Boundary layer transition detection on wind tunnel models during continuous pitch traverse

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For aerodynamic profile tests on aircraft models, boundary-layer transition detection is of great interest. Under ambient flow conditions the infrared technique (IR) is a well-established image-based method for this purpose. In high Reynolds number tests that are conducted at cryogenic temperatures the IR technique is of only limited suitability. In contrast, the image-based Temperature-Sensitive Paint (TSP) technique is well suited for these conditions. Boundary layer transition detection by means of TSP generally requires an artificial temperature difference between model surface and flow. For wind tunnels operated under cryogenic conditions changing the liquid nitrogen injection rate of the working fluid causing a rapid change of the flow temperature can generate this temperature difference ("temperature-step method"). The drawback of this temperature-step method is that during the change of the flow temperature neither the Reynolds nor the Mach number can be kept constant. To overcome this problem, we have recently published an alternative approach where Carbon Nanotubes (CNT) are used to electrically heat the model surface and thus generate a well-defined temperature difference to visualize laminar-turbulent transition. The combination of CNT and TSP, which we call cntTSP, delivered excellent results in different wind tunnel tests from ambient temperatures down to 100 K. The cntTSP sensor visualizes the surface boundary-layer conditions as temperature distribution based on different heat transfer coefficients in the laminar and turbulent flow. Compared to the temperature-step method the cntTSP approach has the advantage and potential to measure boundary-layer transition in a time-resolved manner, e.g. on wind tunnel models when the wind tunnel is operated in continuous pitch traverse mode, which is desired in order to improve the data productivity of the wind tunnel tests. In this paper, the applicability of cntTSP to a continuous moving model (pitch-traverse or pitch-sweep test) is investigated in the pilot facility of the European Transonic Windtunnel (PETW). The laminar to turbulent boundary-layer transition appearing on a 2D model is visualized and compared between the pitch-traverse and pitch-pause tests.

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I. Introduction

The visualization of a temperature distribution on a complete wind tunnel model is possible with TSP by using a paint whose light emission intensity changes with temperature [1]. This paint has to be excited by light at an appropriate wavelength and its temperature-dependent emission is detected by a camera system. TSP is based on the dependence of the intensity or decay time of its luminescence on the temperature, brought about by thermal quenching. For most wind tunnels working at ambient conditions IR thermography has largely been used as an image-based technique to detect surface temperature on models under investigation. For wind tunnels working at cryogenic temperatures, corresponding to high Reynolds number testing, the IR technique is not easily applicable [2] and therefore TSP becomes even more important under these conditions. TSP can employ conventional charge-coupled device (CCD) cameras. In addition, the TSP technique can use conventional optical lenses and glass windows, whereas IR thermography requires special lenses and a special observation window transmitting IR light.

Of special interest is an examination of the laminar-to-turbulent boundary-layer transition behavior on wind tunnel models at high Reynolds numbers, because of the possibility to simulate near-flight conditions. The knowledge of where the flow changes from laminar to turbulent regimes at high Reynolds numbers is of special interest for future aircraft designs using for example natural laminar flow (NLF) or hybrid laminar flow (HLFC) technologies. Since the laminar and turbulent regions of the boundary layer have different temperatures, one can apply an image based temperature measurement system such as IR or TSP to distinguish between them. The naturally given temperature difference to adiabatic wall temperature due to the recovery process is typically too small to be detected with TSP [2]. Therefore for transition detection measurements the TSP technique requires an increase of the adiabatic wall temperature difference. Several methods have been used and reported [2]. The working principle of all of these methods is the imposition of a heat transfer between the flow and the surface of the wind tunnel model. In this paper Carbon Nanotubes [3] are presented as a source for electrical heating in order to generate temperature differences between laminar and turbulent boundary layers which are sufficient to be detected by means of TSP. CNT has several desirable properties: for example a very high electric conductivity and its ease of applicability as a coating with a thickness of some micrometers. This enables an effective combination of CNT with TSP to become a cntTSP for transition detection measurements in a wind tunnel environment [4,5,6,7]. One big advantage of cntTSP is that the boundary-layer transition can be detected without changing the flow parameters. In addition, based on its capability of constant model surface heating, the cntTSP has a potential to be used for the dynamic visualization of boundary-layer transition, leading to the application of cntTSP in continuous model angle-sweep tests. The use of cntTSP in the angle-sweep tests is strongly desirable by the industrial partners in order to improve the data productivity of wind tunnel tests.

