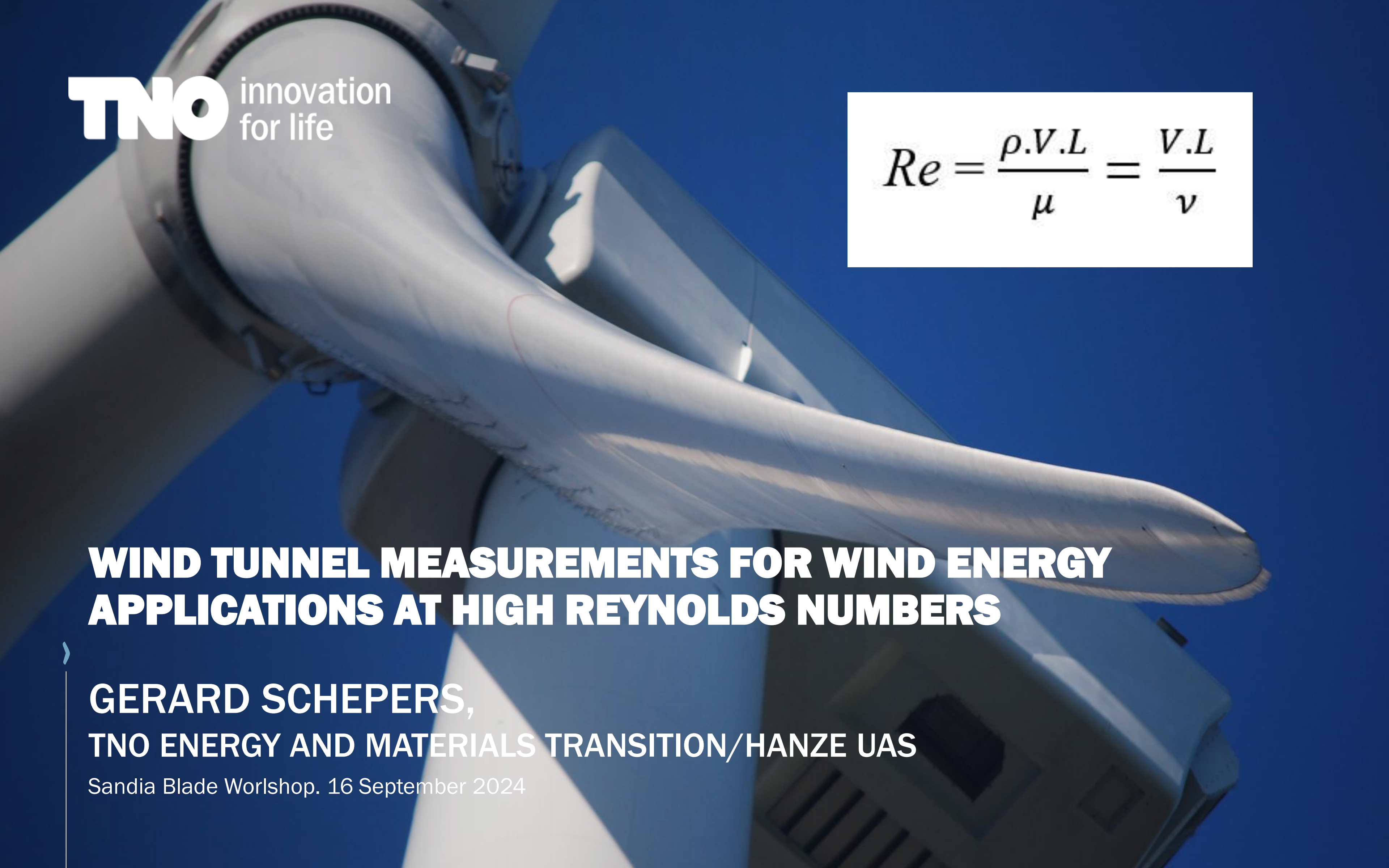

$$Re = \frac{\rho.V.L}{\mu} = \frac{V.L}{\nu}$$

WIND TUNNEL MEASUREMENTS FOR WIND ENERGY APPLICATIONS AT HIGH REYNOLDS NUMBERS

GERARD SCHEPERS,
TNO ENERGY AND MATERIALS TRANSITION/HANZE UAS

Sandia Blade Worlshop. 16 September 2024

OUTLINE

- The Reynolds number at upscaling
- Aerodynamics at high Reynolds number: Uncertainty
- Measurements: Field versus wind tunnel experiments
- The **generally** low Reynolds number in the wind tunnel
- 2D airfoil measurements at high Reynolds number in pressurized DNW-HDG tunnel in EU project AVATAR
- 3D rotating wind tunnel measurements at high Reynolds number:
  Some food for thought
- Conclusions and recommendations

