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Flow Field Measurements by PIV at High Reynolds Numbers

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Stereo PIV measurements have been applied to the wake flow on a high-lift aircraft configuration in the cryogenic pressurized transonic wind tunnel ETW at realistic Mach and Reynolds numbers. A cryo PIV system, developed specially for the ETW to enable flow field measurements at gas temperatures down to 110 K and gas pressures of up to 450 kPa, has been adapted to a large measurement field extending over the complete span width of the half wing model. The specific seeding technique using ice particles and the optical systems are described as well as the automation the PIV measurements linked with the wind tunnel control system. First results of the vortical wing wake flow obtained at a Reynolds number of 17 million will be presented.

I. Introduction

Developments for new generation transport aircraft usually require comprehensive wind tunnels tests at real flight conditions, viz. mainly a matching of the Mach and Reynolds numbers. This means that transonic Mach numbers in the range of M = 0.15 – 0.9 at high Reynolds numbers ranging from R = 10 to 80 million have to be simulated on scaled aircraft models. Such conditions are presently possible only in the European Transonic Windtunnel (ETW) in Cologne and in the National Transonic Facility (NTF) at NASA Langley. Both facilities adopt the same concept of using a test gas of moderately compressed pure nitrogen at cryogenic temperatures (see Figure 1).

Moreover, advanced image based measurement methods[1,2] have become more and more important for wing optimizations. On such method is the Temperature Sensitive Paint (TSP) technique[2] for detection of transition lines, for example, on wings featuring natural laminar flows (NLF). Such data are also required for validations of CFD computations. Flow field measurements using Particle Image Velocimetry (PIV) have also been used to investigate the performance of wing devices, particularly on high-lift configurations. For example, the influence of the wake flow produced by a nacelle on flow separations on the main wing has been investigated within the EU project Eurolift II using the unsteady as well as time-averaged velocity vector fields obtained in different planes of the flow field[3]. Characteristic flow parameters such as vorticity distributions, turbulent fluctuations or the positions of vortices and their circulation strengths can be used to characterize the flow quantitatively[4]. However, these investigations took place in conventional wind tunnels at moderate Reynolds numbers; i.e. far from realistic flight conditions. Therefore, the possibility of applying PIV in a facility like the ETW is of particular interest.

The specific conditions existing in pressurized cryogenic transonic wind tunnels like the ETW, where gas temperatures down to T_0 = 110 K and pressures of up to p_0 = 450 kPa can be reached, have so far precluded an application of complex optical measurement techniques like PIV. In contrast to most other optical techniques, PIV requires

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in particular high quality imaging to resolve single flow tracers within the whole measurement plane as well as pulsed laser light of high energy for an illumination of the flow field. Main issues are also the generation of suitable tracer particles in cryogenic flow, the limited optical access through a large pressure shell encapsulating the test section and the necessity of placing optical components within a cryogenic environment. Furthermore, optical effects such as light ray deflections (which are also dependent on gas conditions such as temperature and pressure) have to be taken into account.

First quantitative flow field measurements were performed in the ETW by Willert et al., 2005[5] using the Global Doppler Velocimetry (GDV) technique. However, such measurements are complex and very dense flow seeding is needed, which was achieved in the ETW by using ice particles at cryogenic temperatures, albeit with an accompanying risk of icing within the test section. Furthermore, in contrast to PIV, the GDV technique can only measure time averaged flow velocity fields. First measurements in the ETW by means of PIV has been demonstrated by Konrath et al., 2010[6], showing that for PIV a sufficiently dense seeding of ice particles can be achieved by injecting only very small quantities of H_2O, thereby avoiding icing on the wind tunnel walls.