In the first part of this paper the cntTSP method and its relevant properties are described. Then the experimental setup for the measurement performed in the PETW is presented. Finally, the TSP results obtained on a two-dimensional model that is continuously moving (pitch-sweep test) are presented and compared with the pitch-pause results.

II. Temperature-Sensitive Paint Method

The working principle of TSP is based on the thermal quenching process of dye molecules, also called luminophores, inside a binder material. A dye molecule can be excited by absorption of light of an appropriate wavelength range, which is specific for the dye molecule. The excited dye molecules can return to the electronic ground state by emission of light, which is Stokes-shifted to a longer wavelength relative to the excitation wavelength. The thermal quenching process leads to a radiationless transition of the dye molecule to the electronic ground state; the degree of quenching depends on the temperature. The emission intensity of the TSP dye decreases with increasing temperatures, since the degree of thermal quenching increases with temperature. The relationship between the emission intensity of the TSP and the temperature is given by the Arrhenius relation [1].

Well-known dye molecules, which are used in TSP, are complexes of Ruthenium ($\lambda_{excitation}$ = blue light, $\lambda_{emission}$ = red light) or Europium (λ_{ex} = UV light, λ_{em} = red light) [1]. The "ideal TSP" for the measurements must combine the following properties: high luminescent intensity, high temperature sensitivity, and low-pressure sensitivity. It was found that a Europium-based TSP is a suitable candidate for this application at ambient conditions [8] and Ruthenium-based TSPs are well suited for cryogenic testing [9]. Especially ruthenium terpyridine complexes, including $Ru(terpy)_2Cl_2$, have been employed in TSPs for cryogenic testing [9]. As a binder material for TSP, commercially available transparent binders such as polyurethane, polyacryl or polyepoxid resins are suitable. In the work presented here a three component polyurethane-based binder (PU) was used. For both, electrical and thermal insulating reasons an additional PU-based screen layer is applied between the TSP active layer and the wind tunnel model surface.

Boundary layer transition detection by means of TSP involves visualization of the temperature difference between the laminar and turbulent flow regimes. The "natural" temperature difference between the laminar and turbulent domains near the model surface is rather small (< 0.1 K at low-speed flows), due to the different recovery factors for the two boundary layer states. For successful transition detection, the temperature difference must be artificially enhanced by creating a temperature difference between flow and surface. Due to the different heat transfer coefficients for convection flow for the laminar and turbulent boundary layers, heat transfer between flow and model surface is faster within the turbulent region than within the laminar one. Thus, the laminar-turbulent temperature difference at the surface can be increased to detectable values (to approx. 1 K), enabling transition detection by means of the TSP technique. The required temperature difference can be achieved by conditioning the model temperature. This can be accomplished by means of a variety of known methods [10].

III. Carbon Nanotubes for electrical heating

CNT are allotropes of carbon having a cylindrical nanostructure. In 1991 Iijima published his results on helical microtubules of graphitic carbon and introduced CNT into the scientific community [3]. The cylindrical carbon structures have properties such as a very high electrical conductivity (>1,000 times greater than copper) that can be used for example as electrical resistance heater even in very thin layers. Previously, [4,5] we have embedded multi-walled CNT into an aqueous dispersion of an acrylate-based binder. Since polyacrylates can easily crack at cryogenic temperatures the corresponding CNT layer could not be operated safely below 150 K. It was observed that the complete coating cracked and finally peeled off the model surface [5]. To overcome this difficulty we embedded CNT into the same PU binder material, which is known to be well suited for cryogenic temperatures [6]. For the combination of single-walled CNT (OCSiAL, TUBALL 201), which can be embedded easily into the PU polymer with high-speed mixing or/and by using a three-roll milling system (EXAKT, 80E PLUS), the resulting resistance values of the PU-based CNT layer reached values in kilo Ohm. To further reduce the resistance value an electro conductive (EC) carbon black (AkzoNobel, Ketjenblack EC-600JD) is added. The resulting resistance values are depending on the CNT and EC concentration in the PU polymer and can reach values as low as ≤ 100 Ohm (Table 1). This resistance value is sufficient for operations in laboratory and wind tunnel environment.

