Final report of IEA Task 29, Mexnext (Phase 1):
Analysis of Mexico wind tunnel measurements

J.G. Schepers, K. Boorsma, T. Cho
Energy Research Center of the Netherlands, ECN

S. Gomez-Iradi
National Renewable Energy Center of Spain, CENER

P. Schaffarczyk, A. Jeromin, W.Z. Shen
University of Applied Sciences Kiel/CEWind EG

T. Lutz, K. Meister
The Technical University of Denmark

B. Stoevesandt
University of Stuttgart

S. Schreck
National Renewable Energy Laboratory

D. Micallef, R. Pereira, T. Sant
Delft University of Technology

H.A. Madsen, N. Sørensen
RISØ-DTU

February 2012
ECN-E–12-004
Acknowledgement

The authors would like to thank IEA Wind for facilitating the Mexnext project in their framework. The contributions of the participants to Mexnext have been funded in various national programmes:

- The contribution from ECN has been funded through the EZS subsidy from the Dutch Ministry of Economic affairs
- The contribution from the University of Victoria has been funded through the Natural Sciences and Engineering Research Council (NSERC)
- NREL participation in IEA Task 29 was funded by the US Department of Energy through the Wind and Water Power Program
- The contribution from RISØ-DTU and DTU MEK has been funded by the Danish Research and Development Program EUDP under contract: 63011-0190 "MexNext Analysis of Wind Tunnel Measurements and Improvement of aerodynamic models"
- The participation of CENER in IEA Task 29 was internally funded and thanks to the MICINN (ICTS-2009-40) program, CPU hours for CFD computations were obtained at CESGA supercomputing centre.
- The researchers from Israel would like to thank the Israel Ministry of National Infrastructures/ Office of the chief Scientist, for the support of the research that was carried out at the Technion - Israel Institute of Technology, Haifa, Israel
- The participation from UAS Kiel was funded by German Federal State of Schleswig-Holstein and the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). Part of the CPU hours for computation was supplied by North-German Supercomputing Alliance (HLRN).
Abstract

This report describes the work performed within the first phase of IEA Task 29 Mexnext. In this IEA Task 29 a total of 20 organisations from 11 different countries collaborated in analysing the measurements which have been taken in the EU project ‘Mexico’. Within this Mexico project 9 European institutes carried out a wind tunnel experiment in the Large Low Speed Facility (LLF) of the German Dutch Wind Facilities DNW on a rotor with a diameter of 4.5 m. Pressure distributions were measured at five location along the blade along with detailed flow field measurements around the rotor plane using stereo PIV.

The following organisations (and persons) cooperated in the projects:

- Canada: École de technologie supérieur, Montréal, ETS (C. Masson, S. Breton, C. Sibuet), and University of Victoria, UVIC (C. Crawford)
- Denmark: RISØ-DTU (H. Madsen, N. Sørensen, P. Rethouré) and the Technical University of Denmark DTU-MEK (W. Z. Shen)
- Germany: University of Stuttgart, Ustutt (T. Lutz, K. Meister), University of Applied Sciences at Kiel/CEWind EG (P. Schaffarczyk and A. Jeromin), ForWind (B. Stoevesandt and I. Hernandez)
- Israel: Technion, Israel Institute of Technology (A. Rosen, V. Ognev, R. Gordon)
- Japan: Mie University/National Institute of Advanced Industrial Science (T. Maeda, Y. Kamada, J. Murata)
- Korea: Korea Institute of Energy Research KIER, (H. Shin) and Korea Aerospace Research Institute, KARI (C. Kim, T. Cho)
- Netherlands: Energy Research Center of the Netherlands, ECN (G. Schepers, K. Boorsma, H. Snel), Delft University of Technology, TUDelft (G. van Bussel, N. Timmer, D. Micallef), Suzlon Blade Technology, SBT (A. Verhoeff), Technical University of Twente, TUTwente (E. van der Weide)
- Norway: Institute for Energy Technology/Norwegian University of Science and Technology, IFE (A. Knauer, J. van Rij)
- Sweden: Royal Institute of Technology/University of Gotland, KTH/HGO (S. Ivanell and K. Nilsson)
- USA: National Renewable Energy Laboratory, NREL (S. Schreck)

The Energy Research Center of the Netherlands, ECN acted as Operating Agent.