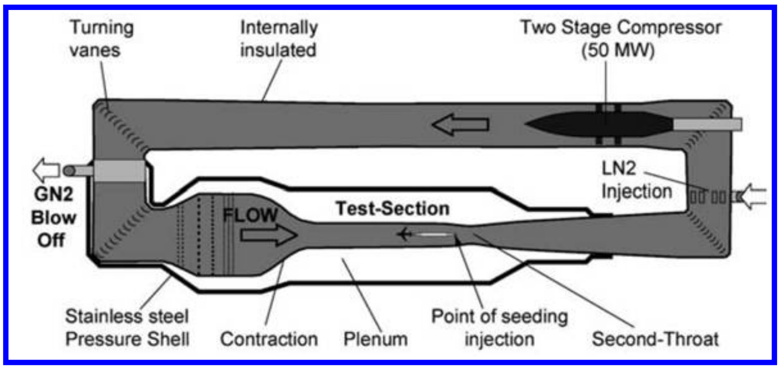

Figure 1. Sketch of the European Transonic Wind tunnel (ETW) facility for flight Mach and Reynolds number testing.

The present paper focuses on the application of a cryo PIV system in the ETW to the wake flow of a high-lift wing configuration (s. Figure 2); this has been carried out in the framework of the research program DeSiReH[8] (Design, Simulation and flight Reynolds number testing for advanced High-lift solutions). The very large measurement field made an adaptation of the cryo PIV system necessary which is described below with special attention to the seeding technique and the optical components as well as the employed PIV arrangement. First results showing the wing wake at flight conditions, viz. at a chord-based Reynolds number of about 17 million, will be presented.

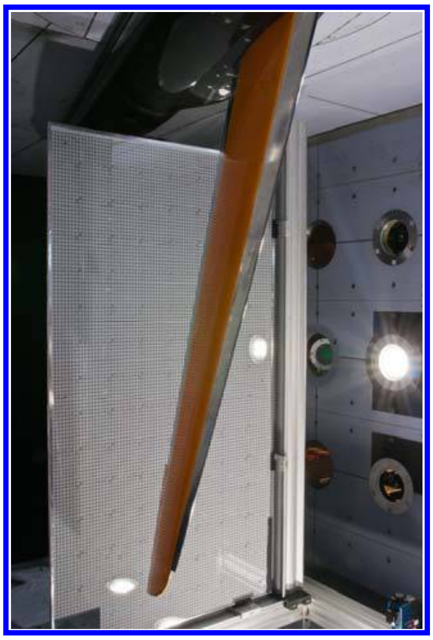

Figure 2. Half-wing high-lift model of DeSiReH[8] in the test section of ETW with the camera calibration target for PIV in the background.

II. Flow tracer generation in ETW

In conventional wind tunnels oil droplets are commonly used as flow tracers for PIV measurements. Oil droplets of the order of about 1 µm can be easily produced; this is small enough to ensure that the tracers can track the flow faithfully even at transonic flow conditions. Furthermore, a moderate tracer concentration in the flow is necessary to get good spatial resolution within the measured vector field. However, in the case of the ETW the usage of oil is not suitable since the wind tunnel circuit is internally cladded with porous insulation material. The droplets would accumulate on the floor and penetrate into the insulation material, meaning that there is a risk of permanent damage of this material. Therefore, new seeding techniques have been tested in the ETW using ice particles (H_2O) at cryogenic temperatures, which would sublimate completely once the gas is warmed up. So the seeding substance can be easily removed from the wind tunnel circuit without leaving residuals, so constituting the big advantage of using ice particles in cryogenic wind tunnels, and particularly so in the case of the ETW.

To determine the temperature limit below which micron-sized ice particles can be used as flow tracers, their life time is calculated as a function of the gas temperature and pressure (using method of Taylor et al, 2006[6]). Here, the lifetime is defined by the sublimation time to get an ice particle diameter of 0.5 µm which is usually just large enough for detectable light scattering off them with a digital camera. The results are plotted in Figure 3 assuming a spherical particle shape and a dry nitrogen environment. From this, a temperature range between 200 K and 240 K can be identified, below which the sublimation rate is quite small and micron-sized ice particles can persist for a long time in the flow. However, in reality, a loss of ice particles has to be taken into account due to the wind tunnel blow-off (s. Figure 1) and due to losses by a settling of the particles on the floor and on other fixtures such as the screens. Above this temperature range the ice particles vanish quickly, which is in good agreement with observations made in the ETW and other cryogenic facilities.