Table 1 Influence of CNT and EC concentration in PU polymer on the resistance of CNT layer (Coated surface: 0. 1 m × 0. 2 m, electrically contacted on the shorter sides)

PU-Clearcoat / ml	OCSiAl, TUBALL 201 / g	EC-600JD	R / kOhm
20	3.5	-	1.1
20	3.5	3.5	0.1

The PU-based CNT layer can be applied by an airbrush, when the viscosity is adapted by adding enough thinner to the PU polymer. This means that this layer can also be sprayed onto complex 3D surfaces. A typical thickness of such PU-based CNT coatings is about 10 µm. Due to the reasonable electrical resistance of this CNT layer, an effective heating with this layer can be achieved by operating at moderate voltages. By applying electrical power to the CNT coating very homogeneous temperature distributions can be achieved [4,5,6]. The temperature variation on the cntTSP heating is typically below ±0.1 K over the investigated model surfaces.

By using the newly developed PU-based CNT coating, it is possible to apply the TSP layer directly on top of this layer without any further treatment, and no interaction has been observed between the CNT and TSP layers, since all components are either embedded (CNT and EC) or dissolved (TSP) in exactly the same PU-based material. With this combination of CNT and TSP a very effective and fast temperature change (1 K in several seconds [6]) can be generated.

IV. Application of CNT and TSP an the wind tunnel model

Before any coating can be applied to the wind tunnel model, a proper surface cleaning of the model has to be carried out. A silicon and oil free surface has to be attained to ensure proper adhesion of the coating and hence avoid the loss or damage of the coating during wind tunnel testing. The coating was applied immediately after cleaning. For the combined use of CNT and TSP suggested here, five different paint layers were applied: primer (approx. 20 µm), first white screen layer for thermal and electrical insulation (approx. 60 µm), PU-based CNT (approx.

20 μm) on the suction side of the model only, second white screen layer for image registration reasons [5] (approx. 10 μm), for image processing reasons 3D markers and 10%-tick marks were placed on top of the second white screen layer, and finally TSP (approx. 40 μm). Electrical connections based on self-gluing copper tape were adhered onto the first screen layer, after which the CNT layer was applied. Fig. 1 shows the coated model with all layers and a resistance value of 250 Ohm directly after coating. When the curing process for all paint layers was finished a resistance value of less than 200 Ohm was measured.

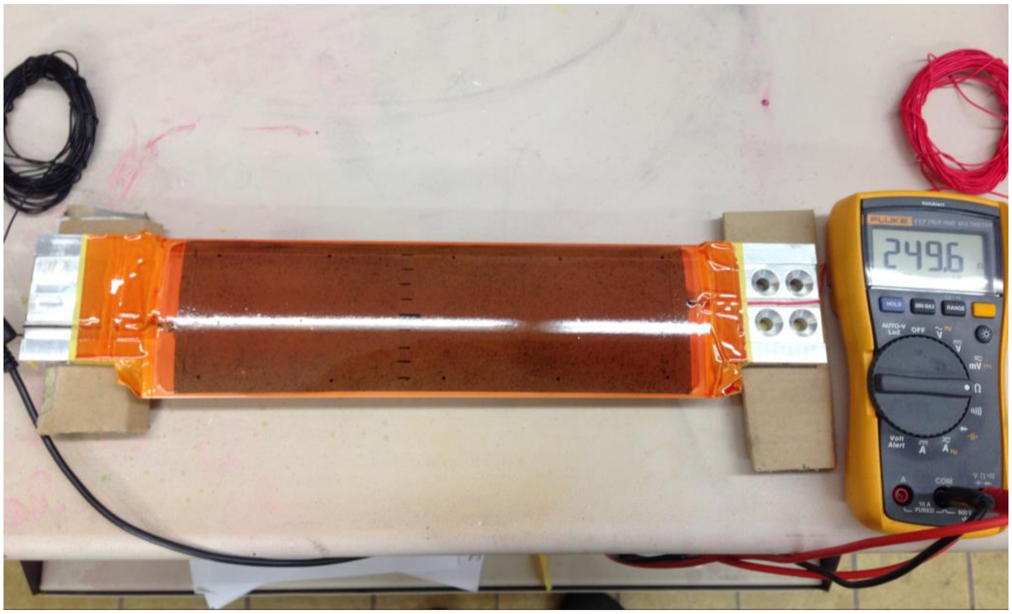


Fig. 1 CNT and TSP coated model and electrical connections

V. Experimental setup

The main purpose of this investigation was the TSP data acquisition on the model under cryogenic conditions in a time-resolved manner during continues model movement (pitch-traverse mode) and to compare the obtained boundary-layer transition results with those gathered on the same model at fixed angle of attack (pitch-pause mode).

