Adaptation of PIV for Application in Cryogenic Pressurized Wind Tunnel Facilities at High Reynolds Numbers

Robert Konrath[1], Dirk Otter[1], Reinhard Geisler[1], Janos Agocs[1], Hartmut Mattner[1], Eric W.M. Roosenboom[1], Uwe Fey[1] Jürgen Quest[2], Christian Kühn[2]

1: Institute of Aerodynamics and Flow Technology, German Aerospace Center (DLR), Göttingen, Germany, robert.konrath@dlr.de
2: European Transonic Windtunnel GmbH (ETW), Cologne, Germany, jq@etw.de

Abstract A measurement system has been developed for an application of Stereo-PIV in the cryogenic transonic wind tunnel ETW to enable detailed flow field analyses on scaled models of transport aircraft at flight Mach and Reynolds numbers. The specific conditions in such wind tunnels - cryogenic gas temperatures down to 110 K and moderate gas pressures of up to 450 kPa as well as a large plenum encapsulating the test section - made specific developments necessary. This comprises the generation of suitable flow tracers for cryogenic flows considering the specific requirements for an application in the ETW as well as the provision of laser light of high pulse energy and the placement of optical components within a cryogenic environment. Optical effects due to gas density changes within the wind tunnel plenum and light beam deflections or shifts are considered in the optical design of the Cryo-PIV system. The applicability of the developed Cryo-PIV system was recently demonstrated in the ETW during two test campaigns on a full scale and a half model of a transport aircraft. The employed Stereo-PIV system and first results will be presented.

1. Introduction

Modern state-of-the-art image based measurement techniques like PIV are now commonly used in industrial wind tunnels (Kompenhans et al. 2007). The non-intrusive measurement technique of PIV (Raffel et al. 2007) is able to determine unsteady as well as time-averaged velocity vector fields inside a slice of the flow field. The obtained vector fields can be further analyzed to determine characteristic flow parameters such as, for example, vorticity distributions, turbulent fluctuations or the circulation strengths of vortices (Konrath et al. 2008, 2009). Flow separations at rudders or flaps, for example, or the generation of vortices at flow control devices or propellers can be visualized and their interaction with the flow on the wing can be investigated quantitatively (Schröder et al. 2005, Roosenboom et al. 2009). PIV is also a useful tool for the validation of CFD computations (Hummel 2005, Pallek et al. 2008). However, such PIV applications in “warm” wind tunnels are usually limited to moderate flow Reynolds numbers.

The development of new generation aircraft requires tests in cryogenic and pressurized wind tunnels which enable aerodynamic optimizations at flight Mach and Reynolds numbers ($M = 0.15 – 0.9$, $R = 10 – 80 \cdot 10^6$) on scaled models. This is presently possible only in the European Transonic Windtunnel (ETW) in Cologne (Fig. 1) 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. The benefits of this simulation technique could be impressively demonstrated during the last decade, leading to modifications of modern aircraft design chains revealing a fruitful cooperative application of numerical design tools and wind tunnel testing. As an outcome of this symbiosis customers expressed additional needs for information about the flow field around the model in addition to the classical force, pressure and moment measurements. Quest et al., 2008 describe a wide range of measurement techniques for the ETW which are currently under development or have reached a mature status for industrial applications; examples are the Temperature Sensitive Paint (TSP) technique for transition measurements or an optical deformation technique to determine the geometry of wind tunnel models under wind load. First quantitative flow field measurements were performed in the ETW using the Global Doppler Technique (Willert et al., 2005). However, measurements using this technique are complex and a very dense flow seeding is needed, which can be achieved in the ETW by using ice particles at cryogenic temperatures, but with an accompanying risk of icing within the test section. Furthermore, in contrast to PIV the Global Doppler Technique allow only for a measurement of time averaged flow velocity fields.

