

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA ICAI

MASTER EN INGENIERÍA INDUSTRIAL

INVESTIGATION OF ICE ON A WIND TURBINE

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Madrid

April 2017

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VII

Nomenclature

Abbreviations

AoA Angle Of Attack
CWT Climate Wind Tunnel
LWC Liquid Water Content
MVD Median Volumetric Diameter
TI Turbulence Intensity

Coefficients

- C_2 Offset
- C_d Drag Coefficient
- C_l Lift Coefficient

Dimensionless parameters

- M_a MachNumber
- R_e Reynolds Number

Variables

- A Area $[m^2]$
- c Scale [m]
- D Diameter [m]

F_d	Drag Force $[N]$
F_l	Lift Force $[N]$
g	Gravity acceleration $[m/s^2]$
m	Mass $[Kg]$
P	Pressure [bar]
R_a	Gas Constant $\left[\frac{J}{molK}\right]$
T	Temperature $[C]$
t	Time $[s]$
V_0	Wind Speed $[m/s]$
W	Section Width $[m]$
α	Angle Of Attack []
γ	Ratio of the specific heat $[-]$
δ	Droplet size $[\mu m]$
μ	Viscosity $\left[\frac{Kg}{ms}\right]$
ρ	Density $[Kg/m^3]$
au	Accretion Time $[min]$

Abstract

Energy consumption has been growing without stopping over the last years. Due to pollution problems some regulations were needed and some energy alternatives of energy production showed up.

In 2012, Wind Farms in cold climates respresented the 25% of the total wind energy capacity. Placing a Wind Farm in cold climate regions involve big icing issues in the wind turbines and in the worst cases shutting down these wind turbines is needed. In order for wind energy to become a viable source of sustainable energy wind turbines need to be prepared to work as much as possible without shutting down them.

This research has several purposes. First of all to understand how a climate wind tunnel works and see which are its limitations. To take care about a delicate machine and to be creative to solve and repair problems while a test is running. Secondly, to test different types of ice on a NACA profile at different wind speeds and different angles of attack to analyze their characteristics and compare them to the theory.

Finally to obtain empirical data to compare it with theoretical data provided by PhDs students in the Seul National University, SNU.

Results are provided and as it was expected torsion, lift and drag coefficients are modified in different ways. Big amount of ice are accreted to the NACA profile, but some uncertainties exist due to the equipment used that for further studies could be implemented.

Resumen del proyecto

El consumo de energía a lo largo de los años ha ido incrementando sin cesar. Debido a problemas de contaminación, algunas restricciones y regulaciones erean necesarias por lo que surgieron diferentes tipos de producción de energía.

En 2012, los parques eólicos construidos en regiones de condiciones climáticas adversas representaban el 25% del total de la capacidad eólica instalada. Elegir un emplazamiento con condiciones climatológicas adversas incluye problemas de crecimiento de hielo en las palas de los aerogeneradores y en los peores casos es necesario apagar las aeroturbinas. Para que la energía eólica pueda convertirse en una fuente viable de energía alternativa, los aerogeneradores deben estar preparados para poder trabajar todo el tiempo posible sin tener que apagarlas o bloquear sus rotores.

Este estudio tiene diferentes propósitos. El primero de ellos es entender como funciona un CWT (Climate Wind Tunnel) y ver cuales son sus limitaciones. Cuidar de una máquina tan delicada y poder ser creativo a la hora de resolver todos los problemas que pueden aparecer a la hora de realizar un test.

En segundo lugar, testear diferentes tipos de hielo en una pala NACA a diferentes velocidades de vientos y ángulos de ataque para poder analizar sus características y comparar los resultados con la teoría.

Por último se obtendrán datos empíricos los cuales se enviarán a la universidad nacional de Seúl (SNU) para poder compararlos con los datos teóricos que ellos están obteniendo gracias al software que están desarrollando. Se incluyen todos los resultados de los tests al igual que las formas del hielo obtenidas de los diferentes tests. Como era de esperar las fuerzas lift, drag y el momento de torsión varían de diferentes manera dependiendo de las condiciones meteorológicas de cada uno de los tests. Sorprendentemente se ha obtenido una cantidad considerable de masa de hielo adherida en la pala del aerogenerador. Existen alguna incertidumbre debido al equipo usado que puede ser renovado para futuros estudios.

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Part I

Report

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Chapter 1

Introduction

Over the years, energy consumption has been growing without stopping. At first, energy production was mainly set by the consumption of fossil fuels and a very little part using what nowadays we call green energy. After the industrial revolution in XVII almost all cities in the world were using fossil fuels for almost everything and because of that, air became more and more polluted. That is why some regulations where needed and some alternaties of energy production were needed.

In order to live in a more sustaibable world and also to stop the problem of the climate change, in 2009 the Renewable Directive set some targets for all European Countries to, at least, reach a 20% share of energy production from RE (Renewables Energies) by 2020. The most common sources of RE are hydro, solar, wind or geothermal. So the implementation of the RE in the system will contribute by reducing the dependency on fossil fuels and therefore greenhouse emissions will be reduced.

Via Figure 1.1 it can be seen the evolution of the electricity generated by RE from 2004 to 2014. In 10 years the percentage of renewable energy power production has increase from almost 15% to almost 28%, resulting on an increment of 73.08%. This increment is due to many factors and many RE but as it can be seen, the larger contribution and so the biggest evolution is thanks the Wind Power production.



Figure 1.1: Evolution of electricity generated by RE from 2004 to 2014. [1]

Changing the production from a traditional fossil fuel production to a new green technology requires several factors, but two of them are much more important than the others. First of all a mentality change is needed. Apart of the regulations and the penalties, EU's governments need to be realistic and to take part in the energy change, otherwise it will more than complicated that these green energies can develop their technology. Once when the governments want to take part and admit that the climate change is a reality an investment is needed to be done. To give an example, Norway in 2013 approved a \$ 3 billion investment in Wind Power Plants to triple the existing capacity. [2] Considering that the initial investment is the biggest amount of money in green energy, it is needed to choose carefully which green energy will be and also another important factor its location.

To be able to choose the ideal green energy and its location, this RE has to achive the expectations and the goals that every country has. To give two examples, Denmark is one of the biggest investors on Wind Energy. The Danish Government based its 2020 projections on the existing legislation and framework. Its main goal is to cover the 50% of the total demand with just Wind Energy, which is the most important Renewable energy in the country. [3] Moreover, Denmark was already able to deliver the 39% of the total energy demand with just Wind Energy.

Another example is Spain. In the most optimistic scenario that was calculated by APPA (Spanish Renewable Energy Association) in colaboration with Deloitte expect to reach up to 28.3% of RES (Renewable Energy Sources) in gross final energy consumption by 2020. Number which is bigger than the expectation from the Spanish Government. However the main RES is expected to be also the Wind Energy. [4]

With all these ambitious goals and seeing that Wind Energy is the main RES one of the biggest issues is where to locate the Wind Farm. In Figure 1.2 it can be seen the wind speed distribution.



Figure 1.2: Wind speed distribution. [13]

As Figure 1.2 shows, the wind speed is higher in the north of Europe, so placing the Wind Farm in the north means a bigger production of energy. However the climate in those areas complicate the energy production of wind turbines due to the cold climate. Despite the basic problems that placing a Wind Farm in a cold climate, some countries like U.S.A, Canada and Sweeden, for example, are trying to install more capacity in those areas. [5]

As of 2012, around the 24% of the total wind energy capacity, about 69GW, were situated in cold climate areas and so they could suffer the issues of icing conditions.