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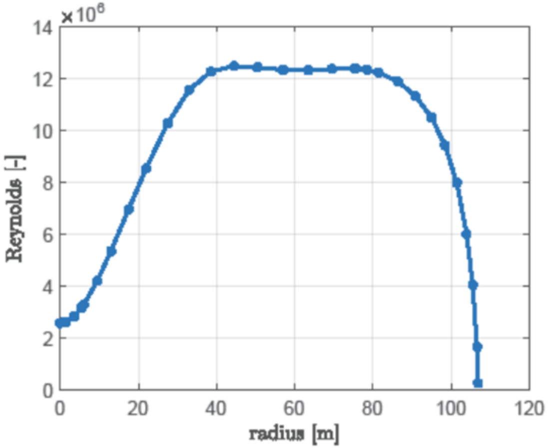
The Reynolds number Re at upscaling

$$Re = \frac{\rho . V_{eff} . c}{\mu} = \frac{V_{eff} . c}{\nu}$$

$$V_{eff} = \sqrt{[(1-a)V_w]^2 + (\Omega r)^2} \approx \Omega r$$

With:

- ρ: Air density
- μ dynamic viscosity
- ν kinematic viscosity
- Ω: Rotational speed
- r radial position of blade section
- V_w the wind speed and a the axial induction factor
- V_{eff} effective velocity at a blade section which is roughly Ωr ($\Omega r >> V_w$ except near the inner part of the blade)



The Reynolds number for the “small” 12 MW Stretch RWT at below rated conditions

Upscaling:

- Tip speed ΩR (despite a trend for slightly higher tip speeds) ~ constant (with Mach number say < 0.3)
  → V_{eff} independent of size
- ν is independent of size and **generally** 1.5 10^{-5} m^2/s
- Re scales with the chord which (despite a trend towards more slender blades) roughly scales with the turbine dimensions
- Re can easily be > 10 M (even 15 M+) for 10 MW+ turbines!

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Aerodynamics at high Reynolds Numbers:

Two basic (and partly opposite) effects

1) Generally thinner boundary layer as a result of higher Reynolds number and less decambering *), but:

2) Earlier laminar to turbulent boundary layer transition, which tends to thicken the boundary layer.

So there is a lot of uncertainty. **Validation** with **good** measurements is urgently needed

“No mature industry will ever design a Multi-MEuro machine with unvalidated tools”

M. Stettner, GE-Global Research

*)High Re effects might enable thicker airfoils without drag penalties, → reduced weight for large blades?

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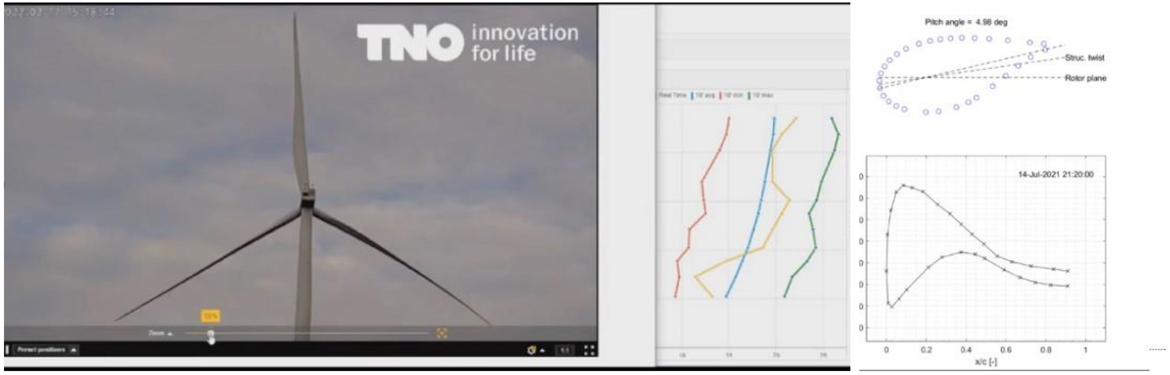
Measurements: Field and wind tunnel measurements are complementary

Field measurements

1) Full scale (representative Reynolds number)

2) Representative external conditions



TheTIADE field experiment

Wind tunnel measurements

1) Generally constant, uniform and known external conditions

2) Controllable conditions

The Mexico wind tunnel experiment

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How can we steer the Reynolds Number in a wind tunnel

$$Re = \frac{\rho.V.L}{\mu} = \frac{V.L}{\nu}$$

1) Change size L: Constrained by wind tunnel dimensions and blockage effects
2) Change velocity V: Constrained by (undesirable) compressibility effects

‘Conventional’ wind tunnels at standard atmospheric conditions donot give us Reynolds numbers of say >6 M. Reynolds number is much lower than the Reynolds numbers on a large 10 MW+ turbine unless we change the **kinematic viscosity** ν by pressurizing (higher ρ) and/or cooling to cryogenic temperatures (higher ρ and lower μ)

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2D airfoil measurements in the pressurized wind tunnel HDG of DNW up to a Reynolds number = 15 M were done in the EU project AVATAR ^{1,2})

AVATAR
AdVanced Aerodynamic Tools for lArge Rotors

Consortium

Coordinator:
ECN

Advisory Board:
DNV-GL (Menno Kloosterman)
ONERA (Arnaud le Pape)

Partners in alphabetical order:

CENER | CENTRO NACIONAL DE ENERGÍAS RENOVABLES NATIONAL RENEWABLE ENERGY CENTRE
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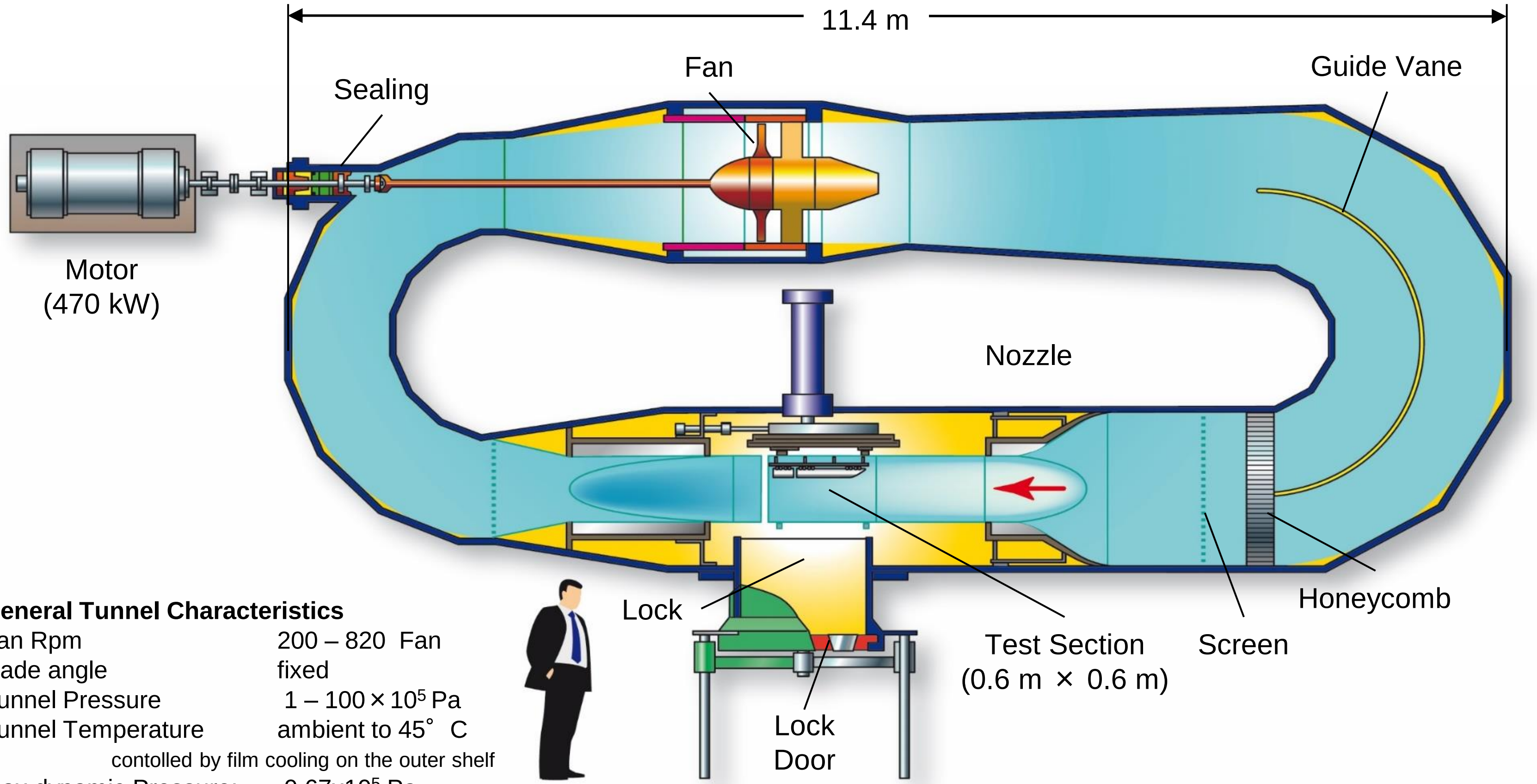
National Technical University of Athens
POLITECNICO DI MILANO
TU Delft Delft University of Technology
UNIVERSITY OF LIVERPOOL
University of Stuttgart Germany

FP7-ENERGY-2013-1/ n° 608396

1) J.G. Schepers, K. Boorsma, N. Sørensen, Voutsinas, G Sieros, H. Rahimi, H. Heisselmann, E. Jost, T. Lutz, T.Maeder, A. Gonzalez, C. Ferreira, B. Stoevesandt, G. Barakos, N. Lampropoulos, A. Croce, J. Madsen *Final results from the EU project AVATAR: Aerodynamic modelling of 10 MW wind turbines*, Journal of Physics: Conference Series, Volume 1037, number 2, http://stacks.iop.org/1742-6596/1037/i=2/a=022013 (2019)

2) Ozlem Ceyhan, Oscar Pires, Xabier Munduate, Niels N. Sorensen, Alois Peter Schaffarczyk, Torben Reichstein, Konstantinos Diakakis, Giorgos Papadakis, Elia Daniele, Michael Schwarz, Thorsten Lutz, and Raul Prieto 35th Wind Energy Symposium. Grapevine, Texas. *Summary of the Blind Test Campaign to predict the High Reynolds number performance of DU00-W-210 airfoil*

