Wind turbine size has increased continuously in the past to extract more energy from the wind. Correspondingly, the Reynolds numbers have increased. The Reynolds number effect can therefore no longer be ignored in design and optimization of wind turbines. Reliable profile test data should be available.

A suitable facility for testing wind turbine profiles at high Reynolds numbers is the Cryogenic Wind Tunnel Cologne DNW-KKK. By means of injection liquid nitrogen the tunnel can be cooled down to 100K and the Reynolds number can be raised. The maximum Reynolds number for the 2D profile test can reach 27 x 10^6. The lift is determined from pressure taps on the model. The drag is measured using a wake rake. The boundary layer in the intersection areas between the model and the tunnel walls can be controlled by blowing high pressure gas or using vortex generators. The laminar to turbulent transition line can be detected using infrared imaging or temperature sensitive paint (TSP).

In this paper the test uncertainty and the flow quality of DNW-KKK were analyzed. Then some test results on the Reynolds number effect of the wind turbine profiles were presented. The Reynolds number effect is different from model to model. Especially for thick profiles and flow control devices the Reynolds number effect is not always like the description in literature.

Another work in this area is the aeroacoustic test. A pretest with a cryogenic microphone array is already finished. The data processing is still ongoing.

**Key words**: aerodynamics of wind turbine profiles; Reynolds number effect; cryogenic wind tunnel test

**Nomenclature**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>alpha</td>
<td>Angle of attack [°]</td>
</tr>
<tr>
<td>Cd</td>
<td>drag coefficient [-]</td>
</tr>
<tr>
<td>Cl</td>
<td>lift coefficient [-]</td>
</tr>
<tr>
<td>Cm</td>
<td>pitching moment coefficient referred to the quarter of chord [-]</td>
</tr>
<tr>
<td>C_N</td>
<td>normal coefficient [-]</td>
</tr>
<tr>
<td>Cp</td>
<td>pressure coefficient [-]</td>
</tr>
<tr>
<td>C_T</td>
<td>tangential coefficient [-]</td>
</tr>
<tr>
<td>cl/cd</td>
<td>lift drag ratio, aerodynamic efficiency [-]</td>
</tr>
<tr>
<td>Ma</td>
<td>mach number [-]</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number [-]</td>
</tr>
<tr>
<td>p</td>
<td>pressure [Pa]</td>
</tr>
<tr>
<td>p_st</td>
<td>tunnel static pressure [Pa]</td>
</tr>
<tr>
<td>p_t</td>
<td>total pressure [Pa]</td>
</tr>
<tr>
<td>q</td>
<td>dynamic pressure [Pa]</td>
</tr>
<tr>
<td>T</td>
<td>Temperature [K]</td>
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<td>x</td>
<td>x coordinate of pressure tap</td>
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<tr>
<td>y</td>
<td>y coordinate of pressure tap</td>
</tr>
<tr>
<td>α</td>
<td>Angle of attack [°]</td>
</tr>
<tr>
<td>σ</td>
<td>standard derivation</td>
</tr>
</tbody>
</table>

1 Head of Cryogenic Wind tunnel, DNW, Linder Hoehe, 51147 Cologne, Germany.
2 Project manager, Cryogenic Wind tunnel, DNW, Linder Hoehe, 51147 Cologne, Germany.
1. Introduction

The rated power of a wind turbine is proportional to the diameter squared, so larger and larger wind turbines are built to extract more energy from the wind. The profiles used in the blade are specially designed to improve its efficiency. With the increasing size, the Reynolds number increases also. A 5 MW wind turbine can reach a Reynolds number of $11 \times 10^6$ and 20 MW can reach even $25 \times 10^6$. The effect of Reynolds number should be taken into account in design the profiles.

There are many CFD programs available that can be used to predict the profile properties. With these programs the profile can be optimized quickly. The problem is that some properties, such as post-stall behavior, the maximum lift ($C_{l_{max}}$) and the minimum drag ($C_{d_{min}}$) could not be determined accurately using the state-of-art CFD program. These properties do not always get better with higher Reynolds numbers. For thin profiles $C_{l_{max}}$ increases, $C_{d_{min}}$ decreases and aerodynamic efficiency increases at higher Reynolds number. But for thick profiles or profiles with thick trailing edge the trend will be inverted. These properties can only be determined accurately in a wind tunnel at the real Reynolds number. One facility that can do these tests is the Cryogenic Wind Tunnel DNW-KKK. In this paper the test capability of this tunnel is analyzed and then some representative results are summarized.