Icing conditions can lead to a decrease of the power production due to the icing and also for safety conditions. The existing ice on the wind turbine blade can modify the aerodynamics of itself and so the efficiency of producing power. Also due to the safety regulations it is not permited to have operational wind turbines if there is any risk of icing release. This problems are estimated to have a loss in energy production between 20-50% [6], so many manufacturers are improving the components and the designs in order to be able to continue producing energy in those areas in such conditions.



Figure 1.3: Main aspects that icing conditions affect. [14]

Via Figure 1.3 it can be seen 3 main aspects that icing condition affects, design, safety and economics. All these aspects are interrelated and so to improve the energy production it is needed to improve the designs of the components to be able to resist the icing conditions and also the different types of ice.

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Chapter 2

Theory

This study focuses on the investigation of the ice on a wind turbine. Through this chapter some basic theory is going to be explained in order to understand why the ice accretion can affect the wind power production. Also this chapter provides a brief and selective introduction of ice accretion, types of ice and some different ways of getting rid of it.

2.1 Wind turbines

A wind turbine transforms the kinetic energy in the wind to mechanical energy and thanks to a transformer in electrical energy, so the power of the wind turbines follows Equation 2.1.

$$P = \frac{1}{2}\dot{m}V_0^2 = \frac{1}{2}\rho A V_0^3 \quad [W]$$
(2.1)

Where \dot{m} represents the mass flow, V_o is the wind speed, ρ the air density and A is the area that the wind pass through the wind turbine. As Equation 2.1 shows, the power of the wind turbine increases with the cube of the wind speed and only linearly with the area and the air density, so placing the Wind Farm in a location where it has high wind speeds is an important factor.

In this research only horizontal axis wind turbines (HAWT) are going to be taking into account, and due to the configurations of the tests, downwind turbines are studied. A Downwind HAWT can be seen in Figure 2.1. Three-bladed wind turbines have also more aerodynamic efficiency and that is why they are more chosen than two-bladed wind turbines.



Figure 2.1: Downwind HAWT. [15]

2.1.1 Aerodynamics

To understand the effects of the ice in a wind turbine blade is necessary to know how a blade works. The blades moves thanks to its design and of course depending of the amount of wind that faces. As it was said before, the electrical power is generated thanks to the kinetic energy of the wind, so in order to do so, some forces are needed to be generated by the wind. The blade is designed to create a pressure gradient and it acts like a centripetal force pushing and moving the blade as it can be seen from Figure 2.2.



Figure 2.2: Lift generation. [7]

The forces that the blade suffers whereas the wind are called lift and drag and both forces take part in the power generated by the wind turbine.



Figure 2.3: Lift and Drag Forces [7]

The total force that the blade faces can be split into two perpendicular forces called lifts and drag, those forces can be seen in Figure 2.3. The drag force is a force that is always parallel to the wind speed that faces the blade, in this case it will be V. This force represents the resistance of the blade to the wind speed. The lift force is always perpendicular to the drag force and so perpendicular to the air flow. In a case where the flow is completely horizontal, the lift force is the force that overcomes the gravity and lifts the blade.

Angle of attack (α) is the angle between the chord line and the flow vector. This angle shows how twisted the blade is. The chord line can be defined as the line from the nose of the airfoil to the tail. With the values of the lift and the drag and the geometry of the blade it is possible to calculate the power that the wind turbine is producing, so it can be seen the importance of this values. These forces have two different coefficients, C_l and C_d , which are non-dimensional and they can be calculated as it is seen in Equiations 2.2 and 2.3.

$$C_l = \frac{L}{\frac{1}{2}\rho V_o^2 c} \tag{2.2}$$

$$C_d = \frac{D}{\frac{1}{2}\rho V_o^2 c} \tag{2.3}$$

The maximum power is obtained on a wind turbine when the ratio between the C_l over the C_d is maximized (max $\frac{C_l}{C_d}$). Now can be understand more into detail why the ice accretion affects the power production in a wind turbine. Ice accretion affects the aerodynamics of the blade and, as it was seen before, the drag force is the air resistance that is seen in the blade, so if the drag force has a bigger value, its coefficient will be in the same way bigger. Also ice accretion modifies the airfoil shape so the lift coefficient is also modify. Ending up with a lower value of the lift-drag ratio mentioned before.
2.2 Ice introduction

Once the basic theory of how wind turbines work and the importance of having an uniform flow has been explained, it is time to go a bit further on ice growth, different types of ice and also in which way ice affects the flow and so the energy production in a wind turbine.

In Section 2.2.1 the different types of ice will be explained. Ice growth depends on many different atmospherical conditions and so there are different types of ice. However there are some parameters that characterise more the ice growth such as the droplet size or the Median Volumetric Diameter(MVD). What MVD represents is the mean size of the droplets in the cloud. It indicates that the half of the droplets are smaller and the other half are bigger than the value given.

Also, there are more parameters to be taken into account when ice accretion is happening, such as Liquid Water Content (LWC), that is the measure of the mass of water in a cloud in a specified amount of dry air. More parameters that affect the ice accretion and the type of ice are the air density, temperature, air pressure, wind speed, object speed, roughness of the surface, surface materials, exposure time among others.

A realistic estimation of ice accretion it is hard to get due to the fact that some meassures like the MVD and the LWC they are not as easy to get as the temperature, air pressure or others. Therefore there is an empirical way to calculate an estimation of the ice accretion thanks to the ISO 12494. [8] Equation 2.4 is only able to predict the mass of ice due to an in-cloud icing. In-cloud icing occures when the structures itself is inside the cloud and the droplets began to freeze on the surface and rime ice is the most typical ice type of in-cloud icing.

$$m_i = 0.11 \cdot v_i \cdot T_i \cdot W \qquad [Kg/m] \tag{2.4}$$

m_i	Ice mass in time i
v_i	Wind speed in time i
T_i	Duration time in the in-cloud condition in hours
W	Width of the object in m

Table 2.1 explains the meaning of each one of the components in Equation 2.4.

Table 2.1: Components in Equation 2.4

Equation 2.4 only can be use when the heigh of the lowest point of the cloud is lower than the interest point and it is assumed that if the ice falls, the accretion time begins again. This equation only gives the estimation of the ice mass that the blade is going to have through its surface but it does not show in which way it will affect the power production. As it was said before any variation of the aerodynamic shape of the wind turbine blade will cause an alteration in the power generated by the wind turbine.



Figure 2.4: Wind turbine blade with and without ice [9]

From Figure 2.4 it can be seen that the force F_y has a lower magnitude when there is ice on the wind turbine blade than when there is not any ice on it. The effect of ice accretion on the wind turbine blade results in a reduction on the lift coefficient, and as the surface is not as aerodynamic as it was previously, it causes also an increase in the drag coefficient. Therefore the ratio between the lift and the drag coefficients $\left(\frac{C_l}{C_d}\right)$ will be reduce and so the power generated by the wind turbine.

2.2.1 Types of ice

In this section, types of ice will be explained. Different types of ice require different types of growth. This research will only be focused in two different type of ice, rime ice and glaze ice.



Figure 2.5: Rime and glaze ice growth [10]

From Figure 2.5 it can be seen two different types of growth, what is called dry growth and wet growth.