DNW-HDG High Pressure (100 bar) Wind Tunnel in Gottingen, Germany
Test section: 0.6x0.6m



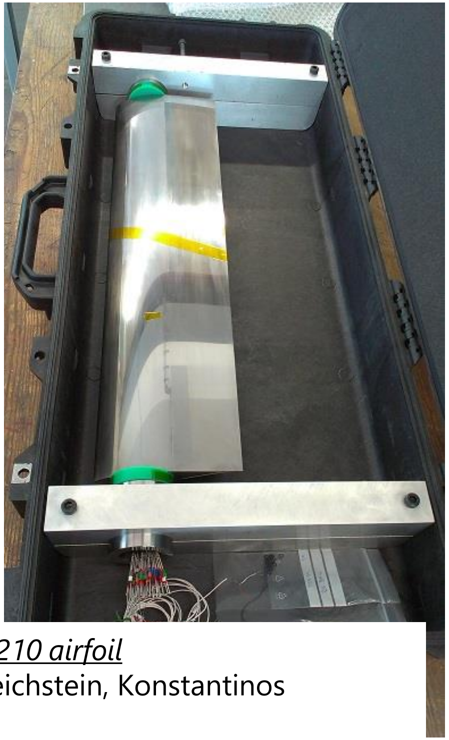
General Tunnel Characteristics

Fan Rpm	200 – 820 Fan
blade angle	fixed
Tunnel Pressure	1 – 100 × 10^5 Pa
Tunnel Temperature	ambient to 45° C
	contolled by film cooling on the outer shelf
Max dynamic Pressure:	0.67x10^5 Pa

Measurements in DNW-HDG pressurized tunnel

- Measurements up to Re = 15M (and low M)
- DU00-W-212 airfoil (t/c =21%), c= 15 cm
- Pressure distribution measurements (90 pressure sensors, including 5 unsteady pressure sensors)
- Wake rake for drag determination
- Estimation of transition location mainly from visual inspection of kink in (very dense) pressure distribution
- Flourescent oil flow visualization
- Results are publicly available
  https://zenodo.org/record/439827#.YNRodhFxfIU
- Measurements are simulated by CFD and panel methods in a ‘blind test’, see [1])

DNW-HDG model, c=15 cm

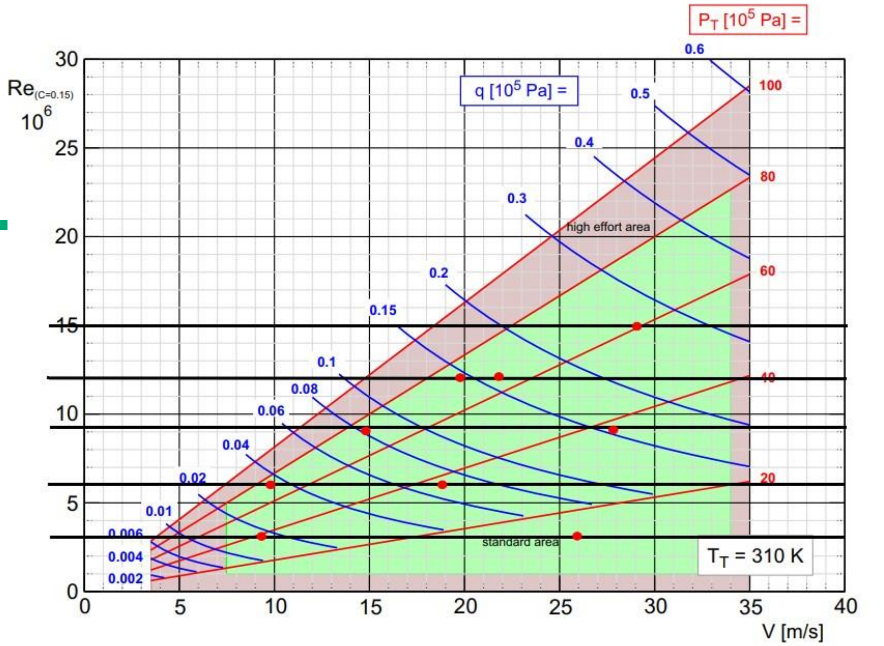


Summary of the Blind Test Campaign to predict the High Reynolds number performance of DU00-W-210 airfoil
Ozlem Ceyhan, Oscar Pires, Xabier Munduate, Niels N. Sorensen, Alois Peter Schaffarczyk, Torben Reichstein, Konstantinos Diakakis, Giorgos Papadakis, Elia Daniele, Michael Schwarz, Thorsten Lutz, and Raul Prieto
35th Wind Energy Symposium. Grapevine, Texas.