2. Test Facility

2.1 The Cryogenic Wind Tunnel Cologne DNW-KKK

The Cryogenic Wind Tunnel Cologne (KKK) is a closed circuit low speed tunnel (Fig. 1). To achieve high Reynolds-numbers, the gas temperature in the tunnel circuit can be lowered down to 100 K by injecting liquid nitrogen. The Reynolds number can be thus increased by a factor of 5.5 while the drive power and Mach number remain constant. Due to the possibility of independent variation of the gas temperature and flow velocity, the influence of the Mach number and Reynolds number on the aerodynamic characteristics can be investigated separately.

![Fig. 1 Tunnel circuit of DNW-KKK](image)

The test section area consists of the test section itself, the model access lock and the model conditioning room. The test section is 2.4mx2.4m. Both sidewalls of the test section are equipped with eight windows in two rows. Each window enables application of flow visualization and optical measurement techniques. The access lock and the model conditioning room are located underneath the test section. They allow model changes at ambient temperature while the tunnel is maintained at cryogenic temperature. In this way high productivity can be achieved.
The wind tunnel’s degree of turbulence \((T_u' = \sqrt{u'^2 / U^2})\) was determined using heated wire arrays. Dependent on Mach and Reynolds numbers, it lies between 0.04\% und 0.1\% for \(0.1 < M_a < 0.3\) and \(100k < T < 300K\).

For the 2D profile test the set-up as shown in Fig. 2 can be used\(^4\). The model is spanned from tunnel floor to the ceiling. Both turntables in the upper and lower tunnel walls are synchronized to minimize the deformation of the model, so that the flow around the model is two dimensional. In addition, tangential blowing through slots on the turntables in front of the airfoil further improves the two-dimensionality of the flow.

Fig. 3 shows a wind turbine profile model tested in DNW-KKK. The model is manufactured from aluminum alloy. Its chord is 0.5m, instrumented with 62 pressure taps. The model is painted with TSP to detect the transition\(^7\).

### 2.2 Estimation of test uncertainty

The lift and moment are determined from the pressure distribution on the model. The lift coefficient is calculated using Eq. 1:

\[
C_l = C_N \cos \alpha - C_T \sin \alpha
\]  

(1)

The normal and tangential coefficients are integral of pressure coefficients over the model surface:

\[
C_N = \sum_{i=1}^{N} \frac{1}{2}(Cp_i + Cp_{i+1})dx_i = \frac{1}{q} \sum_{i=1}^{N} \frac{1}{2}(p_i + p_{i+1})dx_i
\]  

(2)

\[
C_T = \sum_{i=1}^{N} \frac{1}{2}(Cp_i + Cp_{i+1})dy_i = \frac{1}{q} \sum_{i=1}^{N} \frac{1}{2}(p_i + p_{i+1})dy_i
\]  

(3)

The pressure coefficients are defined as:

\[
C_{pi} = \frac{P_i - P_{out}}{q}
\]  

(4)

If we assume that the standard deviations of the \(N\) model pressures are equal, the standard deviation of \(C_N\) can be estimated as:

\[
\frac{\sigma_{C_N}^2}{C_N^2} = \frac{\sigma_p^2}{q^2} + \frac{\sigma_p^2 \sum_{i=1}^{N} dx_i^2}{(C_N q)^2}
\]  

(5)

Similarly, the standard deviation of \(C_T\)

\[
\frac{\sigma_{C_T}^2}{C_T^2} = \frac{\sigma_p^2}{q^2} + \frac{\sigma_p^2 \sum_{i=1}^{N} dy_i^2}{(C_T q)^2} C_N
\]  

(6)

So the standard derivation of lift coefficient can be estimated as:
\[ \sigma_{Cl}^2 = \sigma_{Cv}^2 \cos^2 \alpha + \sigma_{dN}^2 \sin^2 \alpha + \sigma_{Cy}^2 \sin^2 \alpha + \sigma_{dC}^2 \cos \alpha \]  