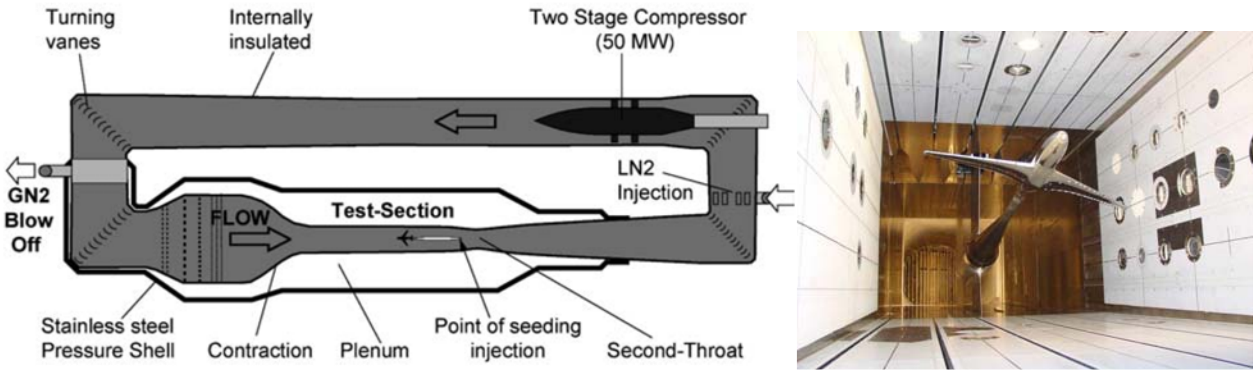

Fig. 1 Left: sketch of the European Transonic Wind tunnel (ETW) facility for flight Mach and Reynolds number testing, right: picture of test section (2.4 m width x 2 m height x 9 m length) with ETW reference model

Therefore, the possibility of applying PIV in a facility like the ETW is of particular interest since this would enable detailed flow field analyses at the same Mach and Reynolds numbers of real transport aircraft. However, many difficulties have so far hindered PIV application under conditions that prevail in such specific wind tunnels, where gas temperatures down to T_0 = 110 K and pressures of up to p_0 = 450 kPa can be reached; such difficulties are mainly:

- Generation of suitable tracer particles in cryogenic flows
- Limited optical access through a plenum encapsulating the test section
- Placement of optical components within cryogenic environment
- Optical and mechanical effects due to pressure and temperature changes

In contrast to most other optical techniques, PIV requires in particular high quality imaging to resolve single flow tracers within the whole measurement plane and pulsed laser light of high energy for an illumination of the flow field. The developed Cryo-PIV system for the ETW is described below, consisting of the seeding methods, the developed optical systems and the employed Stereo-PIV setup used in two test campaigns in the ETW with first results being available.

2. Flow tracer generation in cryogenic flows

For applications of PIV at transonic speeds, flow tracers in order of 1 µm are required to ensure that the particles follow the flow sufficiently. Furthermore, a moderate concentration in the flow is necessary to get a good spatial resolution within the measured vector field. Good experience was gained in former PIV measurements at cryogenic temperatures down to 100 K in the DNW-KKK by using oil droplets, which were generated using DLR's droplet generators (Konrath et al. 2009). However, in the case of the ETW the usage of oil is not suitable since the droplets accumulate on the bottom of the wind tunnel circuit, such that after a warm-up the oil can penetrate into the isolation shell leading to a permanent damage of the isolation material. Therefore, alternative tracer substances and seeding techniques must be determined, generating tracers which produce suitable signals for PIV and vanish after some time without leaving residua. One well known possibility for cryogenic flows is to generate ice particles (H_2O) which sublimate completely if the gas is warmed up. Assuming a dry nitrogen environment, the calculated lifetime of micron-sized ice particles is plotted in Fig. 2 as a function of the gas temperature and pressure. Here, the lifetime is defined by the sublimation time to get an ice particle diameter of 0.5 µm; i.e. a size for which particles usually scatter just sufficient light to be detectable with standard PIV–components. From this, a temperature range between 200 K and 240 K can be determined below which the sublimation rate is quite small and micron-sized ice particles persist long enough in the flow. Above this temperature range the ice particles vanish quickly.