As a result of the international collaboration within this task a very thorough analysis of the data could be carried out and a large number of codes were validated not only in terms of loads but also in terms of underlying flow field.

The detailed pressure measurements along the blade in combination with the detailed flow field measurements gave a unique opportunity to better understand the response of a wind turbine to the incoming flow field. Deficiencies in modelling have been established and directions for model improvement could be given.
## Contents

1. Introduction .......................................................... 9
2. Goal ........................................................................ 13
3. Value of aerodynamics .................................................. 15
4. Mexico: Description of experimental set-up ....................... 19
5. Workplan .................................................................. 23
6. Task 1: Processing/presentation of data, uncertainties .......... 27
   6.1 Kulites ................................................................ 28
   6.2 PIV measurements .................................................. 29
   6.3 Balance measurements ........................................... 30
   6.4 Blade contour measurements .................................... 34
7. Task 2: Tunnel effects in the Mexico experiment .................. 37
8. Task 3: Comparison between calculations and measurements ...... 41
   8.1 Introduction .......................................................... 41
   8.2 First round: Axial flow ............................................. 42
      8.2.1 Pressure distributions ......................................... 42
      8.2.2 Loads ............................................................. 46
      8.2.3 Lifting line variables ........................................... 51
      8.2.4 Axial velocity traverse ....................................... 55
      8.2.5 Radial velocity traverse ..................................... 60
   8.3 Second round: Yawed flow ......................................... 80
      8.3.1 Loads ............................................................. 81
      8.3.2 Lifting line variables ........................................... 91
      8.3.3 Axial velocity traverse ....................................... 105
      8.3.4 Radial velocity traverse ..................................... 113
9. Task 4.1: Parked conditions ........................................... 129
   9.1 Introduction on Task 4.1 ............................................ 129
   9.2 Standstill Experiments ............................................. 129
   9.3 BEM Computations .................................................. 134
   9.4 CFD Computations .................................................. 137
   9.5 Conclusions & Future Steps from Task 4.1 (Parked conditions) 145
10. Task 4.2: Sensitivity of results on Reynolds Number and Rotational speed 147
   10.1 Introduction on Task 4.2 ............................................ 147
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.2</td>
<td>Influence of rotational speed on aerodynamic coefficients</td>
<td>147</td>
</tr>
<tr>
<td>10.3</td>
<td>Measurements performed by INTA, Spain</td>
<td>150</td>
</tr>
<tr>
<td>10.4</td>
<td>CFD Modeling of Reynolds number sensitivity</td>
<td>151</td>
</tr>
<tr>
<td>10.5</td>
<td>Summary and Conclusions on task 4.2: Sensitivity of results on Reynolds Number and Rotational speed</td>
<td>152</td>
</tr>
<tr>
<td>11</td>
<td>Task 4.3: Angle of Attack</td>
<td>155</td>
</tr>
<tr>
<td>11.1</td>
<td>Introduction on task 4.3</td>
<td>155</td>
</tr>
<tr>
<td>11.2</td>
<td>Results</td>
<td>156</td>
</tr>
<tr>
<td>12</td>
<td>Task 4.4: Near wake aerodynamics, including tip vortex trajectories and the turbulent wake state</td>
<td>163</td>
</tr>
<tr>
<td>12.1</td>
<td>Introduction on task 4.4</td>
<td>163</td>
</tr>
<tr>
<td>12.2</td>
<td>Task 4.4-A Near wake flow field and wake deficit</td>
<td>163</td>
</tr>
<tr>
<td>12.3</td>
<td>Task 4.4-B Vortex trajectory and vortex strength</td>
<td>165</td>
</tr>
<tr>
<td>12.4</td>
<td>Task 4.4-C Impact of numerical set-up and discretization</td>
<td>168</td>
</tr>
<tr>
<td>13</td>
<td>Task 4.5: Flow non-uniformities in the rotor plane</td>
<td>173</td>
</tr>
<tr>
<td>13.1</td>
<td>Introduction on task 4.5</td>
<td>173</td>
</tr>
<tr>
<td>13.2</td>
<td>Radial traverses</td>
<td>173</td>
</tr>
<tr>
<td>13.3</td>
<td>Flow non-uniformities in the rotor plane</td>
<td>175</td>
</tr>
<tr>
<td>14</td>
<td>Task 4.6: 3D-Flow Effects</td>
<td>185</td>
</tr>
<tr>
<td>14.1</td>
<td>Introduction on task 4.6</td>
<td>185</td>
</tr>
<tr>
<td>14.2</td>
<td>Effects observed in the measurement</td>
<td>185</td>
</tr>
<tr>
<td>14.3</td>
<td>3D flow phenomenon from CFD results</td>
<td>185</td>
</tr>
<tr>
<td>14.4</td>
<td>3D-effect models</td>
<td>189</td>
</tr>
<tr>
<td>14.5</td>
<td>Conclusions on task 4.6: 3D-Flow Effects</td>
<td>192</td>
</tr>
<tr>
<td>15</td>
<td>Task 4.7: Instationary Airfoil Aerodynamics</td>
<td>195</td>
</tr>
<tr>
<td>15.1</td>
<td>Introduction on task 4.7</td>
<td>195</td>
</tr>
<tr>
<td>15.2</td>
<td>Validation of the Beddoes-Leishman Dynamic Stall Model in the HAWT Environment, Using the MEXICO Data</td>
<td>196</td>
</tr>
<tr>
<td>15.3</td>
<td>Rotational Augmentation Disparities in the MEXICO and UAE Phase VI Experiments</td>
<td>203</td>
</tr>
<tr>
<td>16</td>
<td>Task 4.9: Dynamic inflow</td>
<td>217</td>
</tr>
<tr>
<td>16.1</td>
<td>Introduction on Task 4.9</td>
<td>217</td>
</tr>
<tr>
<td>16.2</td>
<td>Participants</td>
<td>217</td>
</tr>
<tr>
<td>16.3</td>
<td>Initial data analysis by ECN</td>
<td>217</td>
</tr>
<tr>
<td>16.4</td>
<td>Analysis of blade bending moments - pitch step</td>
<td>217</td>
</tr>
<tr>
<td>16.5</td>
<td>Analysis of blade bending moments - steep ramp in rotor speed</td>
<td>217</td>
</tr>
<tr>
<td>16.6</td>
<td>Comparison with simulations</td>
<td>218</td>
</tr>
</tbody>
</table>
1 Introduction