(7)

Similarly, the standard derivation of moment coefficient can be estimated using

\[ \sigma_{Cm}^2 = \sum_{i} \frac{1}{q_i^2} (\sigma_{p_i}^2 + \sigma_{p_{st}}^2 + \sigma_{q_i}^2 (C_{p,i}^2 + C_{p,i+1}^2)/2) (dy_i^2 + dx_i^2) \]  

(8)

DNW-KKK uses a pressure measuring system that has an accuracy of 10.3Pa. To improve the accuracy, 128 values are averaged. So for the evaluation the standard derivation of model pressure reaches 0.9Pa. The dynamic pressure is calculated from the difference between the tunnel total pressure and the static pressure at the test section. The standard derivation of the dynamic pressure is 1.8Pa. The error of angle of attack is very small, about 0.01°. To have a feeling of the lift coefficient accuracy, the standard derivation of lift and moment coefficient of a typical wind turbine profile test was estimated using Eq. 7. The results are illustrated in Fig. The maximal derivation of lift coefficient is about 0.0009, i.e. 0.09 lift count. The maximal derivation of moment coefficient is 0.0003.

![Fig. 4 Estimated standard derivation of lift and moment coefficient at Ma=0.20](image)

The drag of the profile is measured using a wake rake. To estimate the derivation of the drag coefficient, we use the simplified drag calculation equation

\[ C_d = 2 \int (\sqrt{C_g} - C_g) dy \approx \sum (\sqrt{C_{g,i}} + C_{g,i} + \sqrt{C_{g,i+1}} + C_{g,i+1}) dy_i \]  

(9)

The standard derivation of drag coefficient can be estimated as

\[ \sigma_{cd}^2 = \sum (\sigma_{C_{g,i}}^2/4C_{g,i} + \sigma_{C_{g,i+1}}^2/4C_{g,i+1} + \sigma_{C_{g,i+1}}^2/4C_{g,i}) dy_i^2 \]  

(10)

Because the tubes in the wake rake are usually equally spaced, eq. 9 can be simplified as:

\[ \sigma_{cd}^2 = \sum (\sigma_{C_{g,i}}^2/2C_{g,i} + 2\sigma_{C_{g,i}}^2) \Delta y^2 \]  

(11)

The standard derivation of pressure coefficient can be estimated using:

\[ \sigma_{C_{g,i}}^2 = \frac{1}{q_i^2} (\sigma_{p_i}^2 + \sigma_{p_{st}}^2 + C_{g,i}^2 \sigma_q^2) \]  

(12)

For the attached flow, 14 tubes of the rake are typically located in the wake depression area. The standard derivation of drag coefficient is usually under 0.00005, i.e., 0.5 drag count. To improve the accuracy further, the wake depression can be recorded twice. In the second measurement the rake is displaced about \( \Delta y / 2 \) in the direction perpendicular to the model cord. The standard derivation can thus be reduced to 0.35 drag count.

### 2.3 Test quality for 2D profile

The wake rake is mounted on a traverse mechanism; it is therefore possible to assess the overall test quality by means of scanning the wake in the span direction. Fig. 5 shows the measured drag as a function of rake position in span direction. The zero position is defined at the middle of the model. The data were taken at three temperatures: 290K, 250K and 230K. The Mach number and the angle of attack were the same for the 3 cases. It is clear to see that the 3 curves have the identical characteristic: in the midsection (\( Rz=0 \)) where the pressure taps are located the fluctuation in drag is large; in the region 350mm up the middle line the second fluctuation occurs;
and the third fluctuation appears in the region 700mm up the middle line. The latter two are caused by some imperfections in the model. The model is composed of 4 parts, and they are assembled together using screws. In these two regions the screw tops are not fitted perfectly with the contour. Vortex was generated in the wake.

Outside these disturbed regions the drag value is very stable. The fluctuation of drag in this 900mm span section is smaller than 0.5 drag count. This proofs that the flow around the model is two dimensional. For the productive test the rake is placed in the stable region.