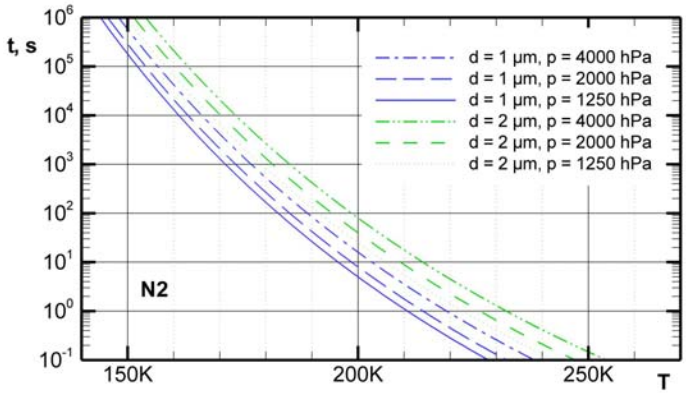

Fig. 2 Lifetime of a spherical ice particle with an initial diameter of 1 µm and 2 µm in terms of time to get a diameter of 0.5 µm due to sublimation in dependency of temperature and pressure assuming a nitrogen environment of zero humidity and no slip velocity between gas and ice particle (calculated according to Taylor et al. 2006)

Another issue is whether ice particles can be generated in the flow with size distributions and concentrations suitable for PIV. Since the underlying physics of ice particle formation, their growth and sublimation with a dependency on the gas dew point, pressure and temperature are complex (Baka et al. 1988), pretests were performed to determine useful methods for a cryogenic wind tunnel like the ETW.

Two methods are considered for the ETW: First, a warm humid and saturated nitrogen gas stream is injected to the wind tunnel circuit. For this a pipe is used which starts outside the plenum and ends at a point on the center line of the wind tunnel just downstream of the test section as indicated in Fig. 1. Assuming enough nuclei in the gas, ice particles are formed directly after the humid gas is mixed with the cryogenic gas, which may further grow by water vapor diffusion. This method was successfully applied by the ETW in former applications of optical techniques such as the Doppler Global Velocimetry (Willert et al. 2005) or light sheet visualization (AIRWI Lufo-4 project). However, in both cases a CW-laser was used to illuminate a plane in the test section, providing insufficient light energy for a detection of individual particles with size of the order of 1 µm, so that little is known about the particle distributions produced in these experiments. However, the images of the light sheet visualizations give an indication that small amount of larger ice particle clusters are present in the flow, which should be avoided, because the lag between the particle and flow velocity is usually no longer negligibly small, leading to larger measurement errors, especially in regions where stronger flow gradients, such as in vortices, occur.

The second method is to produce an aerosol with small water droplets which is cooled down such that the droplets freeze. The resulting "cryogenic aerosol" is then injected into the wind tunnel. Using this method alternative seeding substances to H_2O can be applied as well. Before its application at the ETW (Fig. 3) this method was first tested in the PETW; a scaled-down version (1:8.8) of the ETW. Particle images are captured using a single camera PIV setup (Fig. 4) that allows for an evaluation with respect to light scattering intensities, particle concentration and homogeneity. For reference, images were also taken with a seeding of DEHS droplets, such as are usually applied to PIV measurements in conventional wind tunnels (e.g. Konrath et al. 2008). However, since arbitrarily shaped ice particles scatter light differently in comparison to DEHS droplets (Raffel et al. 2007) it is not possible to predict the particle sizes from the intensity distributions. Figures 5 and 6 show for both seeding substances the responses of the particle image intensities averaged across a small area inside the test section for an injecting period of 5 seconds. Comparing the particle images of DEHS droplets and ice particles, it seems that a suitable seeding can be produced with ice particles, although some larger ice particle images still appear in the images. One reason for this could be an irregular growing of scattered particles. Reasonable high ice particle concentrations were obtained for temperatures below and at 200 K. At a gas temperature of 220 K low concentration particle images were obtained, which seem to arise from larger particle clusters. When increasing the temperature above 230 K no ice particles could be detected, since they vanish quickly due to the high sublimation rates, as shown by the calculations shown in Fig. 2.

Fig. 3: Ice particle seeding system at ETW showing the DLR Laskin droplet generators for high volume rates and high operation pressures