A. Wind tunnel model

The wind tunnel test was performed on a CAST-10-2 profile. A description of the profile together with coordinates and previous results can be found in [11]. The airfoil is made out of aluminium with a chord of 0.07 m and a span of 0.27 m. The model was not equipped with pressure taps. The handling of cntTSP together with pressure taps has been already successfully presented recently [5, 7]. Finally, after the painting, the TSP layer was polished with sandpaper to a given low roughness value. The complete TSP coated model was finally hand finished to Ra < 0.1 micrometer for the wind tunnel test.

B. Pilot European Windtunnel

The wind tunnel tests were performed in the pilot European Transonic Windtunnel (PETW). The PETW has a test section size of 0.22 m × 0.27 m and is a Goettingen type of wind tunnel using pure nitrogen as the test medium for cryogenic tests. It is capable of operating at stagnation temperatures from about 100 K – 273 K and stagnation pressures from 100 kPa – 450 kPa, with Mach number variation between 0.2 to 0.9. The Reynolds number capability of up to $Re_c = 10 \times 10^6$ is based on the chord length 0.07 m and a Mach number of 0.7.

C. Illumination of TSP

Illumination of TSP was achieved by commercially available LEDs (Lumiled 450 nm blue), output power of 5 W. The LEDs were operated continuously, which guaranteed a stable output. The LEDs were operated without optical filters, causing some reflection in the final image-based results and therefore have to be changed for future testing.

D. Image acquisition

TSP images were taken with a CCD camera (type PCO pixelFly) that is equipped with a 4 mm pinhole TV lens from COSMICAR/PENTAX, having a pixel resolution of 1,392 x 1,024 pixel and a 12 bit analog-to-digital converter. In front of the CCD array an optical bandpass filter is placed (630FS75). All images were taken with 1 Hz data acquisition rate.

E. Optical access in PETW

For the work presented here the model is installed horizontally, optical access is realized from the top. Fig. 2 shows the horizontally mounted model in the test section of PETW before closing the side wall of the wind tunnel.