Dry growth ocurres when there is no any liquid layer between the droplets in the cloud and the surface. Droplets freeze immediately when impacting the surface. The resulting ice is what is called "rime ice"

Wet growth, on the other hand, ocurres when a liquid layer appears before the surface, so only a part of the droplet freezes when touching the surface and the rest of it continues through the surface realising latent heat and so freezing slowly. The resulting ice is called "glaze ice"

2.2.1.1 Rime Ice

Rime ice appears when, in dry gorwth, supercooled droplets impacts the surface and freeze immediately. The size of the droplets is between $15-30\mu$ m. There are two types of rime ice, soft and hard rime ice. From Figure 2.6 soft and hard rime ice can be seen.



(a) Soft rime ice [16]



(b) Hard rime ice [17]

Figure 2.6: Different types of rime ice

Soft rime ice appears during light freezing fog and low wind speeds. It looks like white and thin needles on trees and in the edge of the wind turbine blades. It falls easily with almost no contact and that is why is one of the most dangerous type of ice due to the fact that a blade can throw it and cause damages not only in the Wind Farm, but also on its surrounding area. As is a fragile type of ice it has a low density value, between 100-600 Kg/ m^3

However, hard rime ice appears with higher wind speeds and a dense fog. It has a higher adhesion coefficient so its density has a higher value than soft rime ice, between $600-900 \text{Kg}/m^3$. It has a comb-like appearence or clear ice, but not transparent, also it is difficult to shake off.

As it was said, rime ice appears in dry growth with wind speed, therefore it exists a line that is called the **stagnation line**. this line is a location on the surface where the relatively speed on it is 0 so there is almost no droplet impact and so there is almost no ice on it. An example of a stagnation line can be seen in Figure 2.7.



Figure 2.7: Stagnation line [18]

2.2.1.2 Glaze ice

Glaze ice appears when, in wet growth, larger supercooled water droplets impact a surface and they are not able to freeze immediately. They go through the surface and it take some time to freeze, leaving a trace after them. The supercooled water droplets are bigger in comparison with the rime ice, $0-100\mu$ m. This type of ice has a higher adhesion and it is extremely dangerous due to its transparency making it hard to detect.



Figure 2.8: Glaze ice [19]

It has a higher density compared to rime ice, $900 \text{Kg}/m^3$ and due to its higher adhesion it is harder to melt and it takes more time and energy. From Figure 2.8 an example of glaze it can be seen.

To sum up, from Figure 2.9 it can be seen which type of ice will it be due to the wind speed and the droplet size. The main different aspect as it can be seen, is the temperature. In order to obtain glaze ice a relatively low temperature is needed,

15

between 0 and -5 degrees. On the other hand, rime ice need even lower temperatures for the same wind speed and also for the same droplet size.

Rime ice is, in comparison with glaze ice, the most critical type of ice. It can easily brake off the blades as its adhesion factor is lower than the glaze ice and it can cause mass unbalances on the rotor. Although also it can cause damages due to be thrown far away from where the wind turbines are.



(a) Type of ice depending the wind speed



(b) Type of ice depending droplet size

Figure 2.9: Comparison between glaze and rime ice

2.2.1.3 Mixed ice

As its name says, mixed ice is a combination of rime ice and glaze ice. It is common in nature when there is a transition between dry and wet growth. Initially when the water droplet hits the surface the first layer freezes immediately creating a rime ice layer where the next water droplet impacts and does not freeze immediately so in this case glaze ice appears and it has characteristics of both type of ice. An example of mixed ice can be seen in Figure 2.10.



Figure 2.10: Mixed ice

2.2.1.4 Hoar frost

Hoar frost is another type of ice which is totally different from the others. As glaze and rime ice appears thanks to the water droplets, hoar frost occurs due to the dew droplets when there are low wind speeds. Hoar frost consists in the accumulation of ice that form in humid air. The process of hoar icing consists in that the dew drops do not freeze immediately, they transform and become supercooled dew droplets that freeze in cold conditions and low wind speeds. So in conclusion, hoar frost must not be confused with glaze or rime ice which they appear thanks to different ice layers instead of individual dew droplets.



Figure 2.11: Hoar frost

2.3 Scaling Methods

2.3.1 Introduction

In the following section different scaling methods are going to be presented, likewise how are they used and why. As its name says, is a method, without recreating the same climate conditions, which obtains the same results as exposing the structure to the environment. Considering some limitations, many components cannot be fully-size tested in a CWT (climate wind tunnel). Moreover, these facilities can only provide a range of wind speeds, droplet size and LWC.

The main purpose of having a scaling method is to ensure that, the amount of ice, the aerodynamic penalties and the ice shape are the same as what it would be obtained from the original one in the environment.

However, a CWT is only able to provide the test conditions and in order to have the results as closer as possible to the desire ones some similarities have to be taken into account.

• Geometric similarity

As ice grows on the model, to obtain similar results it is needed that the shape of the test model and the model that will be used has to be similar, so the flowfiled similarity is maintained. This similarity as it will be explained later has nothing to do with size, size can be change and so there are some scaling methods that take into account the possibility of changing size due to the fact that for some parts and structures it is impossible to be tested in a CWT.

• Flowfield similarity

Flowfield similarity suggests that the Reynolds and the Mach numbers for the scaled have to be equal to the full-size model.

- Reynolds number

The Reynolds number, Re, is a dimensionless number which indicates the flow situation. It is normally used to describe if a flow is laminar or turbulent. It is the ratio of the inertial forces to viscous forces within a fluid that is moving.

Laminar flow occurs at low Reynolds number, which is characterized by constant fluid motion and the viscous forces are prevailing. [11]

Turbulent flow occurs at high Reynolds number where inertial forces are dominant and are inclined to provoque caos in the flow with vortices and instabilities. [11]

$$Re_a = \frac{Vd\rho_a}{\mu_a} \tag{2.5}$$

From Equation 2.5 the Reynolds number can be calculated. The length of the scale d represents, in case that the model is a cylinder, its diameter or in case that the model is an airfoil, twice the leading edge radious. Vrepresents the velocity of the fluid, ρ_a the air density and μ representd the viscosity of the fluid.

– Mach number

The Mach number is dimensionless number that represents the ratio of flow velocity past a boundary to the local speed of sound, but in fluid mechanics the Mach number is also used to determine how complessible a gas is. So this number can show us if a gas can be treated as incompressible and so make the calculations much easier. This number make the calculations much simpler due to the fact that the properties of the gasses change because of the atmospherical conditions.

From Equation 2.6 it can be seen how the Mach number can be calculated.

$$M_a = \frac{V}{\sqrt{\gamma R_a T_{st}}} \tag{2.6}$$

were V represents the velocity of the fluid, γ that is the ratio of the specific heat, in this case 1.4 because the fluid is air. R_a is the gas constant and T_{st} is the temperature.

However, when the scale model is for example half of the reference model, to match the Reynolds number, for the same conditions, the flow velocity has to be the double. As γ and R_a are constant properties of the air, the Mach number will double the reference value. So it is clear that it is impossible to match both, the Reynolds number and the Mach number when the scale model is different from the reference model. However this problem can be skipped if it is suppose that the Mach number, for most icing conditions is relatively low and compressibility conditions can be neglected. Also the Reynolds number can be avoided by saying that the boundary layer is very thin in the leading edge, where the ice grows mostly, and so the viscous effects can be ignore. [12]

• Drop Trajectory similarity

Drop Trajectory similarity propose that, the mass of water that reaches each part of the test model must be similar both, in mass and where the drop impacts the surface. So the drop trajectory in the scale model and in the reference model should be matched.