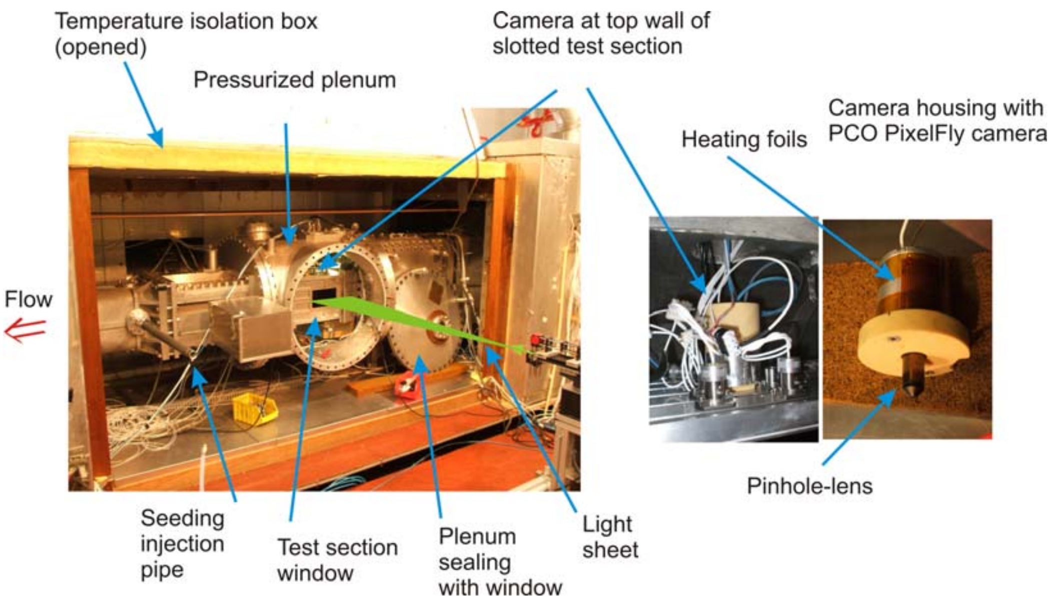

Fig. 4: PIV arrangement at pilot wind tunnel of ETW (PETW) for seeding tests

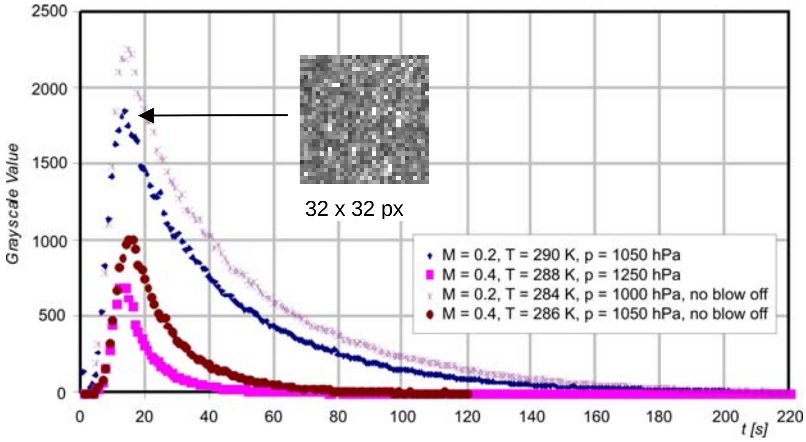

Fig. 5: Response in time of seeding with DEHS droplets for 5 s in the PETW in terms of PIV image brightness for two Mach numbers, also shown is the effect of the wind tunnel blow off (s. Fig. 1)

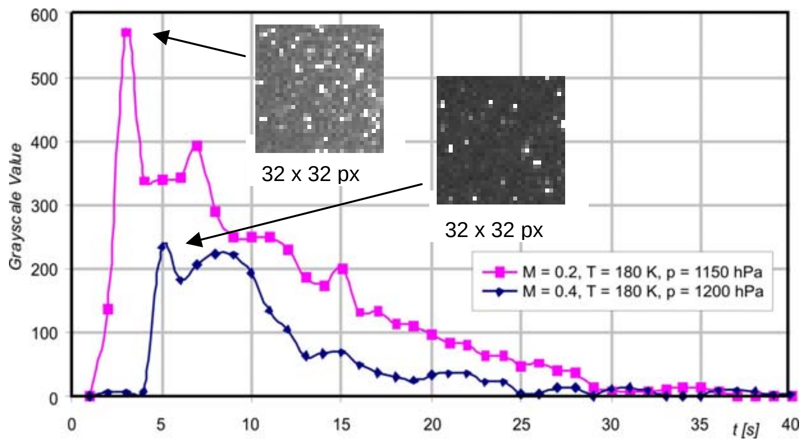

Fig. 6: Response in time of seeding with ice particles for 5 s in the PETW in terms of PIV image brightness for two Mach numbers for a cryogenic gas temperature of 180 K