The formation, growth and sublimation of ice particles, however, depend on the dew point, pressure and temperature of the test gas. Also the amount of injected water must be kept small in order to preclude icing on the test section walls. So, the development and testing of specific methods to generate and to control the size distributions of the ice particles within the wind tunnel circuit was necessary. Positive experience was gained with a “cryogenic aerosol” produced external to the wind tunnel circuit. For this an aerosol of small water droplets is generated by a large number of Laskin nozzles (Figure 4a), which is cooled down inside a mixing chamber by extremely cold gaseous nitrogen such that the droplets freeze. The resulting “cryogenic aerosol” is then injected to the circuit using a bypass tube ending at a location beneath the plenum shell, where the seeding system is placed, and at a nozzle at the trailing edge of a profiled center body located in the second throat section (Figure 4b). In this way, the seeding is injected downstream the test section and does not disturb the free stream flow.

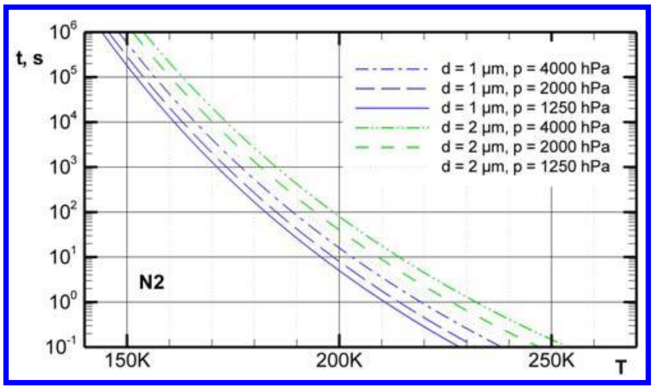

Figure 3. Lifetime of spherical ice particles in terms of time to reach diameter of 0.5 µm from their sublimation using initial diameters of 1 µm and 2 µm due to sublimation in dependency of temperature and pressure assuming a nitrogen environment of zero humidity and no slip velocity between gas and ice particle (calculated according to Taylor et al. 2006[9]).

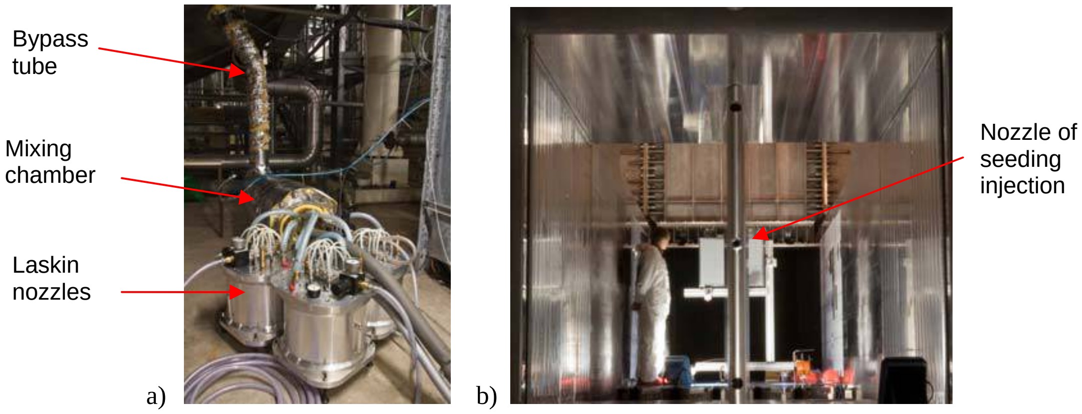

Figure 4. a) Seeding setup with droplet generators and mixing chamber outside the wind tunnel and b) injection into the circuit using a nozzle downstream of the test section; i.e. in the section of the second throat.