The equation that describes the motion of a single droplet relative to the airstream is shown in Equation 2.7.

$$\frac{d^2X}{d\Theta^2} = \frac{C_D R e_{rel}}{24K} \left(u - \frac{dX}{d\Theta} \right) \tag{2.7}$$

where the relative drop Reynolds number is based on the relative velocity between the air and the drop as it is shown in Equation 2.8

$$Re_{rel} = \frac{\delta \rho_a |u - \frac{dX}{d\Theta}|}{\mu_a}$$
(2.8)

In Equation 2.7 K is the non-dimensional inertia parameter that can be calculated by Equation 2.9.

$$K = \frac{\rho_w \delta^2 V}{18 d\mu_a} \tag{2.9}$$

As Equation 2.7 was designed for cylinders, in scaling, using the d as the chord means that same chord airfoils but with different shapes have the same intertia parameters. Changing the d for twice the leading edge radius, this problem is solved. As long as Equation 2.7 is non-dimensional, if the flows that reaches the model and the full scale are similar, the trajectories of the drops will be similar. So the only problem would be matching at the same time the Reynolds number and the intertia parameter and not always it is possible to match them simuntaneously, so the modify inertia parameter introduced by Langmuir and Blodgett [12] solves this problem.

$$K_o = 18K \left[Re_{\delta}^{-2/3} - \sqrt{6}Re_{\delta}^{-1} \arctan\left(\frac{Re_{\delta}^{1/3}}{\sqrt{6}}\right) \right]$$
(2.10)

Parameter that will be used in the following scaling methods.

• Water Catch similarity

The total amount of ice accreted on a model depends on:

- The amount of water in the cloud.
- The fraction of water that reaches the model.
- The portion of water having reached the model that actually freezes.

A factor that should be taking into account is the freezing factor that represents if all the water reaches the surface freezes (n=1) or the just the opposite, if there is no local freezing water (n=0). This parameter leads to the accumulation parameter and it can be calculated from Equation 2.11.

$$A_c = \frac{LWCV\tau}{\rho_i d} \tag{2.11}$$

Where τ represents the icing time in minutes.

Keeping in mind all of this similarities, it can be said that in conclusion many factors as geometry, AoA flow, etc, have to be similar to compare the results.

In Table 2.2 a comparison between some of published scaling methods are shown. All of these methods will be explained in the following sections.

Mathad		Test conditions									
Method	d	t_{st}	p_{st}	V	δ	LWC	au				
LWCxtime	М	М	М	М	М	S	calc				
Olsen	М	calc	М	М	М	S	calc				
Ingelman-Sundberg	s	М	a	s	calc	М	calc				
ONERA	s	a	a	calc	calc	calc	calc				
Ruff AEDC	s	calc	calc	s	calc	calc	calc				

Table 2.2: Comparison of some published scaling methods [12]

Mathad		Similarity parameters											
Method	K_o	A_c	n_o	b	r_a	ϕ	Θ	C_a	Re_a	We_{δ}	Ma		
LWCxtime	(m)	М				(m)	(m)	(m)	(m)	(m)	(m)		
Olsen	(m)	М	М					(m)	(m)	(m)	(m)		
Ingelman-Sundberg	М	М											
ONERA	М	М	М	М									
Ruff AEDC	М	М	М	(m)		М	М						

Table 2.3: Comparison of some published scaling methods [12]

In Table2.2 and 2.3 M represents that the scale parameter has to match the reference value, (m) that they coincidentally matches, s that that value it is specified

by the user, **a** that has to be determined by ambient conditions and test parameters and **calc** that that value has to be calculated by the other reference values.

2.3.2 Scaling Methods without size scaling

$2.3.2.1 \quad LWC \ x \ Time = Constant \ method$

This is the simpliest scaling method and it is used for LWC scaling and only satisfies water catch similarity by matching the accumulation parameter. In this method, scale size, wind speed, pressure, droplet size and temperature are matched to the reference values [12] as it can be seen from Equation 2.12 to 2.16.

$$C_s = C_R \tag{2.12}$$

$$t_{st,S} = t_{st,R} \tag{2.13}$$

$$p_{st,S} = p_{st,R} \tag{2.14}$$

$$V_S = V_R \tag{2.15}$$

$$\delta_S = \delta_R \tag{2.16}$$

Supposing that the geometry and the AoA are still the same as the reference and when the scale and the reference values match for the accumulation parameter and so the constants are cancelled, the product of the LWC and the time are equal.

$$LWC_S\tau_S = LWC_R\tau_R \tag{2.17}$$

Through Equation 2.17 if the user specifies the LWC scale, the accretion time can be obtained. This method would be effective for rime conditions if the temperature in the test section is maintained for all LWC values and for glaze it is effective only for very short accretion times. In conclusion, this method is the simplest method to use and convinent to use when LWC values are not reachable in an icing tunnel.

2.3.2.2 Olsen Method

The Olse and Newton method is an improvement of the LWCxtime method explained in Section 2.3.2.1. As is an improvement the basics are the same and the user has to select the LWC scale while maintaining Equations 2.12, 2.15 and 2.16. As the size, the wind speed and the droplet size for the test model are still the same as the reference model values, the modify inertia parameter, from Equation 2.10, remains the same.

$$K_{0,S} = K_{0,R} \tag{2.18}$$

What makes the Olsen-Newton method different from the LWCxtime method is that the Olsen method matches the freezing fraction instead of the static temperature and the static temperature is calculated from the scale freezing fraction. Because of this, the Olsen method is less advisable to use in comparison to the LWCxtime method, but the ice shape generated by this method will be more similar to the shape obtained if the conditions could have been tested. This method shows that the freezing fraction parameter is one the fundamental similarity parameters.

2.3.3 Scaling Methods with size scaling

In this section some scaling methods that do not match the size of the test model with the reference value are going to be presented. From Table 2.4 this methods are presented.

Test Parameter	Ingelman-Sundberg	ONERA	Ruff
c_S	user selects	user selects	user selects
$t_{st,S}$	$= t_{st,S}$	$t_{tot,S}$ known	$\phi_S = \phi_R$
V_S	user selects	$n_{o,S} = n_{o,R}$	user selects
MVD_S	$k_{o,S} = k_{o,R}$	$k_{o,S} = k_{o,R}$	$k_{o,S} = k_{o,R}$
LWC_S	$= LWC_R$	$b_S = b_R$	$n_{o,S} = n_{o,R}$
$ au_S$	$A_{c,S} = A_{c,R}$	$A_{c,S} = A_{c,R}$	$A_{c,S} = A_{c,R}$
$p_{st,S}$	$p_{tot,S} = p_{tot,R}$	$p_{tot,S} = p_{tot,R}$	$p_{tot,S} = p_{tot,R}$

Table 2.4: Scaling methods for size scaling

2.3.3.1 Ingelman-Sundberg method

This model was provided by a Swedish-Soviet working group on Aircraft Safety and it only matches to the reference values the similarity parameters of the modify inertia K_o and the accretion parameter A_c and the tests conditions t_{st} and the LWC value.

