light sheet. The illuminated seeding particles in the flow are captured by a CCD-camera. Two consecutive pictures are taken with a time interval Δt. Using cross correlation, the two pictures are compared to each other, wherefore the pictures are split into interrogation windows, to derive the particle displacements. With the known Δt the velocity vectors can be computed. Further information on PIV can be found in [3].

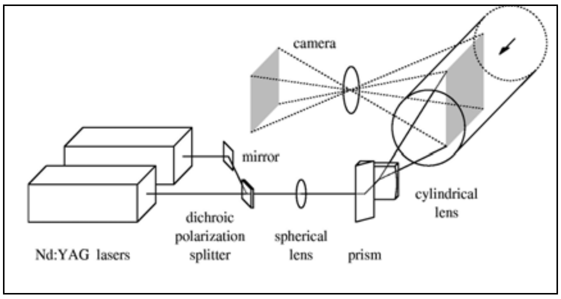

Figure 5: Principle of PIV

For the experiments described here the PIV system is set up as follows. A double pulsed Nd:YAG-Laser provides laser light with a wavelength of 532 nm and a maximum energy of 50 mJ. The laser-beam is guided through a laser arm to the optic which forms the light sheet. This optic is mounted near the measuring section so that the laser sheet directly illuminates the desired measuring plane in the measuring section. The CCD-camera is mounted perpendicular to the laser sheet. The camera has a resolution of 1260x1024 pixels, where one pixel has the size of 6.7 µm x 6.7 µm, and a frame rate of 8Hz. The minimum time interval Δt is 200 ns.

For the experiments with the parameters (Ma, Re, Tu) described above the following settings are used. The time interval Δt is set to 2 µs and the size of the interrogation window is set to 256 x 256 pixel using adaptive multi-pass with decreasingly smaller sizes of 32 x 32 pixel.

SEEDING THE FLOW

Before measurements with injected water droplets of different sizes can be accomplished the airflow itself has to be analysed. In [4] it is proposed that particles smaller 1 µm in size are small enough to follow the flow as desired and deliver signals intensive enough to be detected.

Therefore a particle atomizer is used which delivers particles of the desired size (approximately 0.3 µm). As particle medium Di-Ethyl-Hexyl-Sebacate (DEHS) is used. These particles do not evaporate on their way from the plenum chamber to the measuring section and deliver good signals. Nevertheless these particles accumulate on the glass windows and Plexiglas plates, which leads to lower signal-to-noise-ratios (SNR). Since a relatively low density of particles is needed for LDA measurements (the particle generator is set up so it generates an aerosol flow rate of approximately 8.3 l/min) measuring times of more than 4 hours can be accomplished before cleaning of the windows is necessary. But for PIV measurements a much higher density of particles (at least twice as much as for LDA measurements) is required and the higher accumulation of particles on the windows leads to unusable pictures within 30 minutes to one hour. Therefore the higher particle supply is only turned on while PIV measurements are performed and is turned off right after.

Depending on the boundary conditions, condensation upstream of the cascades occurs. If those water particles are small enough, they are used as seeding particles. Which leads to longer measurement times.

Because particles smaller than 1 µm cannot be measured with the PDA system the particle sizes of the DEHS are not discussed here. Experiments with injected water showed that the particle sizes of the injected water range form 10 to 100 µm depending on the water pressure and nozzle used. But the windows fog up very quickly although demineralised water is used, which shortens measurement times. The following discussion focuses on the LDA measurements.

FIVE-HOLE-PROBE

Measurements with a five-hole-probe are accomplished to compare the results of the LDA and PIV measurements. Figure 6 shows a five-hole-probe with the relevant geometric parameters.

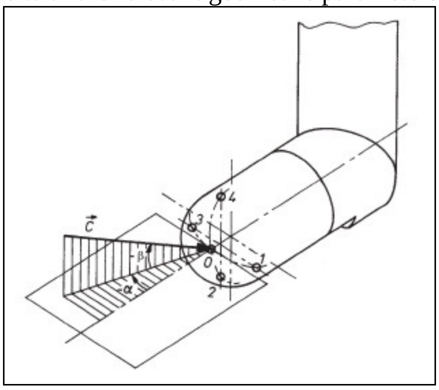

Figure 6: Five-Hole-Probe

The window below the cascade is exchanged with a metal plate which allows to insert the probe into the measuring section to perform measurements behind the blades. The probe is adjusted so that the pressure difference between hole 1 and 3 is zero. Using the traverse system the probe is moved up behind the blades taking the stagger angle of the blades into account.