III. Optical modules of cryo PIV system

The ETW test section provides a number of window openings in the side walls as well as in the bottom and top walls behind which lamps and observation cameras can be installed, which is necessary since a pressure shell made of stainless steel and with a diameter of 10 m encloses the test section. For a placement of PIV cameras and light sheet optics, special optical modules, consisting of heated housings (because of the cryogenic environment within the plenum) were developed. Since these components are no longer accessible when the wind tunnel is closed for a cool-down, necessary adjustments have to be remotely controlled. Additionally, the operational costs of the ETW make it in particular essential that the whole measurement system and controlling units operate reliably to avoid costly tunnel access. The cooling down or warming up of the whole wind tunnel takes several hours and, for the cooling, consumes a huge amount of liquid nitrogen and electrical power.

The PIV laser is placed outside the wind tunnel plenum and the laser beam is directed via laser mirrors through a small window in the plenum pressure shell to the light-sheet optics module installed in the rear side of the test section wall. Therefore, the beam passes through the pressure shell of the plenum and the foam material for the insulation, which means that the beam is subject to deflections due to optical effects when the pressure or temperature within the plenum changes. Furthermore, shifts of the beam in the test section were anticipated because the structure carrying the ETW test section is mechanically decoupled from the plenum and temperature changes induce relative movements between the test section and the laser outside the wind tunnel. To compensate for beam position and direction deviations inside the light sheet optics module, a beam monitor is employed in this module which permits automatic repositioning and redirection of the laser beam using motorized mirrors. Therewith, the beam is kept on the optical axis of the light sheet forming optics while the tunnel temperature or pressure change. The light-sheet box also consists of optics to remotely adjust the light-sheet orientation and thickness in the test section.

Figure 5a shows the developed light sheet module, containing the light sheet forming optics, the beam monitor and electrical components for the operation of mirror actuators and servo motors such that the whole system can be operated under computer control from the main control room via a single Ethernet fibre connection. A program (written in LabView) allows for a setting of the mirror actuators to perform an automatic alignment of the beam with the optical axis of the module. This option is also used for the setup of the cryo PIV system to save time by not needing to perform manual adjustments.

A CAN bus is used to connected the light sheet modules with the four available camera modules. These modules are designed for stereoscopic viewing; i.e. the housings are inclined by ±45° degrees with respect to the test section walls. Their small size allows for an installation from the inside of the test section through the window openings. Specifically developed camera adapters allow for a remote adjustment of the lens focus, the Scheimpflug angle and lens F-number such that an optimization of the particle imaging is possible. The camera modules can be equipped with high quality lenses (F-Mount) as well as with PCO digital double-frame cameras. For a fast image data transfer to a computer located in the main control room of the ETW, separate optical fibre connections are used.

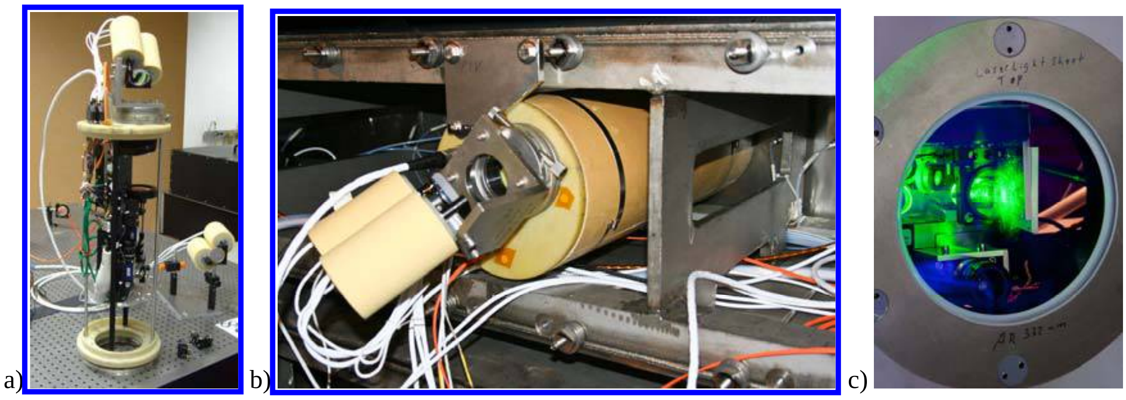

Figure 5. Photos of light sheet module a) Opened module for preparation in laboratory b) installation in side wall of the ETW test section viewed from the rear side c) exit of laser light for an illumination of the measurement plane inside the flow.