2.3 Set-up for transition detection

The detection of transition is important both for the tunnel operator and profile designer. It allows the tunnel operators to make sure that the tunnel is free of dusts and has the prescribed degree of turbulence. The model surface has the required quality. For the profile designer the position of transition is required for many CFD-programs. The transition location determines to a great extent the profile drag. As a rule of thumb the drag is reduced by 10% when the transition point moves 10% to the trailing edge. Because turbulent boundary layer is less susceptible to dusts, ice, insects etc, it is also very import to know the transition position for the design of a robust profile.

The transition detection methods used in DNW-KKK are based on the Reynolds analogy, in which there exists a linear relationship between the heat convective coefficient and surface shear stress coefficient. The surface shear stress in a turbulent boundary layer is of an order of magnitude greater than that in the laminar boundary layer. If there is a temperature difference between the flow and the model, the turbulent boundary layer reaches the flow temperature more quickly than the laminar boundary layer. At a suitable time the temperature difference in the two boundary layers can be observed. Internal heat conduction in the model tends to reduce this temperature step. An insulation coat of 80µm is thus needed for the model made of aluminium alloy.

We use three methods to introduce a temperature difference between the flow and the model actively:

- Heating the model. Heating foils or stabs can be integrated into the model. The model should be made of heat conductive material. It should be considered during the model design phase. Later adaption is difficult. Another way of heating model is to use infrared heat lamp.
- Cooling the tunnel. After upgrade of the liquid nitrogen system of DNW-KKK it is now possible to cool down the tunnel quickly to get required temperature step.
- Heating up the tunnel. It works well for Ma>0.25. Due to the good insulation of the tunnel walls, the tunnel temperature rises at high Mach number if the liquid nitrogen system is turned off.

The temperature on the model surface can be scanned using infrared thermograph or TSP.

Infrared thermograph can be used in the range from ambient temperature to about 230K. At lower temperature the radiation is too weak to be detected. The infrared camera used in DNW-KKK is cooled with liquid nitrogen. It has 256x207 pixels. The thermal sensitivity NETD is 50 mK. The camera is placed in front of a germanium glass window, which is transparent in the infrared spectrum. Thin copper leafs are adhered on the model surface.
as markers to identify the location of the transition. More than 8 images are averaged to get one high quality image.

To detect transition at cryogenic conditions temperature sensitive paint (TSP) developed by DLR\textsuperscript{3} can be used. TSP is a thin paint layer containing luminescent material (luminophore) within a binder. When the luminophore is excited by a light source, it emits light at longer wavelengths. The radiation intensity is temperature dependent and this phenomenon is known as temperature quenching. In the case of cryogenic TSP, a Ruthenium complex is used as luminophore. It exhibits high temperature sensitivity in the range of 100K to 230K. The luminescent intensity decreases with an increase in temperature. The wavelength ranges of excitation and emission of the luminophore are $425 < \lambda_{exc} < 525\text{nm}$ and $580 < \lambda_{em} < 680\text{nm}$, respectively.

In DNW-KKK a blue LED lamp is used as excitation light source. A cooled black-white OMT-1024Y CCD camera with 1280x1024 pixels and 12 bit dynamic range is used to acquire images. An interference filter is mounted direct in front of the CCD chips, selecting the wavelength of $580 < \lambda < 680\text{nm}$.

For each test point 10 images are taken under stable condition. The average of them is defined as reference image. Then a temperature step is started. A series of images is taken to capture the temperature difference on the model surface. The average of the images is rationed to the reference image. The information concerning the absolute temperature distribution is not calculated, since the primary interest is the location of the transition.

A two-component TSP was developed by DLR in recent years\textsuperscript{3}. It allows the transition to be detected over the whole temperature range, from 100K to ambient temperature. In the warm range, from 240K to ambient temperature, UV-light is used as excitation. In the cryogenic range, from 100K to 240K, the blue light is used as excitation.

3. Representative Results

3.1 Reynolds number effect of clean profile

For the clean thin profile the Reynolds number effect is typical, just like the description in the classical literature\textsuperscript{8}. As shown in Fig. 6 and 7, with increased Reynolds number, $Cl_{max}$ increases, lift curve is more linear, its slope goes up slightly, $Cd_{min}$ decreases and the laminar bucket becomes smaller.

Some times designers want to know the behavior of profiles under back wind. A 360°-polar was taken as shown in Fig. 8. Because the profile is not symmetrical, it produces lift even when it stands perpendicular to the wind. From 90° to 180° it produces downwards force. From 180° to 270° it produces upwards force.