3. Laser light supply and optical PIV components for ETW

For PIV a thin light sheet must be produced inside the test section to illuminate the measurement plane of the flow. Due to the small size of the flow tracers to be recorded, the large dimensions of the wind tunnel and the typical flow field sizes of interest, high energy pulse lasers are necessary. Although several optical windows are provided in the test section walls (Fig. 1), giving good optical access, the test section itself is encapsulated by a large plenum within which cryogenic conditions exist and since optical components and cameras need to be placed directly behind the test sections windows, this makes temperature controlled housings necessary. However, pulse lasers of high energy cannot be easily operated within such a housing, and therefore the PIV laser was placed outside the plenum. This means the laser beam needs to pass the shell with its temperature isolation of the plenum made of foam and the pressure shell made of stainless steel. Fibre optics as used by Willert et al. 2005 to guide a beam from outside the plenum to the test section could not be used in this case, because the high laser energies would destroy the fibre. Therefore, a small window was prepared on the front flange of a penetration allowing the light beam to pass through. This, however, lead to another problem at the ETW: light beam deflections due to optical effects as have been observed similarly in the pressurized transonic wind tunnel in Göttingen, DNW-TWG (Konrath et al. 2008) were seen here also. 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 may induce relative movements between the test section and the laser outside the wind tunnel. To compensate for this, a laser beam monitor and mirrors with actuators are foreseen in the wind tunnel plenum to keep the light sheet in place with respect to the model.

The large plenum of 10 m diameter requires that the light sheet-forming optics as well as the PIV cameras must be placed inside the plenum behind a test section window. Therefore, specific modules encapsulated by temperature controlled housings were designed for the cameras and light sheet optics which can be inserted in the test section window openings. Since these components are no longer accessible when the wind tunnel is operated, 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 consumes a huge amount of liquid nitrogen and electrical power.

The developed optical module for the light sheet optics is shown in Fig. 7 and consists of the light sheet forming optics, a 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 specific software program is written to control the mirror actuators which can perform, if needed, an automatic repositioning and redirection of the beam. This option is also used during the setup of the PIV system at the wind tunnel to save time by reducing the necessary manual adjustments. The laser module also contains the light sheet forming optics allowing a remote adjustment of the light sheet thickness.

The modules for the cameras (Fig. 8) contain adapters which enable a setting of the Scheimpflug angle and lens focus via servo motors which are connected via a CAN bus with the electronics inside the light sheet box and will be operated from the computer inside the main control room as well. The image data of each camera are transferred to computers located in the wind tunnel control room using separate Ethernet fibre connections. The housings of the temperature controlled camera boxes are horizontally inclined by 45° degrees with respect to the test section windows, according to the viewing angles of a typical Stereo-PIV arrangement. They can be placed directly inside the window openings of the test section.