Figure 6. a) Sketch of opened camera module b) installation of angled housing viewed from the rear side of the test section c) camera lens behind test section window (as seen from inside).

IV. Application to complete wing wake flow at high Reynolds number

The application of the above-mentioned cryo PIV system for the wake flow on a half-wing model of a high-lift configuration is described below. The objective of the measurements was to obtain the complete flow field of the wing for different angles of attack, including stall conditions at M = 0.2 and R = 17 million, for a realistic transport aircraft at high-lift conditions. The half-span width of the wing model is $b/2 = 1.5$ m so that for PIV a very large measurement area has to be captured. To achieve a sufficiently high spatial resolution in the measurement data, it was decided to use two stereo PIV arrangements in parallel one for the inboard flow field and another one for outboard flow field. The employed arrangement consisting of two light sheet modules and four camera modules is shown in Figure 7. The half wing model is attached to the model support in the top wall of the test section.

A pulsed Nd:YAG dual-cavity laser with pulse energies of 2 x 500 mJ is placed on a rack fixed to the wall of the wind tunnel building. Because of the long distance of about 8 m from the laser to the test section, a laser with a low beam divergence of less than 0.5 mrad ($M^2 < 2$) is used. The laser beam is directed via mirrors through a small window located in the sealing of a plenum opening to a first 45° laser mirror attached to the rear structure of the test section side wall. This mirror is equipped with two piezo-electric actuators and directs the beam to either one of the two light-sheet modules installed in the test section, one placed directly atop of the other. Another 45° laser mirror is placed at the back of each light sheet module, each equipped with piezo-electric actuators as well, to direct the beam into the housing containing optics to form the light sheet through a window of the test section side wall. This means that either the inboard or the outboard flow field of the wing is illuminated by the upper or lower light sheet module, respectively, and the complete flow field has to be measured successively by separate measurement series. To change the light sheet from the inboard position to outboard and vice versa, the light beam must be pivoted using the actuators of the first 45° mirror. In each case a pair of two motorized mirrors, i.e. four piezo-electric actuators, are available to adjust the beam position and direction onto the optical axis of the selected light sheet module. In the current tests the light sheets are aligned perpendicular to the free stream velocity. In addition to the switching between the upper and lower light sheet module, the light sheet can be pivoted within the measurement plane via a rotation stage and a mirror placed in each modules which is directly located behind the test section window. In fact, this feature has also been used during the wind tunnel tests to improve the light distribution within the different flow sections.

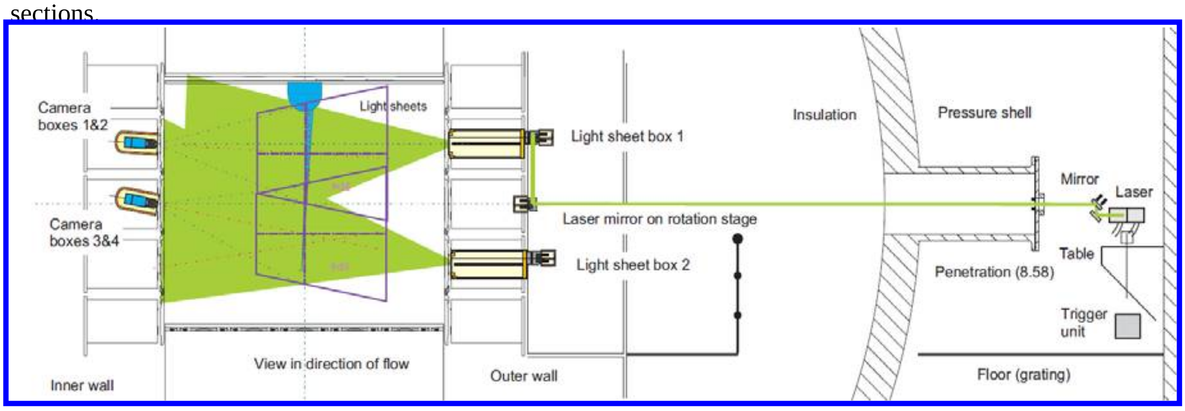

Figure 7. Employed PIV arrangement for wake flow measurements in the ETW on a half wing model.