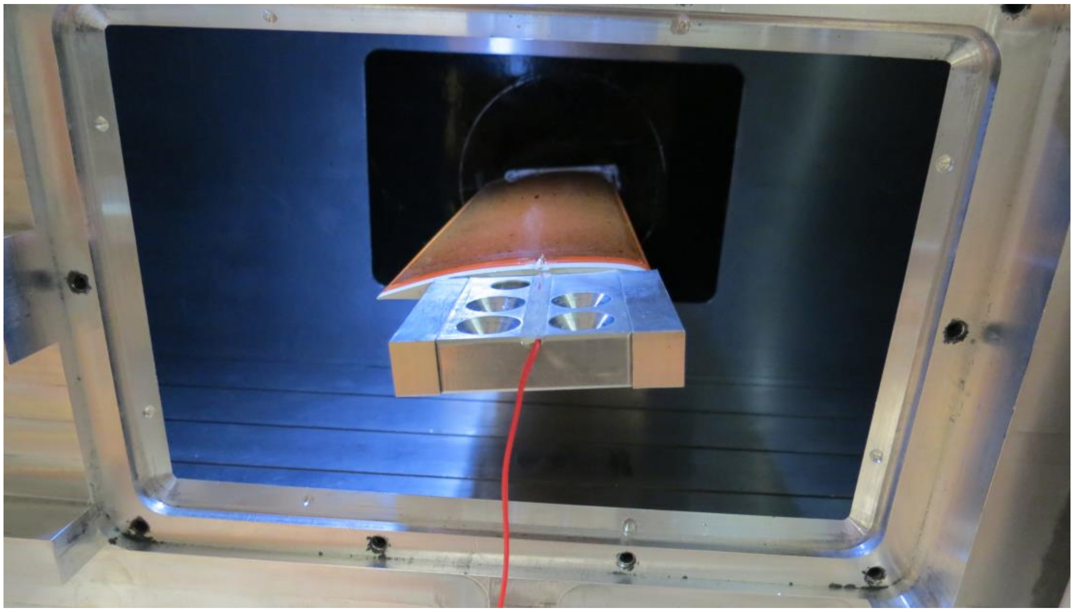


Fig. 3 Horizontally mounted model in the PETW test section

F. Data acquisition

The test procedure for the experiment can be described as follows: once the flow in the wind tunnel is established, the acquisition procedure of the TSP images is started. For both methods (CNT heating and temperature-step method), about 10 initial TSP images are recorded at the so-called reference conditions.

a) Temperature-step method

For the temperature-step method a negative temperature step in the oncoming flow was generated (by increasing the injected liquid nitrogen rate) during which 60 so-called run TSP images were recorded.

b) Electrical heating by means of CNT

The reference images were taken with power off, then power (DC) was applied to the CNT layer. When switching on the electrical heating of the CNT layer 60 so-called run TSP images were recorded.

G. Data processing

For the final TSP result the average of all reference images is divided by the run images. With this rationing method intensity differences between laminar and turbulent areas are enhanced and account has been taken for the influences of inhomogeneous excitation light and coating thickness inhomogeneity.

The TSP data evaluation was performed by means of the in-house software package ToPas [12].

VI. Results from the wind tunnel experiment

In the following images the flow is coming from the left. In all the presented images the darker areas towards the trailing edge of the model indicate a higher heat transfer, which is caused by turbulent flow. Laminar-to-turbulent boundary layer transition was investigated for different wind tunnel total temperatures T_{tot} and a variety of angle-of-attack for M = 0.5, see Table 2 for test conditions.

Table 2 List of test conditions

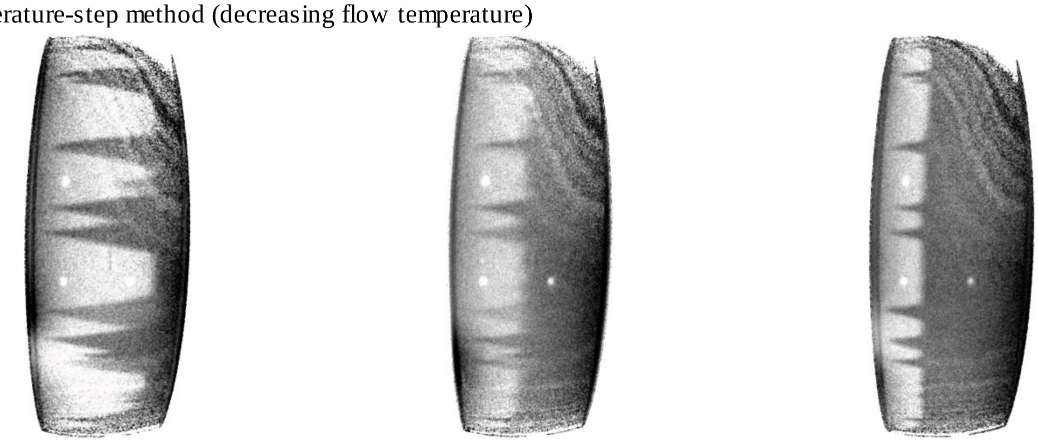
M	0.5			
α / °	-1, 0, 1			
Re_c / 10^6	2.5	3	3	5
T_{tot} / K	273	213	183	123

All presented results here were acquired at T_0 = 183 K, M = 0.5, and $Re_c = 3 \times 10^6$. At this condition the CNT layer was operated with an electrical power of approx. 50 W.