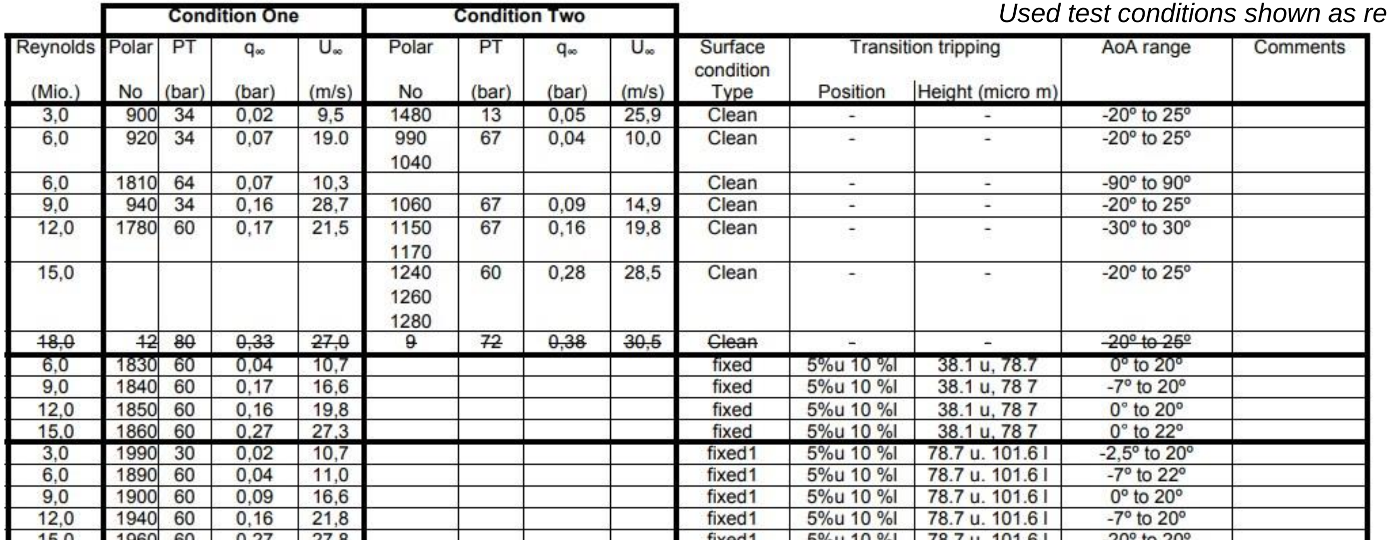
AdVanced Aerodynamic Tools for lArge Rotors

The test matrix:

- Clean and tripped conditions
  (Tripped conditions largely unexplored)
- Re: 3M, 6M, 9M, 12 M,15 M
- Reached through two different combinations of pressure and velocity→ very similar results!