Four camera modules are mounted on the opposite side of the test section to enable two stereoscopic arrangements with viewing angles of about ±45°. The modules are equipped with pco.edge cameras with CMOSs sensors, having a pixel resolution of 2560 x 2160 and a dynamic range of 16 Bits. These cameras provide a fast transfer of double-images directly to a RAID system located in the main control room with a rate of 15 Hz, which corresponds to the repetition rate of the laser. The very high data rate is achieved by using two camera-link interfaces in parallel for each camera. To transfer the image data over the large distance of about 80 m from the test section to the main control room optical fibres are used for which converters providing data transfer rates of 85 MHz had to be installed on both sides; i.e. close to the camera and the RAID computer. For a precise control of the exposure synchronized with the pulsing of the laser light, an external trigger signal is provided from a programmable sequencer that is located close to the pulse laser.

In order to enhance the productivity of the PIV measurements a software tool called "Semcollect" for an automated acquisition of measurement data from wind tunnel experiments was adapted for PIV. Information is exchanged between the ETW wind tunnel control system and the PIV measurement system (s. Figure 8) via an RS232 interface. Thereby, the wind tunnel is informed about the current status (ready) of the PIV system, and a data string containing the parameters of the current wind tunnel conditions is sent to and logged by the PIV system. Furthermore, a PIV measurement can be automatically triggered by the wind tunnel operator while performing a polar measurement, so that for four angles of attack each of 3 x 192 PIV images could be obtained within just a few minutes.

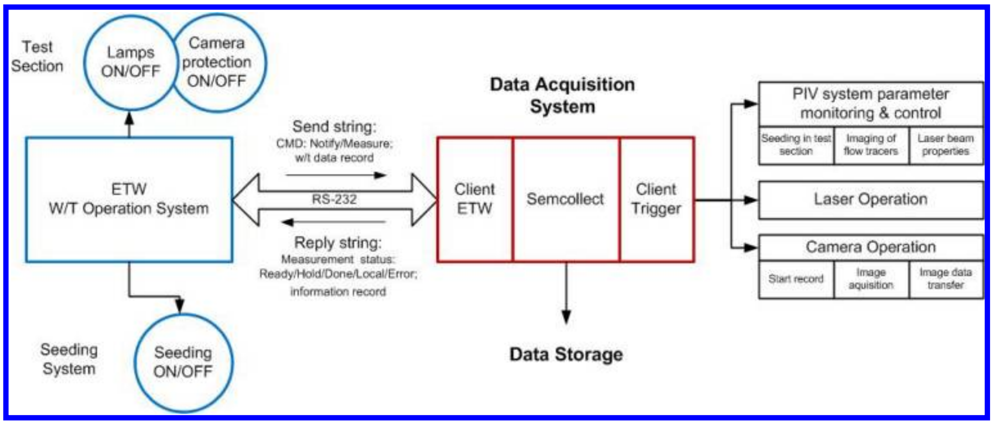

Figure 8. Chart of communication between wind tunnel control system and PIV measurement system for automated data acquisition.

Preliminary results for two medium angles of attack and with T_0 = 115 K and p_0 = 335 Pa (resulting in a chord based Reynolds number of about 17 million) are shown in Figure 10. Shown are the in-plane velocity vectors along with the out-of-plane vorticity distributions. The inboard and outboard flow fields measured with the upper and lower stereo PIV camera system, respectively, are combined in the pictures to visualize the complete wing wake. For that reason, only time averaged data can be shown, produced by using the 192 samples for each stereo image data set. The PIV images are evaluated using a final interrogation spot size of 64 x 64 px which is about twice that usually achievable with results obtained in conventional wind tunnels. The reason for the lower spatial resolution is linked to the reduced optical resolution likely mainly brought about by increased schlieren effects in the test section at high gas pressures. The distances of the vectors are about 10 mm resulting in 154 vectors in the spanwise direction. Two dominating co-rotating vortices can be seen in the velocity and vorticity distributions, originating from the outer flap edge and the wing tip. Within the shear layer a number of smaller vortices can be detected as well. The positive inclination of the shear layer in the shown *yz*-planes arises partly from the produced descent speed by the wing and from the angle between the wing trailing edge and the measurement plane, as indicated in Figure 9.