This report summarizes the results from the first phase of IEA Task 29 Mexnext. Mexnext is a joint project in which 20 parties from 11 different countries cooperate:

- Canada: École de technologie supérieure, Montréal, ETS (C. Masson, S. Breton, C. Sibuet), and University of Victoria, Uvic (C. Crawford)
- Denmark: RISØ-DTU (H. Madsen, N. Sørensen and Pierre-Elouan Rethore) and the Technical University of Denmark DTU-MEK (W. Z. Shen)
- Germany: University of Stuttgart, Ustutt (T. Lutz, K. Meister), University of Applied Sciences at Kiel/CEWind EG (P. Schaffarczyk and A. Jeromin) and ForWind (B. Stoevesandt and I. Hernandez)
- Israel: Technion - Israel Institute of Technology (A. Rosen, V. Ognev. R. Gordon)
- Japan: Mie University/National Institute of Advanced Industrial Science (T. Maeda, Y. Kamada, J. Murata)
- Korea: Korea Institute of Energy Research KIER, (H. Shin) and Korea Aerospace Research Institute, KARI (C. Kim, T. Cho)
- Netherlands: Energy Research Center of the Netherlands, ECN (G. Schepers, K. Boorsma, H. Snel), Delft University of Technology, TUDelft (G. van Bussel, N. Timmer, D. Micallfe), Suzlon Blade Technology, SBT (A. Verhoeft) and Technical University of Twente, TUTwente (E. van der Weide)
- Norway: Institute for Energy Technology/Norwegian University of Science and Technology, IFE (A. Knauer, J. van Rij)
- Spain: National Renewable Energy Center, CENER (X. Munduate, S. Gomez) and National Institute for Aerospace Technology, INTA (C. Redondo Calle)
- Sweden: Royal Institute of Technology/University of Gotland, KTH/HGO (S. Ivanell and K. Nilsson)
- USA: National Renewable Energy Laboratory, NREL (S. Schreck)

The focus of Mexnext lies on improving and understanding aerodynamic calculational models by means of dedicated wind tunnel measurements. These measurements have been performed within the EU project Mexico in the year 2006.