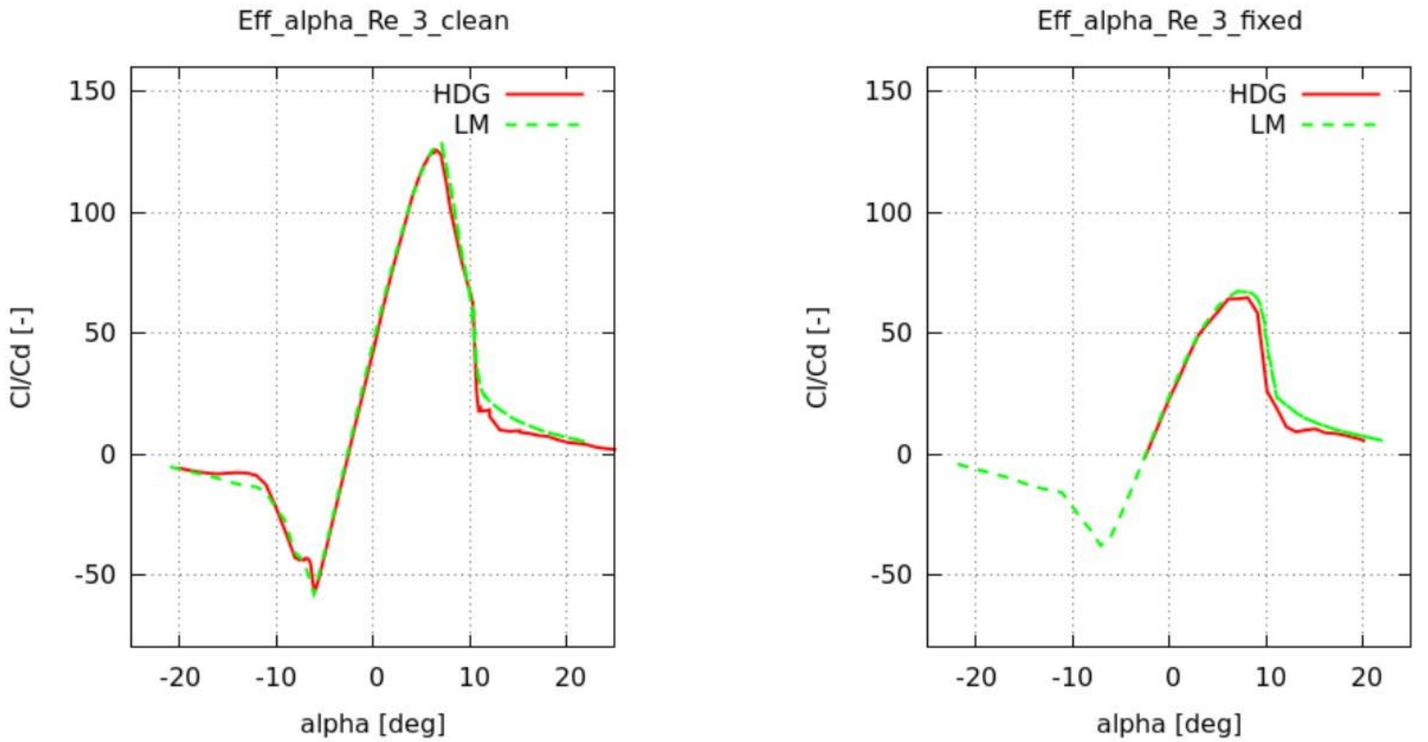


Used test conditions shown as red dots in the tunnel performance diagram



	Condition One				Condition Two								
Reynolds (Mio.)	Polar No	PT (bar)	q_∞ (bar)	U_∞ (m/s)	Polar No	PT (bar)	q_∞ (bar)	U_∞ (m/s)	Surface condition Type	Transition tripping Position	Height (micro m)	AoA range	Comments
3,0	900	34	0,02	9,5	1480	13	0,05	25,9	Clean	-	-	-20° to 25°	
6,0	920	34	0,07	19.0	990 1040	67	0,04	10,0	Clean	-	-	-20° to 25°	
6,0	1810	64	0,07	10,3					Clean	-	-	-90° to 90°	
9,0	940	34	0,16	28,7	1060	67	0,09	14,9	Clean	-	-	-20° to 25°	
12,0	1780	60	0,17	21,5	1150 1170	67	0,16	19,8	Clean	-	-	-30° to 30°	
15,0					1240 1260 1280	60	0,28	28,5	Clean	-	-	-20° to 25°	
~~18,0~~	~~12~~	~~80~~	~~0,33~~	~~27,0~~	~~9~~	~~72~~	~~0,38~~	~~30,5~~	~~Clean~~	~~-~~	~~-~~	~~-20° to 25°~~	
6,0	1830	60	0,04	10,7					fixed	5%u 10 %l	38.1 u, 78.7	0° to 20°	
9,0	1840	60	0,17	16,6					fixed	5%u 10 %l	38.1 u, 78 7	-7° to 20°	
12,0	1850	60	0,16	19,8					fixed	5%u 10 %l	38.1 u, 78 7	0° to 20°	
15,0	1860	60	0,27	27,3					fixed	5%u 10 %l	38.1 u, 78 7	0° to 22°	
3,0	1990	30	0,02	10,7					fixed1	5%u 10 %l	78.7 u. 101.6 l	-2,5° to 20°	
6,0	1890	60	0,04	11,0					fixed1	5%u 10 %l	78.7 u. 101.6 l	-7° to 22°	
9,0	1900	60	0,09	16,6					fixed1	5%u 10 %l	78.7 u. 101.6 l	0° to 20°	
12,0	1940	60	0,16	21,8					fixed1	5%u 10 %l	78.7 u. 101.6 l	-7° to 20°	
15,0	1960	60	0,27	27,8					fixed1	5%u 10 %l	78.7 u. 101.6 l	20° to 20°	

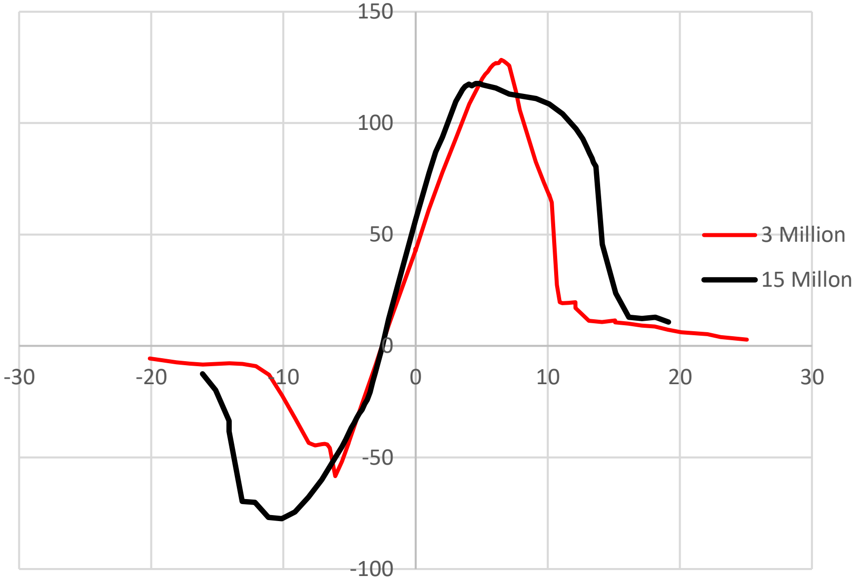
The quality of the DNW-HDG data has been checked further by cross comparing with measurements in the LM wind tunnel on the same DU00-W-212 airfoil at Re = 3M and 6M (courtesy X. Munduate)