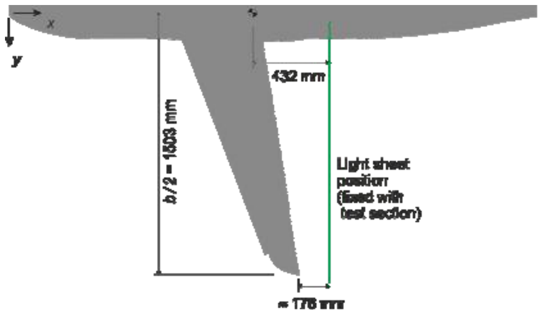

Figure 9. Position of measurement plane (green line) with respect to the wing.

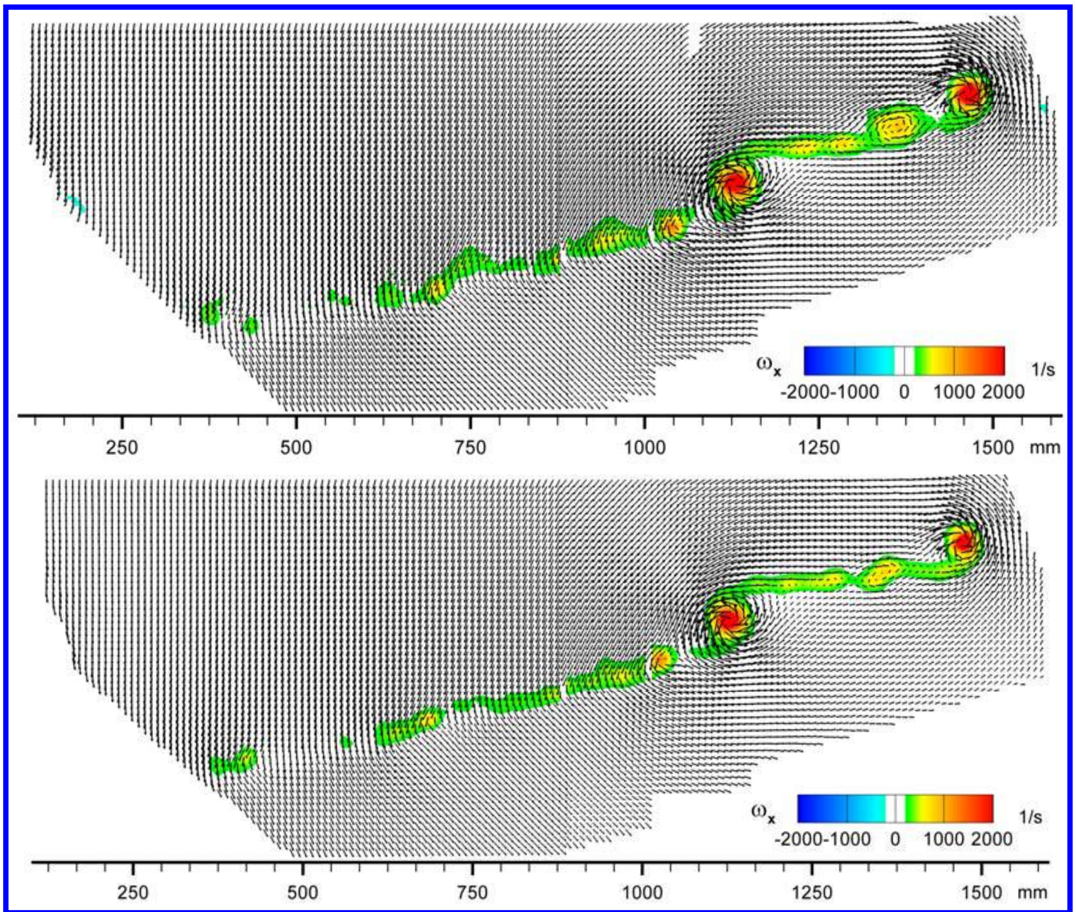

Figure 10. Measured velocity and vorticity distributions at T_0 = 115 K, p_0 = 335 Pa and R_c = 17 million for two different angles of attack.