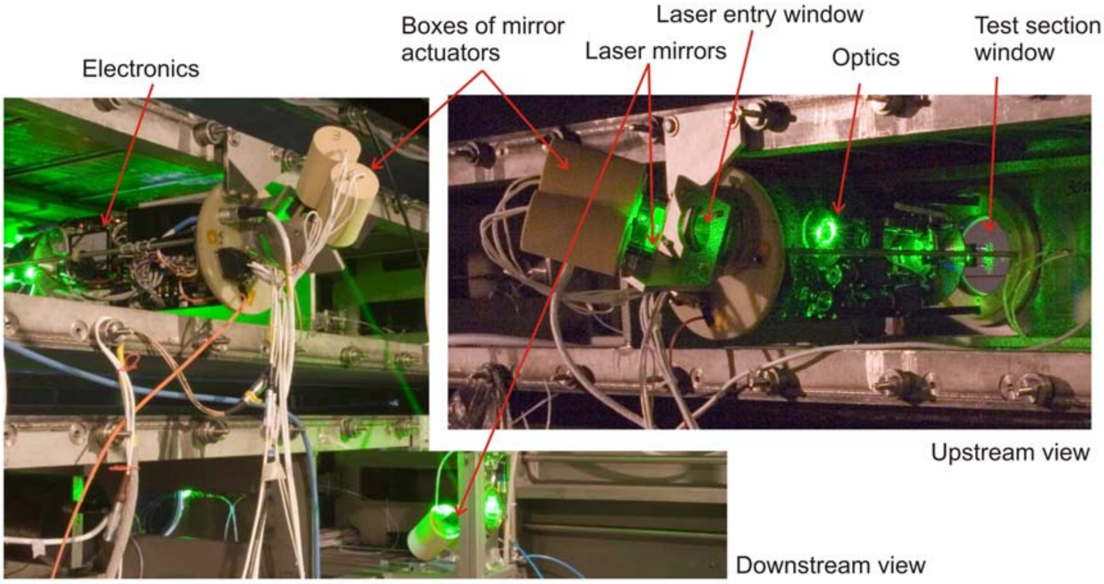

Fig. 7: Pictures of light sheet optics box installed in the ETW opened with removed isolation viewed from back side of test section

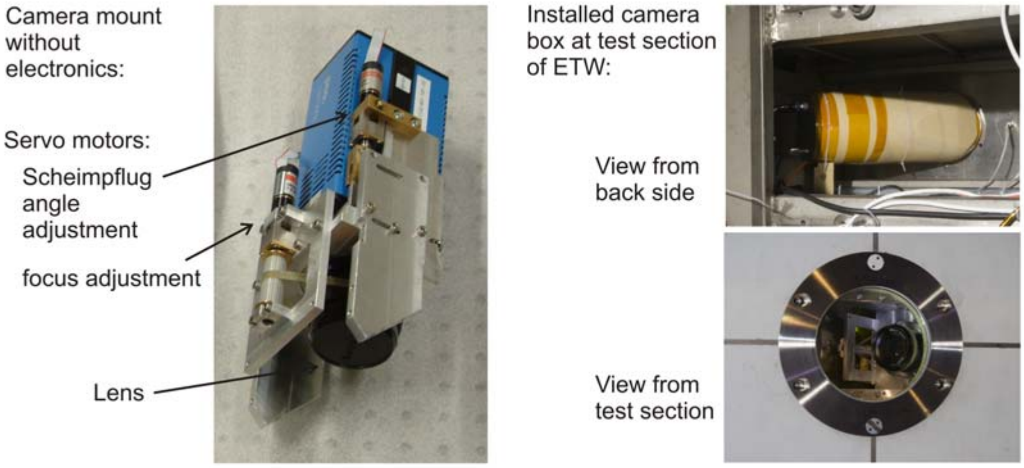

Fig. 8: Picture of camera adapter and temperature controlled box for the ETW

4. Stereo-PIV measurements at the ETW

Two test campaigns were recently performed in the ETW to validate the developed Cryo-PIV system. In the first test campaign the cross velocity fields of the wing tip vortex produced by the ETW reference model, which is a full scale model of b = 1.427 m span width (s. Fig 1) was measured. Tests were performed at Mach numbers of M = 0.2, 0.4, 0.6 and 0.8 at a total pressure of p_0 = 125 kPa and for total temperatures between T_0 = 200 K – 120 K. In a second test campaign the wake of a half model was measured. Within the tests a constant Mach number of M = 0.2 was used, but the total pressure was varied between 125, 200, 300 and 400 kPa for temperatures of mainly T_0 = 120 K. Because the employed PIV setups are similar in both test campaigns, only the setup of the first tests will be described in detail below.

Figure 9 shows the employed Stereo-PIV setup. 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 hall. Because of the long distance from the laser to the test section of about 8 m, a laser with a low beam divergence of less than 0.5 mrad (M^2 < 2) is used. The laser beam is directed via a mirror through a small window (10 cm aperture) located in the sealing of a plenum opening. The glass window is thick enough to withstand pressure differences of more than 3.5 bar according to the wind tunnel conditions. Then the beam passes through an opening in the temperature isolation shell before entering the light sheet box using two 45°-mirrors. The four actuators of both mirrors are computer controlled to compensate light beam deflections and to keep direction and position of the laser beam constant with respect to the light sheet box. Inside the light sheet box the beam passes through a lens arrangement for the forming of the light sheet through the front window of the box. In the current tests the light sheet is aligned perpendicular to the free stream velocity and its height is set for a measurement area of about 300 mm vertically and 600 mm horizontally. The light sheet thickness can be adjusted remotely by changing the focal length of the telescope using a servo motor. The camera boxes are mounted on the opposite side of the test section in a symmetrical arrangement using viewing angles of ±45°. The boxes are equipped with two PCO-1600 cameras giving a pixel resolution of 1600 x 1200 pixels. The camera mounts incorporate servo motors for a remote adjustment of the Scheimpflug angle and the lens focus. The image data is transferred to two separate computers in the main control room of the ETW via two fibre Ethernet connections. Another fibre Ethernet connection is used to connect another computer with the electronics inside the light sheet box. This is used to control all servo motors, mirror actuators and to read out the image data from the observation cameras of the beam monitor. Furthermore a trigger signal is provided for the cameras inside the wind tunnel plenum from a sequencer located close to the PIV laser for a measurement frequency of 15 Hz.