A. Results of pitch-pause test

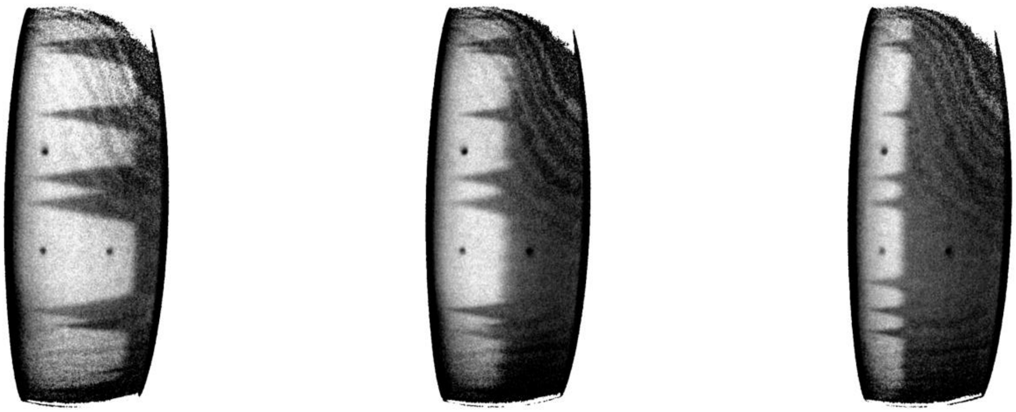
In Fig. 4 a comparison for the transition scenario for the three investigated angles-of-attack is presented. For a) the temperature-step was initiated with decreasing flow temperature, whereas for b) the temperature-step was initiated by switching the CNT-layer heating on. For α = -1° the laminar-to-turbulent transition occurs at approx. 80% chord length, the transition moves downstream to approx. 50% for α = 0°, and to approx. 35% for α = 1°. In addition to this expected shift of transition as a function of model incidence turbulent wedges are visible in the resulting images. It seems that most turbulent wedges do not start at the leading edge of the model indicating possibly remaining local TSP coating imperfections. Anyhow, the laminar-to-turbulent transition could be clearly identified for both temperature-step methods.

a) temperature-step method (decreasing flow temperature)



α = -1° α = 0° α = 1°

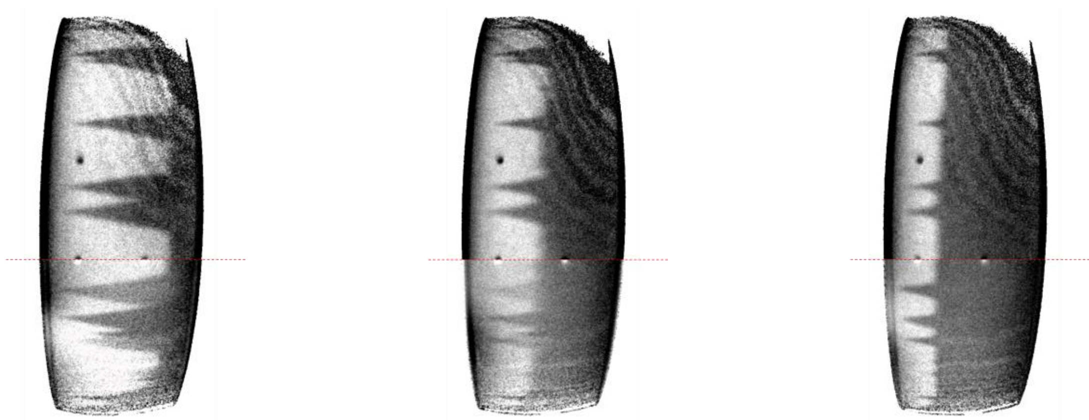
b) CNT approach (surface heating)



α = -1° α = 0° α = 1°

Fig. 4 TSP results for α = -1, 0, 1°,
comparison of temperature-step methods: a) decreasing flow temperature b) surface heating (CNT)

To compare the results of Fig. 4 in respect to the location of laminar-to-turbulent transition position for the different angle-of-attack more easily, these results have been stitched together in Fig. 5. The upper part of the image shows the results obtained by surface heating (CNT) and the lower part of the image shows the corresponding result when the flow temperature was decreased. The red dotted line in Fig. 5 indicates the border area between both methods. The measured transition location is in very good agreement for both methods.