This model gives the user the opportunity to choose the model size and also the velocity. Due to this this method it is not very advisable to use since the velocity is a factor that has too great impact on ice shape and it is not very recommended to choose it arbitrarily. However for rime ice or very short accretions times this model should be adequate.

2.3.3.2 ONERA method

For this method, A_c , K_o , two terms from the energy balance, the freezing fraction n_o and the relative heat factor, b, have to match to the reference values. Also it is assumed that the surface it is at the freezing point, $t_s = t_f = 0^0 C$. With all that information, the ONERA method has developed an energy equation that it is shown in Equation 2.19.

$$\frac{1.058 \cdot 10^6 \frac{Knt}{m^2}}{p_{st}} = t_{st}(1+b) + (1732K) \frac{p_w}{p_{st}} + 79.7 \frac{cal}{g} n_o b + (3.6458+b) \frac{V^2}{8373 \frac{m^2}{s^2 K}}$$
(2.19)

It has to be mentioned that in Equation 2.19 K is not the inertia parameter, it refers to the absolute temperature in Kelvin.

Solving this equation it relates four of the scale conditions, velocity, static pressure, vapour pressure and static temperature. The ONERA method results in scale velocities less than the reference. Scale velocities need to be higher than the reference in subscale models in order to get good simulations.

2.3.3.3 Ruff method (AEDC)

Ruff method was the first one that evaluated scaling methods using several combinations of the similarity parameters.

- Matched K_0 and A_o
- Matched K_0 , A_o and n_o
- Matched K_0 , A_o , b and n_o
- Matched K_0, A_o, ϕ, θ and n_o

It has to be noticed that Ruff's third method is very similar to the ONERA's method, but in the Ruff calculates the static temperature by matching n_o , the freezing fraction and assigns a scale velocity.

Ruff obtains the best results when it matches K_0 , A_o, ϕ , θ and n_o and b is also matched when the last three parameters match to the reference values. This method is also communly known as the AEDC method. This method it is applied in tunnes with altitute simulation capability because it permits determining the value of the static pressure. [12]

Also this method permits to the user to pick one arbitrarily one value for the test conditions that normally is V_s , that it is very usefull for facilitites that have wind speed limitations. However it does not take into account the massive effect of the wind speed on the ice shapes.

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Chapter 3

Experimental Set Up

This chapter describes the different set-ups used to obtain the results of the ice accretion in the climate wind tunnel located in FORCE Technology in Lyngby. A basic description of the CWT itself is provided likewise all the components needed to obtain the data required. Also, the processes of calibration, gathering data and ice shapes are described. Moreover, test objects are described and so the parts designed to get all the set-ups done. In Part II all the technical drawings are presented for the parts that have been designed and manufactured.

3.1 Objectives

The purpose of this research is non other than to seek and study how much ice grows in an airfoil and in rotating cylinders and see the importance of this big isse for future wind turbines generations. The main objectives for this experimental tests are the following.

- To understand how similar conditions can a wind tunnel recreate in comparison to the real atmospherical conditions.
- To provide different results at different wind speeds.
- To provide different results at different temperatures.
- To compare how affects rime and glaze ice.

- To understand the limitations of a climate wind tunnel.
- To compare the results obtained from a climate wind tunnel to the results obtained from a simulation.

3.2 Climate Wind Tunnel

In this section a brief introduction of the CWT that has been used is going to be provided. Also the common parts used for both of the different set ups, are going to be explained in this section.



Figure 3.1: Climate Wind Tunnel sketch

Figure 3.1 shows the Climate Wind tunnel that has been used. As it can be seen the CWT is a close circuit form of:

- A cooling system.
- A fan.
- A spray bar.
- A honeycomb.
- The test section.

The test section is 5m long and has an area of 2x2m. Thanks to the cooling system the CWT is able to create subzero conditions and the honeycomb modifies the turbulence intesity to try to recreate as close real cistumstances as possible. All the basic specifications of the CWT are shown in Table 3.1.

Parameters	Units	Value
Maximum velocity	m/s	30
Turbulence intensity	%	0.6-20
Temperature range	оC	-10-40
Test section area	m^2	2x2
Test section length	m	5

Table 3.1: Basic specifications of the CWT

3.2.1 The spray bar

The spray bar consists in an NACA wooden shape with 15 nozzles that provides the cloud needed to do the tests that are required. From Figure 3.2 the spray bar can be seen.



(a) Spray bar producing the cloud.

(b) Spray bar place in position.

Figure 3.2: Spraybar

The spray bar is located before the construction of the tunnel and right after the honeycomb as it can be seen in Figure 3.2. The spraybar has a NACA profile to not to produce vortex infront of it and so affect the flow of the cloud into the test section. Inside the spray bar there are several heating wires to prevent icing inside the nozzles during tests in cold conditions.

From Figure 3.3 a nozzle can be analyzed.



(a) Nozzle

(b) Disassemble nozzle

Figure 3.3: Nozzle

Also, due to the construction of the tunnel the nozzles that are at the ends of the spray bar are not working. This is on purpose, the cloud produced by those nozzles will hit the wall and there is no interest on that, so water will be wasted. Also reducing the number of nozzles by two it is beneficial for the compressor, it reduces the stress to maintain the air pressure inside the rest of the nozzles.

Moreover, there are some limitations to choose the MVD. Nozzles are made of several parts as it can be seen in Figure 3.3. Water is comming through the smallest cylinder and air through the space that is between the two cylinders, both, water and air are mixed in a chamber right before the tip and then are release.

In conclusion, to be able to have a specific MVD value it is necessary to play with water pressure and air pressure. From Figure 3.4 a graph from the manufacturer can be seen. This figure represents which values are needed to get a specific MVD diameter. Some tests were made before to see if the figure from the manufacturer was reliable or not and they show that it was.



Figure 3.4: Figure provided from the manufacturer to obtain the MVD value.

However, due to how the tunnel was built, water pressure was fixed to 3.6 bar, fact that restricted a lot the capability of the tunnel to obtain different MVD values. It was known that air pressure cannot exceed water pressure, if that happen at some point, water were not able to came out from the nozzle.

One important problem that may spoil the running test is to have a frozen nozzle. Currently there are some heating wires inside the spray bar to heat up the tubes where the water is running throug but these wires are not working properly. This problem can be easily solve by changing the heating wires.

As it was said before another important value to control is the LWC. In this case there were no chance to obtain that value and only looking the ice shapes obtained right after a test, an idea if the value was higher or lower can be obtained.

3.3 Airfoil Set Up

In this section the airfoil set up is going to be explained step by step as so, the calibration needed and done before each tes to obtain results that are reliable. Additionally the software and all parts are going to be shown and analyzed.

3.3.1 Airfoil NACA 0015

For the following tests, a NACA 0015 airfoil is going to be used. From Figure 3.5 the airfoil can be seen.



(b) Side view of the NACA 0015 airfoil Figure 3.5: NACA 0015 airfoil

This NACA 0015 was designed and made by FORCE Technology A/S. It is wooden made, has a length of 1.98m and a chord length of 0.38m. The surface was treated with a specific varnish to prevent cracks as it will be suffering cold climate conditions with ice and water on its surface during all the tests.

The mounting system was also designed and made in FORCE Technology. The mounting system consists in two plates, one on each end of the NACA profile that connects the airfoil with the Force transducers that are on the walls of the CWT.