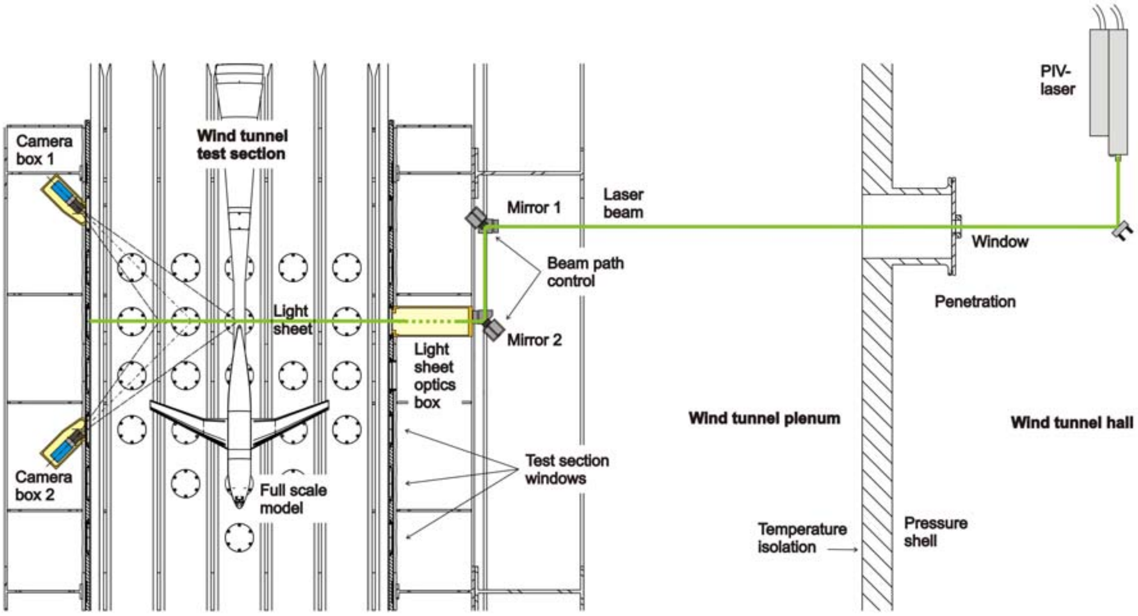

Fig. 9: Sketch of the stereoscopic Cryo-PIV setup at ETW of first test campaign using the ETW's full-scale reference model

Sufficient ice particle densities could be achieved with both seeding methods, as described in Section 2. For gas temperatures of 200 K and below a very small amount of water must be injected into the wind tunnel. Only for temperatures between 200 K and 220 K is increased injection of water necessary, whereas the ice particles vanish completely at higher temperatures, which is in accordance to the results obtained at the PETW. A dense ice particle concentration of moderate intensities can be observed which remains in the flow for a long time, especially at low Mach numbers of 0.2; i.e. when the mass flow of gas which is blown-off through the wind tunnel exhaust is small because of the small mass rate of the liquid nitrogen injection. Nevertheless, a small number of larger particles, i.e. high intensity particle images, can be observed as well. Figure 10 shows an example of a first Stereo-PIV result, where the wing tip vortex from the ETW reference model at an angle of attack of zero can be seen.