The results of the pressure measurements are analysed using multi-parameter approximation to obtain the local angles of the velocity vectors and the local Mach number. For more information on the multi-parameter approximation see [5].

RESULTS

Figure 7 shows the Mach number distribution obtained form early CFD simulations using the standard k-ε-turbulence model. Because not all boundary conditions were known at the time the simulations were performed only the qualitative Mach number distribution is discussed here.

It can be seen, that the stagnation point is situated at the suction side close to the leading edge resulting in the increase in velocity at the pressure side close to the leading edge. This implies a slight off-design incidence angle.

As expected a high Mach number is also visible at the suction side in the last third of the profile. Compared to the suction side the boundary layer at the pressure side is much more developed and a wake at the trailing edge forms.

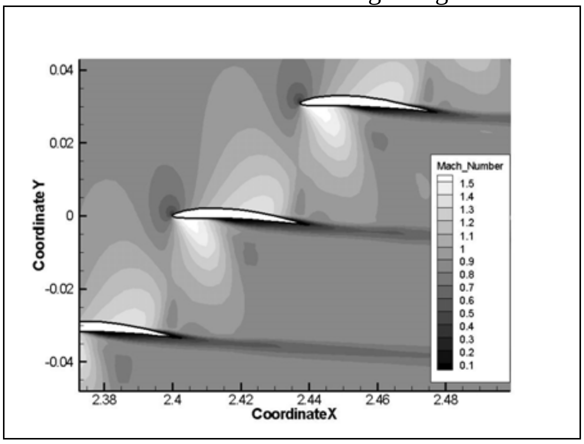

Figure 7: CFD Simulation

Results of LDA measurements at the middle compressor blade in the measuring section are shown in Figure 8. Due to the experimental set-up

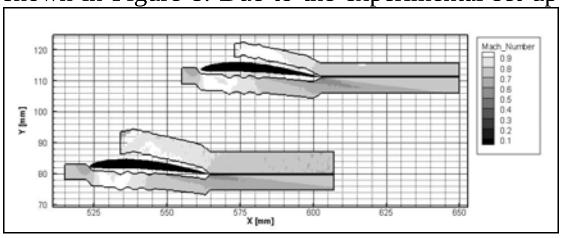

Figure 8: LDA Measurements

of the PDA system and the mount of the blades it is not possible to place the nodes of the measurement-grid very close to the blade. Also the receiving probe has to be mounted 30° above or below the sending probe depending whether measurements above or below the blades are performed. The front section above the blades can't be investigated with the PDA because the Plexiglas plates have a bevel which constrains the measurements. Further the SNR increases with longer measurement times due to accumulation of particles on the windows and Plexiglas plates. Because the measurement-grids are very small meshed (up to 0.25 mm in x and y direction) it is not possible to accomplish all the measurements shown above in one day. Therefore there are small differences in the absolute values of the Mach number distribution around the blades when both blades are compared to each other.

A closer lock at the velocity distribution is taken in Figure 9. Like in Figure 8 the upper and

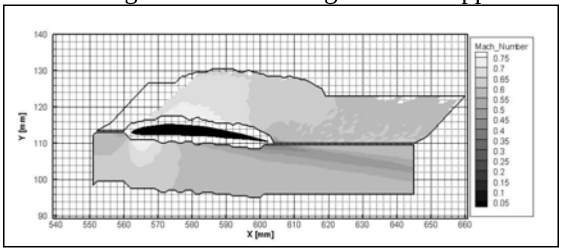

Figure 9: Measured Mach number distribution (LDA)

the lower part of the measurements were acquired on to consecutive days. Nevertheless a good match of the results can be seen. Like the CFD simulations the LDA measurements show the same Mach number distribution.

In the upper left corner of the lower measuring section the run-out of the low velocity resulting from the stagnation point is seen. Also the high increase of velocity on the pressure side close to the leading edge due to the slight off-design incidence angle can be observed. The increase in Mach number at the suction side as well as the development of the boundary layer on the pressure and the suction side and the wake predicted by the CFD-simulations were measured with the LDA.