Excellent agreement between measurements from these 2 tunnels, where the minimal differences are shown to be a result of a different turbulence intensity and Mach number in the different wind tunnels

c_l/c_d at different Reynolds numbers measured in DNW-HDG pressurized tunnel

Main observation: c_l/c_d peak is high and sharp at Re=3M, flattens towards Re =15M.
This difference has a significant design impact!
Wind Tunnel measurements at Re = 3 and 6 M are not representative for large off-shore turbines



c_l/c_d as function of α at Re = 3 and 15 M

Note: For those expecting a **higher** $(c_l/c_d)_{max}$ at Re = 15M:
$c_{l,max,15M}$ = 1.67 versus $c_{l,max,3M}$ = 1.3
$c_{d,min,15M}$ = 5.5 10^{-3} versus $c_{d,min,3M}$ = 7 10^{-3}
→ $(c_l/c_d)_{15M}$ is higher at small angles of attack
However: the laminar bucket is much less pronounced at Re = 15M
→ $c_{d,design,15M}$ is higher and $(c_l/c_d)_{max,15M}$ is lower

Also note $|c_l/c_{d,min,15M}|$ is larger.

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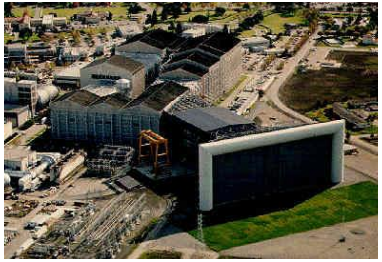
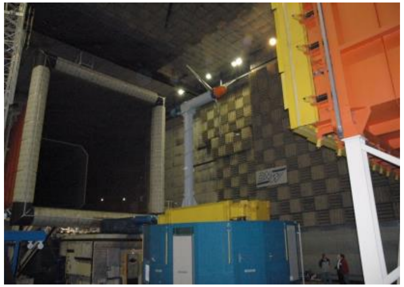
This was about 2D airfoil aerodynamics at high Reynolds number: What about *Rotor* aerodynamic wind tunnel measurements?

- NREL Phase VI
- NASA Ames
- 24.4 x 36.6-m^2 (Closed section)
- D = 10 m
- *Re ~ 1 M*

- Mexico experiment (EU project)
- German Dutch Wind Tunnel DNW-LLF
- 9.5 x 9.5 m^2 (Open section)
- D = 4.5 m
- *Re ~ 0.7 M*





Even the largest wind tunnels worldwide donot yield Reynolds number which significantly surpass 1 M

This is much lower than the Reynolds number for a 10 MW+ turbine where we saw the aerodynamics at low Re to be significantly different than the aerodynamics at representative Re.

Could we do a Mexico-like project in a pressurized or cryogenic wind tunnel?

M.M. Hand, D.A. Simms, L.J. Fingersh,, D.W. Jager, J.R. Cotrell, S. Schreck, and S.M. Larwood *Unsteady Aerodynamics Experiment Phase VI Wind Tunnel Test Configurations and Available Data Campaigns* NREL/TP-500-29955, National Renewable Energy Laboratory, NREL, 2001.

J. G. Schepers and H. Snel. *'Model Experiments in Controlled Conditions, Final report.'* ECN-E-07-042, Energ Research Center of the Netherlands, ECN. http://www.ecn.nl/publicaties/default.aspx?nr=ECN-E--07-042.

THE EUROPEAN TRANSONIC WIND TUNNEL (ETW) HAS PROMISING CHARACTERISTICS IN TERMS OF SIZE, TEMPERATURE AND PRESSURE

- Closed circuit cryogenic wind tunnel, using nitrogen as test gas
- Dimensions: 2.4 meters wide x 2.0 meters high x 9 meters long
- Pressure range: 1.25 to 4.5 bar
- Temperature range: 110 to 313 Kelvin
- Mach number range: 0.15 to 1.3
- Representative Reyndolds number for aeronautics applications: Re = 50 M/m:
- What about the Reynolds number for a rotating wind energy experiment?

Courtesy: ETW

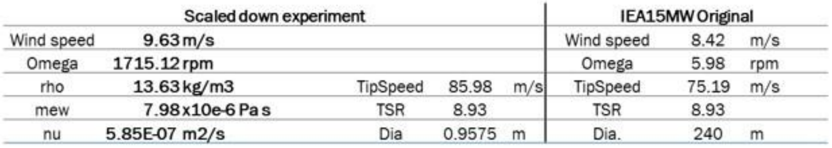
Many people think costs are a show stopper

- EU project Mexico: Costs of DNW-LLF were only 10% of the project costs
- Costs of ETW will be <=20% of the project costs → no show stopper!