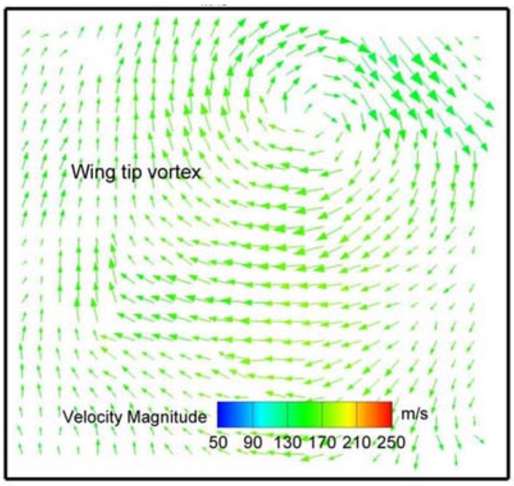

Fig. 10: Subarea (11 cm wide x 10 cm high) of measured instantaneous cross plane velocity field at 44 % span downstream the wing tip of the ETW reference model for M = 0.6, p_0 = 125 kPa, T_0 = 140 K

5. Conclusions

A Cryo-PIV system was developed for an application of Stereo Particle Image Velocimetry in the European Transonic Windtunnel (ETW), which made possible for the first time PIV measurements on scaled models of transport aircraft at flight Mach and Reynolds numbers. In two recently performed test campaigns on a full scale and a half model, the applicability of PIV could be demonstrated in the ETW for cryogenic gas temperatures (≤ 220 K) at sub- and transonic speeds.
Although PIV measurements could be performed successfully, further investigations are planned to improve the quality of the measurement results for the full operation range of total pressure and Mach number. This comprises a reduction of optical effects such as the formation of schlieren along the beam path, which occur especially at high pressure levels. To overcome the problem of inhomogeneous ice particle size distributions, different seeding substances will be investigated to test its applicability to the ETW.

References

Bakan S, Hinzpeter H, Höller H, Jaenicke R, Jeske H, Laube M, Volland H, Warneck P, Wurzinger Ch (1988) Physical and chemical properties of the air. In Meteorology, Volume 4 (Ed. G. Fischer), Subvol. b, Springer Verlag

Hummel, D (2005) The Second International Vortex Flow Experiment (VFE-2) Objectives and First Results. Proc. of 2nd Int. Symp. on Integrating CFD and Experiments in Aerodynamics, Shrivenham (UK), Sept. 6-7

Kompenhans J, Raffel M, Dieterle L, Dewhirst T, Vollmers H, et al. (2007) Particle Image Velocimetry in Aerodynamics: Technology and Applications in Wind Tunnels. Journal of Visualization 2: 229-244

Konrath R, Klein Ch., Schröder A, de Groot K (2009) Experimental investigations on the VFE-2 configuration at DLR, Germany. In Understanding and Modeling Vortical Flows to Improve the Technology Readiness Level for Military Aircraft, RTO Technical Report TR-AVT-113, pp. 19-1 to 19-42, ISBN 978-92-837-0073-9

Konrath R, Klein Ch, Schröder A, Kompenhans J (2008) Combined application of pressure sensitive paint and particle image velocimetry to the flow above a delta wing. Experiments in Fluids 44:357–366

Pallek D, von Geyr H, Schröder A (2008) Experimental and numerical study on the flow behind a TPS, Proc. of 14th Int Symp on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 07-10 July, Paper 1333

Quest J, Leuckert J, Fey U, Konrath R, Egami Y (2008) 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, paper 261, pp 1-12

Raffel M, Willert CE, Wereley ST, Kompenhans J (2007) Particle Image Velocimetry - A Practical Guide, 2nd Ed., Springer Berlin, ISBN 978-3-540-72307-3

Roosenboom EM, Heider A, Schröder A (2009) Investigation of the propeller slipstream with Particle Image Velocimetry, Journal of Aircraft 46: 442-449

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

Taylor PA, Baibakov K, Brown S, Hecht MH, Hudson TL, Li P-Y, Langed CF, Prietod L, Savelyev S (2006) On the sublimation of ice particles on the surface of Mars: with applications to the 2007/8 Phoenix Scout mission, Icarus 181: 375–387

Willert C, Stockhausen G, Beversdorff M, Klinner J, Lempereur C, Barricau P, Quest J, Jansen U (2005) Application of Doppler global velocimetry in cryogenic wind tunnels, Experiments in Fluids 39: 420–430

Acknowledgments

This work has been performed with the funding from the Lufo-IV Framework Program Project "Cryo-PIV" of the Federal Ministry of Economics and Technology of Germany.