α = -1° α = 0° α = 1°

Fig. 5 TSP results for α = 1, 0, -1°, comparison of temperature-step methods,
upper part: surface heating (CNT), lower part: decreasing flow temperature

B. Results of temporal change of transition pattern for different temperature-step methods

Since about 60 run images have been acquired during surface heating (CNT) or when decreasing the flow temperature an analysis of the temporal development of the transition pattern for different time steps of the run image acquisition sequence can be performed for each single image. Fig. 6 shows the development of the measured transition pattern as function of number of the run image number a) by decreasing the flow temperature and b) surface heating (CNT operation). Obviously, when surface heating is used the measured transition pattern is available immediately after the CNT has been switched on whereas for the standard method (decreasing flow temperature) the transition pattern develops in time during the slower change of flow temperature. In addition the standard method shows also an increase of the number of turbulent wedges during time. The results obtained by surface heating are free from any turbulent wedge change in time. This means, that when surface heating is applied the complete data-acquisition system including the model and wind tunnel conditions (Ma, Re, turbulence level) remain exactly the same between reference and run conditions. In other words, the standard temperature-step method introduces also a certain flow conditions change in respect to the data-acquisition system between reference and run conditions. This behaviour was present for all total temperatures and is therefore independent of the Reynolds number.

a) decreasing flow temperature

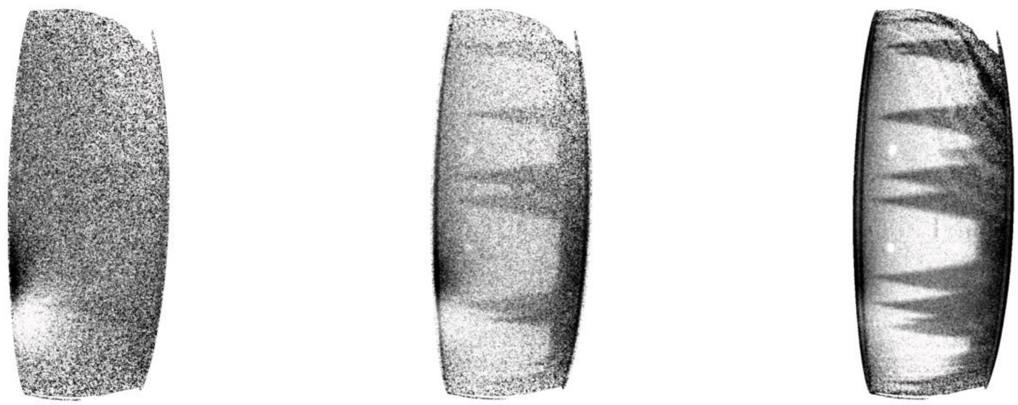


Image #2 #22 #42

b) surface heating (CNT approach)

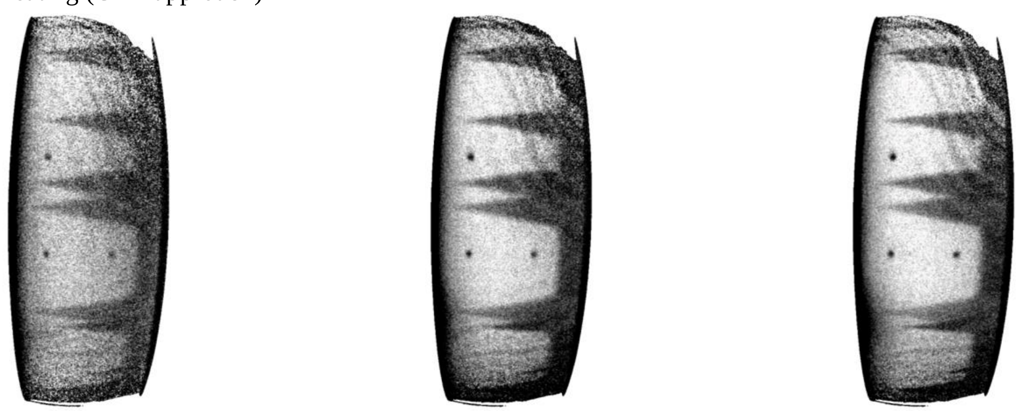


Image #2 #22 #42

Fig. 6 Temporal change of transition pattern during data acquisition time
TSP results for α = -1°, comparison of temperature-step methods: a) decreasing flow temperature b) surface heating