V. Conclusion

A cryo PIV system for flow field investigations at flight Mach and Reynolds numbers in the ETW has been further developed and adapted for measurements of a wing wake flow extending over a complete wing span. To achieve reasonable spatial resolution in the velocity distributions, two light sheets and two stereo camera systems were used for successive measurements. A particular seeding method using ice particles has been optimized for PIV having a very low consumption of H_2O to preclude icing in the wind tunnel. Furthermore, an automated data acquisition system has been implemented, allowing flow field data to be captured while performing complete angle of attack polars with the model, both of which significantly reducing the wind tunnel costs for a given measurement program.

For the first time, flow field data have been obtained of the complete wing wake on a high-lift configuration of an aircraft model at high Reynolds numbers of 17 million; i.e. at realistic high-lift flight conditions. The obtained velocity data enable a detailed investigation of the produced vortical flow structures in dependency of the angle of attack including the maximum lift condition. The PIV data will be further evaluated and used by the project partners of DeSiReH for further analysis and for comparisons with CFD computations.

Acknowledgments

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References

[1]Kompenhans, J., “Quantitative visualization techniques for aerodynamics.” Proc. of 11th Asian Symposium on Visualization, Niigata, Japan. 05.-09. June, 2011

[2]Quest J., Leuckert J., Fey U., Konrath R, and Egami Y., “Development & application of modern measurement techniques for pressurized cryogenic wind tunnels,” Proc. of 26th International Congress of the Aeronautical Sciences, ICAS 2008, Anchorage (Alaska, USA), 14 - 19 September, CP-261, pp 1-12, 2008

[3]Schröder A., Agocs J., Heider A., and Konrath R., “Investigations of strake wake vortices in a high-lift-configuration using Stereo-PIV,” Proc. of DLR/ONERA Meeting, 05-06 April, Lille (France), 2005

[4]Konrath R., Pallek D., Mattner, H., and v.Carmer, C.F., “Analysis of flow field measurements obtained in a large tow tank regarding the decay of wake vortices in the far-field for two- and four-vortex systems.” AIAA 2009-342, 2009

[5]Willert C., Stockhausen G., Beversdorff M., Klinner J., Lempereur C., Barricau P., Quest J., and Jansen U. “Application of Doppler Global Velocimetry (DGV) in cryogenic wind tunnels”, Experiments in Fluids 39: 420–430, 2005

[6]Konrath, R., Otter, D., Geisler, R., Agocs, J., Mattner, H., Roosenboom, E.W.M., Fey, U., Quest, J., and Kühn, C., “Adaptation of PIV for application in cryogenic pressurized wind tunnel facilities at high Reynolds numbers,” Proc. of 15th International Symp. on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, SP-1572, 05-08 July, 2010

[7]Quest, J., and Konrath, R., “Accepting a challenge - the development of PIV for application in pressurized cryogenic wind tunnels, AIAA 2011-3726, 2011

[8]Iannelli P., Wild J., Minervino M., Moens F., and Raets M., “Analysis and application of suitable CFD-based optimization strategies for high-lift system design,” Proc. of ECCOMAS 2012 (CD-ROM), CP- 2833, 2012

[9]Taylor P.A., Baibakov K., Brown S., Hecht M.H., Hudson T.L., Li P.-Y., Langed C.F., Prietod L., and Savelyev S., “On the sublimation of ice particles on the surface of Mars: with applications to the 2007/8 Phoenix Scout mission,” Icarus 181: 375–387, 2006