The root-mean-square (RMS) values of the main flow velocity is shown in Figure 10. The

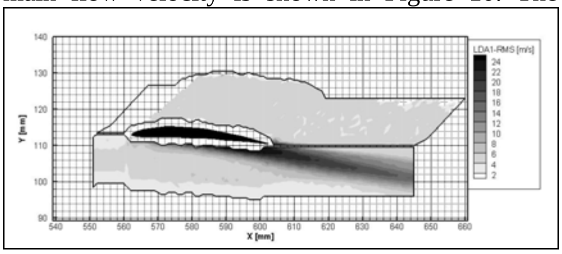

Figure 10: Measured RMS of main flow velocity (LDA)

incoming flow shows low RMS values which correspond to the turbulence level of 0.025 of the undisturbed flow upstream of the cascade. Higher RMS values are perceived in the wake behind the blade due to the high shear flow.

Figure 11 shows PIV measurements for the same boundary conditions like the LDA measurements. The area of interest is illuminated by the laser sheet from below the measuring section. The results of the PIV measurements are averaged over 20 consecutive taken double-frame pictures, which turned out not to be sufficient. Not illuminated parts of the pictures are masked so that no fault-vectors due to unintentional light reflection are shown. As it can be seen the velocity distribution is comparable to the distribution obtained from the LDA measurements and the CFD simulation. The acceleration of the flow close to Ma = 0.9 on the pressure side of the blades and the wake behind the blade is noticed. Condensed water is used as tracer particles here, and an inhomogeneous seeding can be seen in the lower part of the picture.

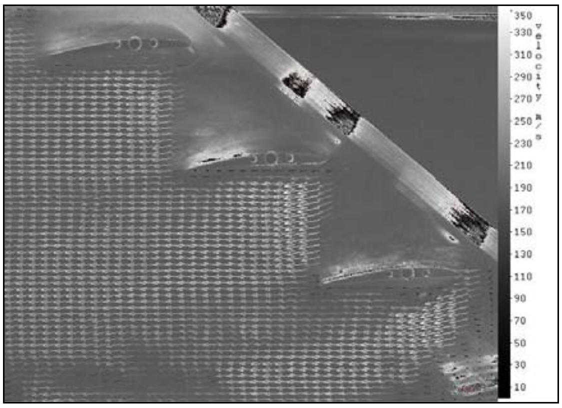

Figure 11: PIV Measurements

The results of the five-hole-probe measurements are shown in Figure 12. The

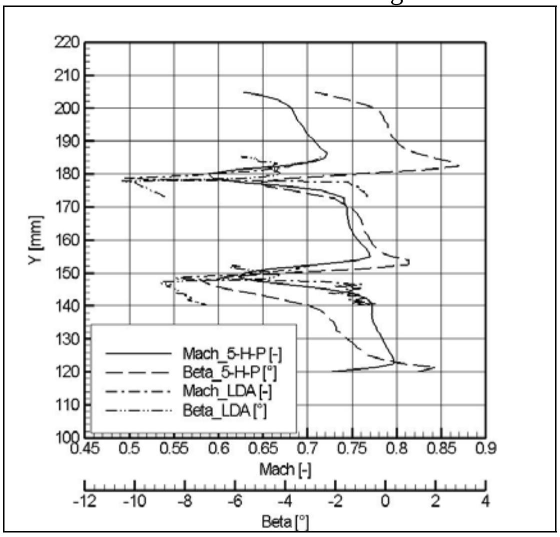

Figure 12: Five-Hole-Probe Measurements

measurements were accomplished over three consecutive blades in the middle of the cascade. Also shown in this graph are the angle and Mach-number distribution behind the blades obtained from the LDA measurements. Similar qualitative results are noticed between the five-hole-probe and the LDA measurements. The difference in absolute numbers can be ascribed to bending of the probe caused by the high flow velocity leading to an decrease in the angle β. In the lower part of the measuring section the probe was standing up straight and the results obtained here are closer to the LDA results. Also the influence of the pressure-probe head is not eliminated in these results and the experiments were performed on different days.

CONCLUSIONS AND FUTURE PROSPECTS

A wind-tunnel for transonic two-phase-flows was designed and tested. The measurement techniques implemented here (LDA/PDA and PIV) were found to be suitable for analyzing the flow in transonic cascades. The results are comparable to measurements with conventional measuring techniques like five-hole-probes. Also early CFD simulations show the same qualitative results.

Problems were encountered with particle accumulation on the optical windows leading to low SNR-values and even to the impossibility of measurements. Also a different alignment of the LDA/PDA probes might has to be thought of to assure the optical accessibility of the entire region of interest around the blades.

The next step will be to measure the velocity distribution and the particle sizes with water injected under different boundary conditions. Also the non-intrusive measurement techniques are to be used to obtain the drag-coefficient when water is injected, because measurements with a five-hole-probe might then not be possible due to water plugging the holes.

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