![Fig. 6 Reynolds number effect on lift for clean profile](image1)

![Fig. 7 Reynolds number effect on drag for clean profile](image2)
3.2 Reynolds number effect of contaminated profile

To simulate the contaminated profile surface through ice, impacted insects, dusts and erosion, carborundum 60 (solid grains of 0.25mm diameter) is sticked on the both sides around the leading edge. This causes the transition of the boundary layer occurs at the leading edge, and is almost independent of Reynolds number. As expected the drag increases dramatically compared to the clean profile. The stall arises also earlier and $C_{l_{\text{max}}}$ is smaller.

Fig. 9 shows the Reynolds number effect on the lift coefficient. With increased Reynolds numbers the boundary layer becomes thinner, but more powerful. The impact of carborundum thus decreases. The stall occurs at higher angle of attack, so $C_{l_{\text{max}}}$ increases. In the region of attached flow the lift increases also noticeably. This effect can be seen in Fig. 10. It illustrates two pressure distributions at the same angle of attack, but under different Reynolds numbers.

3.3 Reynolds number effect of flow control devices

The Gurney flap is an L-shaped metal strip attached to the lower surface of the trailing edge. It increases the maximum lift coefficient ($C_{l_{\text{max}}}$), decreases the angle of attack for zero lift, and increases the nosedown pitching moment ($C_{m}$). It also typically increases the drag coefficient ($C_{d}$). A net benefit in overall lift to drag ratio is possible if the flap is sized appropriately based on the boundary layer thickness.

Fig. 11 and 12 show the effect of a Gurney flap at two Reynolds numbers. It is clear that the selected Gurney flap suitable for the low Reynolds number is not optimal for the high Reynolds number.
A vortex generator is a complementary pair of small low-aspect-ratio airfoils. Generally mounted at opposite angles of attack to each other and perpendicular to the aerodynamic surface they serve. Vortex generators develop lift and produce very strong tip vortices. The vortex draws energetic air from outside into boundary layer and thus delays flow separation and stall.

Fig. 13 and 14 show the effect of vortex generators at two Reynolds numbers. The vortex generators were optimized at ambient temperature. They improve $C_{l_{max}}$ and lift drag ratio. But at the high Reynolds number the lift drag ratio decreases and the increase in $C_{l_{max}}$ is smaller.

The two examples above indicate that the flow control devices should be optimized at the same Reynolds number at which they are to be used.

### 3.4 Re-effect of thick profile

For the inner part of the blade the profile has a large value of thickness to guarantee the needed structural strength and stiffness. Often it has a thick trailing edge. The Reynolds effect of such profile is contrary to that of thin profiles (Fig. 16 and 17). The $C_{l_{max}}$ decreases with Reynolds number and the drag increases.
3.5 Re Effect on the transition position

Fig. 17 shows the transition line detected using infrared thermograph. The laminar boundary layer length changes from 53% to 9% when the angle of attack swept from -8° to 16°.

Fig. 17 Transition detection infrared thermograph by T=230K, Ma=0.30

Fig. 18 shows the transition line detected using TSP. The laminar boundary layer length changes from 37% to 23% when the angle of attack swept from 0° to 12°.

Fig. 18 Transition detection using TSP by T=245K, Ma=0.25

4. Summary and Outlook

To guarantee the performance of a large wind turbine, the profiles used in the blade should be tested at the real Reynolds numbers. The cryogenic wind tunnel DNW-KKK is a suitable facility to do such tests. It has the required measuring accuracy and flow quality.

Noise becomes an important factor in design a wind turbine. It can be reduced through optimized profile shape and trailing edge serrations. Because this noise is Reynolds number dependent, a microphone array that can work from ambient to cryogenic conditions was developed for DNW-KKK. A pretest as shown in Fig. 19 has already finished. The data processing is in ongoing. The microphone array is mounted on the side wall. It has 144 microphones.

Fig. 19 Aeroacoustic test of a wind turbine profile

5. References

[14] Zhai, J. and Rebstock, R., „ „Advancement of 2D profile testing at high Reynolds number in the cryogenic wind tunnel Cologne“, 20th ICIASF, 08.2003