3.3.2 Force transducers

These force transducers are one of the most important parts in the set up. Thanks to these transducers all the forces applied before, during and after the tests in the NACA profile can be record and analyzed afterwards. A force transducer is shown in Figure 3.6.



(a) Top view of the force transducer

(b) Side view of the force transducer

Figure 3.6: Force transducer.

The system is formed by 4 pilars, each of them has a strain gauges. These strain gauges measure deformation, and transform this information into volts, so it can be processed by a computer. This volts then can be calculated and transformed again into a force.

As each force transducer has 4 strain gauges, the system is able to measure forces in the x direction, which is the direction of the wind, and in the z direction, which is the component of the gravity. We are defining this axis when the inclination of the force transducer is 0°. Furthermore, the force transducer is also able to read and measure the torsion that the airfoil is suffering.

The voltage obtained from the strain gauges is related to the force applied on them as Equation 3.1 shows.

$$F = c_1 V + c_2 \tag{3.1}$$

 C_2 represents an offset, and this factor will be set to zero at the beginning of each test. This factor is correlated to the weigh of the airfoil and as this research is only focused on the amount of ice the weight of the blade is not going to be taking into account. On the other hand, C_1 is known as the calibration factor and as it can be seen in Equation 3.1 represents the slope of the equation and it will be set for each of the force transducers separately. The procedure of changing the value of this parameters will be explained in the calibration section.

3.3.3 Airfoil calibration

In this section the calibration made in the NACA profile tests is going to be analized. As it was explained before, forces obtained come from forces transducers and the computer is going to obtain F_x , F_y and M_x or the torsion. As there are two force transducers the program is going to read 6 different values and each one of them has to be calibrated individually.

Table 3.2 shows the nomenclature that is going to be used for the calibration and also to obtain the results.

Nomenclature	Parameter	Units
X_R	Force	Ν
X_L	Force	Ν
Z_R	Force	Ν
Z_L	Force	Ν
M_R	Moment	Nm
M_L	Moment	Nm

Table 3.2: Nomenclature used for obtaining results

To distinguish which side is which, from now on R will be right side from the air flow point of view.

To do the calibration, first of all, several tests putting some weight on the blade have been done to see the performance of the force transducers with the actual values, supposedly already calibrated. There is an order for the calibration, first the X-axis is going to be tested, then th Z-axis and after all the torsion.

This is because if the torsion is checked before the Z-axis and then some parameters of the Z-axis are changed the torsion will be affected and the test needs to be repeated. All the calibration test have been made with an $AoA=0^{\circ}$.

Table 3.3 shows the values obtained from the X-axis tests.

Parameter	X_R	X_L								
Test number	36	36	37	37	38	38	39	39	41	41
Load [g]	500	500	1000	1000	1500	1500	2000	2000	2500	2500
Result [N]	5.60	5.49	8.46	8.36	13.06	12.89	17.42	17.15	26.70	26.34
Error [%]		1.9		1.23		1.26		1.53		1.32

Table 3.3: Results for X-axis tests

As it can be seen the error, or the difference between the values obtained from the two measurements are less than a 2%, something reasonable. The same verifications for the Z-axis and the torsion were made and they are shown in Table 3.4 for the Z-axis and in Table 3.5 for the torsion.

Parameter	Z_R	Z_L								
Test number	29	29	31	31	32	32	33	33	34	34
Load [g]	500	500	1000	1000	1500	1500	2000	2000	2500	2500
Result [N]	5.01	4.59	10.06	9.25	14.92	13.8	19.64	18.69	24.66	23.37
Error [%]		8.36		8.02		7.54		4.81		5.25

Table 3.4: Results for the Z-axis tests

Parameter	M_R	M_L	M_R	M_L
Test number	44	44	45	45
Load [g]	500	500	1000	1000
Result [N]	2.14	0.23	3.19	0.92
Error [%]		89.25		71.15

Table 3.5: Results for the torsion tests

It can be seen in Table 3.4 and 3.5 the difference between the force transducers is not acceptable at all, so it can be assumed that the calibration factor $[C_1]$ that was introduced before is not well calculated. Tests are needed to be done to calculate properly each calibration factor for each force transducer to have reliable values in the experiments.

3.3.3.1 X-axis calibration

For this calibration some equipment is needed:

- Different weights.
- One pulley.
- One support.
- Rope.

All these items can be seen in Figure 3.7.



Figure 3.7: Equipment nedded for the X-axis calibration

The weight of the support that holds the weights is 113g, so if at the beginning there is 1kg in the support, the total force that the airfoil holds supposing that there is no deformation on it, is shown in Equation 3.2.

$$X = (1 + 0.113) \cdot 9.81 = 10.9185N \tag{3.2}$$

Of course there are some considerations that should be taking into account while doing this test. The rope is not perfectly inelastic, so maybe it takes some of the potential energy from the support and that also can affect the displacement. Another issue is that the contact zone between the rope and the airfoil is too small and that can deform the NACA profile. However, the force applied was too small for taking this issues in consideration.

3.3.3.2 Z-axis calibration

The only equipment needed are the different weights. The force that the force transducers are going to read is the weight of the weights that are going to be placed as near as possible to them as it can be seen in Figure 3.8.



Figure 3.8: Z-axis calibration

To obtain the correct value for the calibration factor C_1 some calculations need to be done. As the tests have been done with a weight of 1kg the reference force value is 9.8N. Once the value is compared to the reference the calibration factor was multiplied to the percentage of error between the value obtained and the reference. This procedure is repeated as many times as needed until the error between the measurements and the reference value is lower than a 1In this case there were two different weights of 1kg on each force transducer but each of the calibration parameters were calculated to measure only 1 kg. At the end, the total force applied of the airfoil will be the sum of both values, that in theory if both force transducers were exactly the same should be equal.

3.3.3.3 Torsion calibration

For the torsion calibration 1kg in total has been place at the end of the NACA profile in the CWT. It is known that the chord lenght is 0.38m but as the force transducers are not situated in the tip of the airfoil a new measure needs to be done. This value has been checked twice in order to have a realible result. The distance between the weights and the force transducer is D = 0.27m so the reference value to calculate the calibration parameter is shown in Equation 3.3

$$M = 9.81 \cdot 0.27 = 2.6487Nm \tag{3.3}$$

Figure 3.9 shows the command window with the calibration factors calculated.

index	Ch#	Disable	Callo CH#	REL	GDF Title	G	DF unit	type	Transducer ID	type	Amplifier ID	Constant
0	0	Enable	-1	Rel	KR		N	Load gauge		No gain	Gain 4	14.60495
1	1	Enable	-1	Rel	kr		Ν	Load gauge		No gain	Gain 4	-14.84200
2	2	Enable	-1	Rel	ZR		Ν	Load gauge	9	No gain	Gain 5	22.44476
3	3	Enable	-1	Rel	ΖL		N	Load gauge	1	No gain	Gain 5	21.05208
4	4	Enable	-1	Rel	MR		Nm	Torque gauge	1	No gain	Gain 4	-1.51428
5	5	Enable	-1	Rel	ML	10	Nm	Torque gauge	1	No gain	Gain 4	-1.29590
6	6	Enable	-1	Rel	Pressure contraction	11	Pa	Pressure	9	No gain	Fur #14	99.75634
7	7	Enable	-1	Rel	Pitot Ceeling		Pa	Pressure) () (No gain	Fur #15	99.66266
8	8	Enable	-1	Abs	Temp	1 D	egree	Temperature) ()	No gain		10.00000
9	9	Enable	-1	Rel	Air 1	11	Pa	Pressure	1	No gain	Ch 1	1.00000
10	10	Enable	-1	Rel	Air 2	11	Pa	Pressure	9	No gain	Ch 3	1.00000
11	11	Enable	-1	Rel	Water 1		Pa	Pressure	1	No gain	Ch 2	1.00000
12	12	Enable	-1	Rel	Temp 2	10	egree	Temperature	1	No gain	Ch 4	1.00000
0	0	Disable	0	Rel			N	2 Load gauge	0	Gain check	0	
0	0	Disable	0	Rel		0	N	2 Load gauge	0	Gain check	0	
0	0	Disable	<u>0</u>	Rel		1	N	Load gauge	0	Gain check	0	
umber o hannels 3	f j	GDF inde	×	Ne	w / Insert Delete	,	Mov	save	Cancel	Tacho	Help	Status