IEA 15MW AT BLADE DESIGN POINT IN ETW (TSR AND SOLIDITY MATCH)

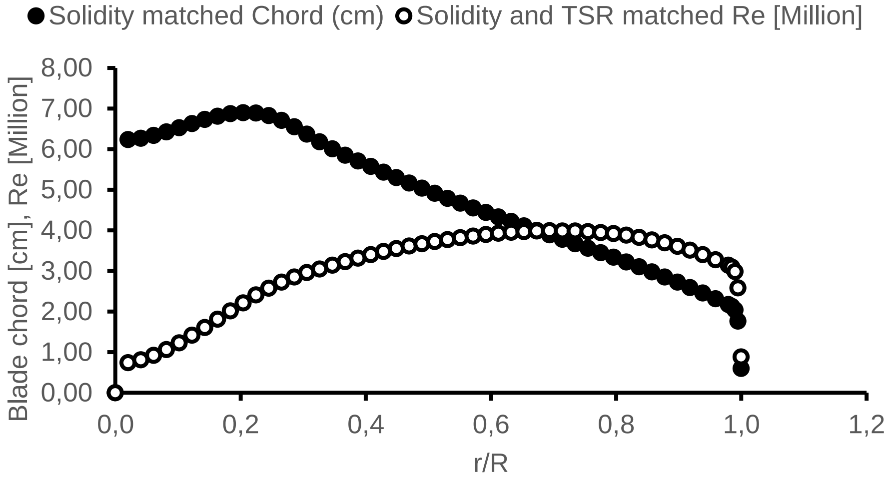
P=450KPA (4.5 BAR), T=-158˚C (115 K), TSR = 8.9

- Closed ETW section limits diameter and chord and so Reynolds nr and leaves litte room for instrumentation
- Sonic speed reduced by cooling
  →Reduce maximum tip speed to avoid compressibility effects
- Compromise blockage ratio and Mach number to relatively high values (15% and 0.4 respectively)
- Increase chord by 1 bladed instead of 3 bladed rotor
- →Re = 4 M at 75% span, much higher than Phase VI and Mexico!



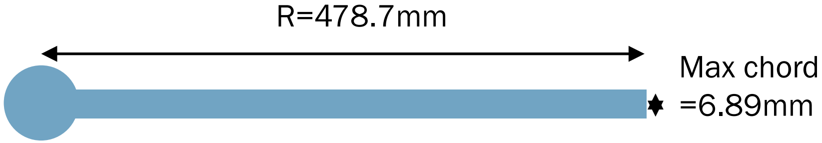
Scaled down experiment						IEA15MW Original		
Wind speed	9.63	m/s				Wind speed	8.42	m/s
Omega	1715.12	rpm				Omega	5.98	rpm
rho	13.63	kg/m3	TipSpeed	85.98	m/s	TipSpeed	75.19	m/s
mew	7.98x10e-6	Pa s	TSR	8.93		TSR	8.93	
nu	5.85E-07	m2/s	Dia	0.9575	m	Dia.	240	m

● Solidity matched Chord (cm) ○ Solidity and TSR matched Re [Million]



Courtesy: K. Vimalakanthan

Kinematic viscosity ratio = $\frac{\nu_{field}}{\nu_{tunnel}} = 24$



Considering only 1 blade, the model chord is scaled up to match the solidity of the original IEA15MW

Resulting in blade aspect ratio around (R/Max chord =) 7 << 21 (IEA15MW Original blade aspect ratio)

TNO innovation for life

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Conclusions

- The Reynolds number for large off-shore wind turbines can be between 10 and 20 M which cannot be reached in ‘conventional’ wind tunnels
- 2D airfoil measurements at representative Reynolds numbers are possible in a pressurized and/or cryogenic tunnel
  - The AVATAR high Re wind tunnel experiment showed significant differences in 2D airfoil aerodynamics between Re = 15 M and Re = 3 (or 6) M
  - See [1]: The blind tests showed good results from CFD at Re = 3M and 6M but deficient results at Re = 15M caused by deficient correlation based transition model SSTLM at 15M; Panel methods based on e^N transition model gave good results
- Rotating wind tunnel measurements at representative high Re are difficult to achieve due to restrictions on size and Mach number
  - By compromizing the blockage ratio and Mach number and by applying a 1 bladed turbine we can still reach 4 M in the ETW cryogenic tunnel which is much higher and more representative than the previous NREL Phase VI and Mexico experiment

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Recommendations

- Analyze further the DNW-HDG measurements (e.g. tripped conditions)
- Perform more high Reynolds number 2D airfoil measurements in pressurized and/or cryogenic wind tunnels (other airfoils, also at eroded conditions, also measuring boundary layer transition)
- Further exploit the possibility of rotating wind tunnel experiment in a pressurized and/or cryogenic wind tunnel *)
- Rephrase ***high Reynolds*** number testing by ***representative Reynolds*** number testing

*) Water tunnels with a 15 times lower kinematic viscosity than air might have potential for 2D testing but their smaller size and low velocity donot give very high Re at rotating experiments. Experiments in open water may have potential (despite the uncontrollable conditions) but requirements of the Froude number could be a limiting factor

Thank you for your attention

Acknowledgement: TNO Knowledge Innovation Program (KIP) 2023/ EU-PF7-Energy-1/608396