C. cntTSP result comparison between the pitch-pause and pitch-traverse tests

Since the presented results in Fig. 6 b) indicate the capability that for the use of TSP in combination with surface heating the measured boundary-layer transition pattern is immediately detectable when the CNT layer is switched on a measurement of the transition location during continuous model movement (pitch-traverse test) becomes possible. In other words, the CNT-layer operation allows to measure in a time-resolved manner the transition location. Fig. 7 compares the measured boundary-layer transition locations for pitch-pause and for pitch-traverse mode for the same angle-of-attack range. The here investigated pitch rate is 0.12°/s and the image acquisition was operated with 1 Hz. In Fig. 7 a), for the first 19 images of the pitch-traverse test the angle-of-attack of the model was not changed. From image #20 the model was continuously moved from -1° to +1°. For image #36 the angle-of-attack of the model reached $\alpha = 1°$ and from image #40 the angle-of-attack of the changed in opposite direction. Image acquisition was stopped at image #49 which corresponds to an angle-of-attack of $\alpha = 0°$. In Fig. 7 b) the boundary-layer transition location is plotted as function of angle-of-attack. From this plot it can be concluded that the use of TSP together with a surface heating system enables time-resolved TSP measurements and with the here investigated model and pitch-traverse speed no hysteresis in boundary-layer transition location was found and is in very good agreement with the data from pitch-pause tests.

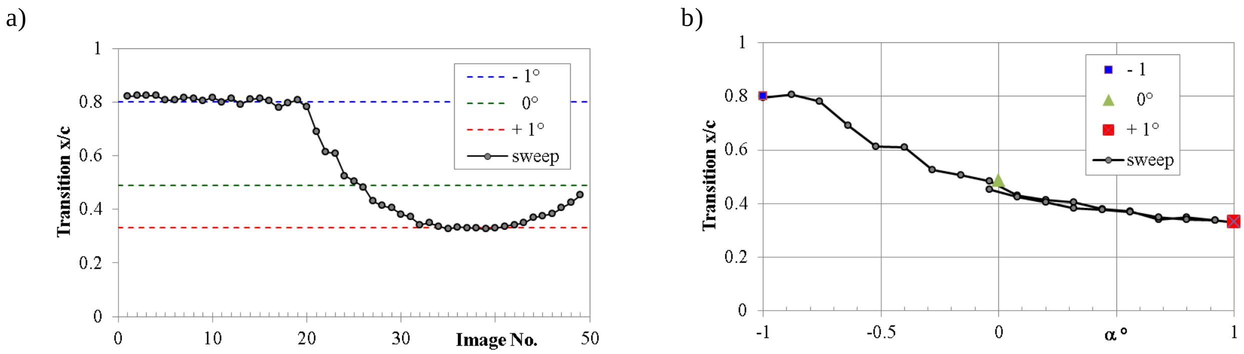


Fig. 7 Comparison of continuous pitch-traverse and pitch-pause tests
Black line („sweep“) represent results for pitch-traverse $\alpha = -1° \rightarrow +1°$ in 0.12°/s.
Colored lines and symbols represent results for pitch-pause data acquisition.
All results obtained by surface-heating method (CNT).

VII. Conclusion

Boundary layer transition measurements on a two-dimensional wind tunnel model by means of Temperature-Sensitive Paint (TSP) in combination with Carbon Nanotubes (CNT) were performed in the cryogenic pilot wind tunnel PETW. The CNT are used to generate a well-defined temperature change of the model surface. This paper describes a sensor development, which is based on the idea that CNT and electro conductive (EC) carbon black components are mixed (CNT and EC) or dissolved (TSP) in exactly the same polyurethane binder material. Both TSP and CNT can be applied by the airbrush technique to the wind tunnel model. Transition location changes on the wind tunnel model as a function of angle-of-attack are presented. By combination of TSP and CNT (cntTSP) as a tool for transition detection measurements, the productivity of the data acquisition can be increased compared to the standard temperature step (decreasing flow temperature) method. Since the heating of the CNT layer is very homogenous, laminar-turbulent transition can already be observed in single result images. The applicability of cntTSP to the continuous moving model (pitch-sweep test) could also be investigated in PETW. The transition patterns varied with the model continuous traverse and could be successfully visualized by cntTSP. Influences of the test parameters, e.g. sweep direction, were examined.

VIII. Acknowledgements

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