Figure 3.9: Calibration factors

3.4 Cylinder Set Up

In this section the cylinders and all the parts that are going to be needed are analyzed. All the parts that have been made specifically for this research are going to be explained and also their technical drawings are included in Section II. For this set up three cylinders of varying diameters are available. Every cylinder corresponds to a particular feature of the airfoil used previously, so with this set up and the rotating cylinders the idea is to proof how much the Magnus effect affects the ice shape.

Table 3.6 shows the cylinders diameter and at which particular feature of the airfoil corresponds to.

Diamater [mm]	Length	Airfoil
32	1985	Leading edge radius
58	1985	Maximum height
105	1985	Double height

Table 3.6: Dimensions of the cylinders and features of airfoil

Also from Figure 3.10 the three cylinders can be seen and the particular features of the airfoil can be observed.



(a) Correlation of airfoil to cyliders



(b) Side profile of the cylinders

Figure 3.10: Cylinders and correlation of airfoil.

In this case to hold the cylinders the force transducers were not available as the idea was to have them rotating so different parts were needed.

- Motor.
- Wall bracket.
- Two shafts.
- Small, medium and large cylinders supports.
- Cylinders.

The cylinders were designed and 3D printed in Force Technology using their rapid prototyping printer, and the rest of the parts were made in DTU's workshop in steel.

3.4.1 Motor

The motor selected for this research was a motor made by Faulhaber. What was needed was a motor able to give a high continues torque at low rotation speed. As it was explained, the aim of this research is to compare ice shapes with rotating and non rotating cylinders to analyze how much the Magnuss effect affects.

The motor selected is a 3268G024BX4 - 32/3S - 86:1 motor with a MC5005SRS motion controler.

3.4.2 Wall bracker

Wall brackers were designed in order to be able to hold the weight of the cylinders, so the motor would not hold any weight and therefore the life time of the rest of the componens would be longer. The basic idea was to have a piece of steel able to have two different parts, one that was able to rotate and the other one fixed to the wall thanks to several screws.

The final design can be seen form Figure 3.11.



(a) Top view of the wall bracker



(b) Side profile of the wall bracker

Figure 3.11: Final wall bracker

To place the wall brackers in position some changes in the walls of the CWT were needed to be done, the main problem was that the lenght of the cylinders is 1985mm and the total lenght of the tunnel was 2000mm without taking into account the thickness of the walls. From the beginning the wall brackers were though to be place outside the wind tunnel due to the icing conditions. These conditions can affect the efficiency of the bearing so it is needed to be place outside the tunnel.

To save material and also to make it cheaper the idea was to have the "U" shape to reduce the distance between the cylinders supports and the wall brackers so this part could go into the wall and so make the shafts smaller and so, lighter. The problem was that the hole in the wall was circular and the wall bracker was not able to go into the wall and to place it, a modification was needed. This modification can be seen from Figure 3.12.



(a) Modification of the hole in the CWT(b) Wall bracker placed in the wall of the CWTFigure 3.12: Wall bracker placed in the CWT

3.4.3 Shafts

The mission of the shafts is to connect the cylinders supports to the wall brackers. One of them is a normal cylinder, 110mm long and with a diameter of 32mm. The other one has two holes, one to harbor the motor shaft and the other one for a screw to tighten the motor shaft so the motion produced by the motor is transmited to the rest of the system. Both shafts can be seen in Figure 3.13.



Figure 3.13: Connection shafts

3.4.4 Cylinders supports

These pieces connect the shafts to the cylinders. Their mission is to tighten those parts hard enough to make the cylinder rotate at the same speed that the motor is rotating.

There were some parts already made. For each cylinder, two pieces are needed, one for each side of it. In this case, for the larger cylinder these parts were already made by a 3D printer in plastic resin, and also one for the smallest and the medium cylinder. Reverse engineering was made to prepare the technical drawings for these parts.

The main problem was that the design for this parts was acceptable for the material used, but as the idea was to have them done in steel some modifications were needed. In Figure 3.14 the first sketch for the cylinders support is shown.



Figure 3.14: First cylinder support sketch [10]

It can be seen that there is not a solid piece. There is a gap that can be smaller or bigger thanks to a screw in the same side. This can be done thanks to the stiffness of the material that it is not very high, but the new piece is going to be made of steel, which has a higher stiffness and so, this design is not going to work. The idea was to make this piece from two symmetrical pieces that can tighten the shaft and the cylinder thanks to two screws.

In the previous design a screw and a nut were needed and it was difficult to tighten up. In the new design the nut was removed so it was easier to connect everything. A comparison between the old design and the new one is shown in Figure 3.15.



Figure 3.15: Comparison between the old and the new cylinder support

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Chapter 4

Results

In this section all the tests perfored are going to be explained and the results obtained are going to be analyzed for both, the airfoil and the cylinder set-up.

4.1 Airfoil results

As it was explained before, the airfoil that is going to be used is a NACA 0015 profile with 0.38m chord length and it is 1.98m long. Right after every test a static test is going to be done in to obtain the mass of the ice accreted in the airfoil. Such test will last 90 seconds.

The aim of this research is to obtain and to be able to compare the difference between galze and rime ice at different AoA and to do so several test were planned. This tests are shown in Table 4.1.

	Accretion time	AoA	Chord	Wind speed	Air temperature	LWC	MVD
	[min]	[deg]	[m]	[m/s]	$[^{\mathrm{o}}\mathrm{C}]$	$[g/m^3]$	$[\mu \mathrm{m}]$
	60	0	0.38	15	-5	0.4	45
Dimo	60	4	0.38	15	-5	0.4	45
nine	60	8	0.38	15	-5	0.4	45
	60	12	0.38	15	-5	0.4	45
	40	0	0.38	25	-1	0.4	34
Claza	40	4	0.38	25	-1	0.4	34
Glaze	40	8	0.38	25	-1	0.4	34
	40	12	0.38	25	-1	0.4	34

Table 4.1: Test conditions for NACA 0015

In total there are 8 different test, 4 cases for rime ice and another 4 cases for glaze ice. Every case has been done twice in order to obtain reliable results. Also several ice shapes have been obtained for each test, so a comparation can be done and also some conclusions can be obtained.

Some premises have to be highlighted. For example, the LWC value that was expected to have in Table 4.1 was impossible to reach. That value was impossible to calculate so the real value it is unknown. After having the results and the ice shapes obtained after the test, it can be said that the LWC value obtained was much bigger than the expected.