Aerodynamic calculational models are extremely important since they form the backbone of every computer program for the design of wind turbine. It is however known from several validation projects, see e.g. [1] and [2], that the uncertainties in the aerodynamic models are very large.

The availability of high quality measurements is considered to be the most important pre-requisite to gain insight into model uncertainties and to validate and improve aerodynamic wind turbine models. However, conventional experimental programs on wind turbines generally do not provide sufficient information for this purpose, since they only measure the integrated, total (blade or rotor) loads. These loads consist of an aerodynamic and a mass induced component and they are integrated over a certain spanwise length. In the late 80’s and the 90’s it was realized that more direct aerodynamic information was needed in order to improve the aerodynamic modelling. For this reason several institutes initiated experimental programs in which pressure distribution and the resulting normal and tangential forces at different radial positions were measured. Under the auspices of the IEA Wind, many of these measurements were stored into a database in Task 14.
and Task 18, see [3]. The results of these measurements turned out to be very useful and important new insights on e.g. 3D stall effects, tip effects and yaw were formed. However, the measurements were taken on turbines in the free atmosphere, where the uncertainty due to the instationary, inhomogeneous and uncontrolled wind conditions formed an important problem (as it is in all field measurements). This problem was overcome in NREL’s NASA-Ames wind tunnel experiment which was carried out in 2000 [4]. In this experiment a heavily instrumented rotor with a diameter of 10 meter was placed in the world’s largest wind tunnel, i.e. the NASA-Ames (24.4 \times 36.6 \text{ m}^2) wind tunnel. As such, measurements were performed at stationary and homogeneous conditions. The huge size of the wind tunnel allowed a rotor diameter of 10 m, with little blockage effects. Obviously this rotor diameter is still (much) smaller than the diameter of the nowadays commercial wind turbines, but nevertheless the blade Reynolds number (in the order of 1 Million) is sufficiently high to make the aerodynamic phenomena at least to some extend representative for modern wind turbines. NREL made the measurements from this experiment available to other institutes and they were analysed within IEA Wind Task 20. This Task was finished in December 2007 see [5]. The Mexnext can be considered as the successor of IEA Task 20. It focussed on the wind tunnel measurements which became available in December 2006 within the EU project Mexico [6]. In this project detailed aerodynamic measurements were carried out on a wind turbine model with a diameter of 4.5 m, which was placed in the largest European wind tunnel, the German Dutch Wind Tunnel, DNW with a size of 9.5 \times 9.5 \text{ m}^2. A unique feature of the Mexico measurements lies in the fact that the flow field around the rotor plane was measured simultaneously with the blade properties. At the end of the Mexico project the database with measurements was still in a rather rudimentary form and only limited analysis were carried out.

For this reason the Mexnext project was initiated in which the measurements from the Mexico project are analysed. Thereto it should be realised that the amount of Mexico data is very vast by which the time needed to analyse all data is extremely long for a single country. As such it was considered very beneficial to organise the analysis of the Mexico data under IEA Wind, since this make it possible to share tasks. Added value also lied in the fact that the task served as a forum for discussion and interpretation of the results. It is then possible to generate more value from the data than the summed value from the individual projects.

The Mexnext project started on June 1, 2008. This report describes the first phase which ended on June 1, 2011.

The report is structured as follows: The goal of Mexnext is described in section 2. Since the subject of Mexnext is aerodynamics it is considered important that the reader understands the value of aerodynamic research. This is explained in section 3.

The Mexico experiment is described in section 4. The working procedure and the work plan of Mexnext is described in section 5. It is then explained that the project is carried out in different tasks, the results of these tasks are reported in the sections 6 to 16. Conclusions and recommendations are given in section 17.