Another thing to take into account is that the only way to obtain the MVD was through the manufacturer, that can be seen in Figure 3.4. Obviously the results that the manufacturer and the real values obtained in the CWT could be different but there was no way to obtain and contrast those values to be completely sure.

Before everytime a new test was done, a little check-calibration was done to know if the force transducers were giving reliable results or not. This calibrations were made at test temperatures. Temperature cannot be ignored, and as the NACA profile is going to be exposed to cold climate conditions, a small deformation of the airfoil can be obtained and so, the force transducers need to be calibrated at that temperature.

4.1.1 Rime ice results

The climate conditions for these tests are shown in Table 4.1. There are different results obtained, but this research is going to analyzed the mean values after the 60 minutes tests in the rime ice cases.

Before doing any icing test, a test for each case has been done to obtain the reference values and so after compare them. The results for the reference tests are shown in Table 4.2.

	AoA[⁰]	Lift[N]	Drag[N]	Torsion[Nm]
No Load	0	25.705	-0.9	3.165
	4	75.924	2.297	3.527
	8	124.890	9.642	3.768
	12	144.026	16.221	3.243

Table 4.2: Reference values for Rime ice tests

As it can be observed that as the AoA increases its value lift and drag do so. The same thing happens to the torsion except for the last result. First of all it is a bit strange that in the first case when the AoA = 0^0 lift has a possitive value. It is supposed to be 0 as the flow is completely parallel to the airfoil. As the calibration has been made by hand here is when the human error is shown.

Via Table 4.3 the results for the icing conditions for the rime ice can be seen.

	$AoA[^0]$	Lift[N]	Drag[N]	Torsion[Nm]
Load	0	6.465	7,063	3,415
	4	24,929	4,067	2,582
	8	52,414	1,289	$2,\!092$
	12	59,522	5,543	2.912

Table 4.3: Results for Rime ice tests

A visual comparison between the reference values and the results obtained after the icing test can be done from Figure 4.1



Figure 4.1: Comparison between Rime ice values and reference values

In all 4 cases it is observed that the lift is reduced significantly. In 2 cases, drag force increases and in the other two decreases. It was expected to increase in all cases due to the aerodynamic breakdown of the ice but it is curious that the same thing happens also in the glaze ice case. Regarding torsion, the only case that it increases is in the first one. If the ice has accreted more in the bottom surface of the airfoil it can increases the surface and so the contact with the wind speed will be bigger and so it can cause bigger torsion.

To know how much the ice affects the lift, drag and torsion a comparison in percentage with the reference values can be seen in Table 4.4

	Percentage loss [%]					
AoA $[^{0}]$	Lift	Drag	Torsion			
0	74.847	-112.794	-7.896			
4	67.164	-77.075	26.767			
8	58.031	86.631	44.477			
12	58.672	69.743	10.217			

Table 4.4: Percentage looses of the lift, drag and torsion in rime ice tests

After all the test another static measurement was taken so the amount of ice of each test was obtained. Table 4.5 shows the results.

$AoA[^0]$	0	4	8	12
Ice Mass [Kg]	5.89	5.42	4.38	5.90

Table 4.5: Ice mass created

It is surprising the huge amount of ice accreted in the airfoil in a 60 minutes test.

From Figure 4.2 to 4.5 different rime ice shapes can be seen and compare. It has to be said that the ice shapes have been obtained from the same test at the same conditions. It can be detected that they are more or less similar in some parts and completely different in others. This is due to the spray bar, the spray bar as it was said has several nozzles that spray water and create a water cloud which hit the NACA profile, but due to the design there is not a perfect uniformity at high wind speeds in the cloud. This problem affects the ice accretion and so the ice shapes obtained from the tests.

Ice shapes have been obtained from an area which did not suffer the direct impact from the nozzle and was as close to the middle of the airfoil as possible in order to try to avoid the wall effect.

In most of the cases the stagnation point can be seen in the ice shapes, or at least the area where it should be.



(a) Rime ice shape with (b) Rime ice shape with $AoA = 0^0 \qquad \qquad AoA = 0^0$

Figure 4.2: Rime ice shapes with $AoA=0^{0}$



(a) Rime ice shape with (b) Rime ice shape with (c) Rime ice shape with $AoA = 4^0$ $AoA = 4^0$ $AoA = 4^0$

Figure 4.3: Rime ice shapes with $AoA=4^{0}$



(a) Rime ice shape with (b) Rime ice shape with $AoA = 8^0 \qquad \qquad AoA = 8^0$

Figure 4.4: Rime ice shapes with $AoA=8^{0}$



(a) Rime ice shape with (b) Rime ice shape with (c) Rime ice shape with $AoA = 12^0$ $AoA = 12^0$ $AoA = 12^0$

Figure 4.5: Rime ice shapes with $AoA=12^{0}$

From Figure 4.6 rime ice obtained through the experiments is shown. The ice obtained included a part of glaze ice as it can be seen, but the top part shows some characteristics of the rime ice as the color and as it was tested after, the low adhesion compared to the glaze ice. Rime ice detached easily from the airfoil, it was very useful after the test to remove the ice, but very dangerous to work with it.



(a) Rime ice shape with $AoA = 0^0$ (b) Rime ice shape with $AoA = 8^0$



4.1.2 Glaze ice results

Climate conditions for these tests are shown in Table 4.1.

As in the previous case with the rime ice results, only the mean values after 40 minutes of tests are going to be analyzed. The reason why only taking into account the mean values is that through the tests sometimes parts of the ice detach from the surface and there are some oscilations after that, and if the value taken from the test was the value right after that the results would not be reliable.

In order to be able to compare the results obtained, first it is needed to do a round of tests without the water cloud produced by the spray bar, but at the same conditions that the tests are running. The results are shown in Table 4.6.

	AoA [⁰]	Lift [N]	Drag [N]	Torsion [NM]
No Load	0	51.766	2.705	8.813
	4	217.158	7.206	10.147
	8	319.685	22.119	10.581
	12	404.4843	44.987	9.542

Table 4.6: Reference values for Glaze ice tests

In this case as the previous one, when the AoA increases, the lift and the drag forces increases as well. The torsion increases except the last case when the $AoA=12^{0}$.

Here also the human error is shown. In the first case, when the $AoA=0^{0}$ lift force it is suppose to be 0, but it is not. This has to be taking into account supposing that the NACA profile it is not perfectly aligned and so there is some errors.

Table 4.7 shows the results for the icing conditions for the glaze ice.

	AoA $[^{\underline{0}}]$	Lift [N]	Drag [N]	Torsion [NM]
Load	0	9.815	15.498	5.356
	4	114.942	11.456	4.409
	8	187.35	6.275	3.972
	12	276.377	2.526	12.231

Table 4.7: Results for Glaze ice tests

To have a faster and easier comparison between the reference values and the results obtained after the tests, a visual comparison from Figure 4.7 can be done.



(c) Glaze ice tests with $AoA = 8^0$ (d) Glaze ice tests with $AoA = 12^0$

Figure 4.7: Comparison between Glaze ice values and reference values

As it can be observed and as in the previous case, lift values are reduced significantly due to ice accretion in all 4 cases and drag values are bigger in the first two cases and lower in the last two. This is a curious fact as it was expected to be bigger in all 4 cases. After all drag force represents the resistance of the blade to the wind speed.

Regarding torsion, in almost all cases, except the last one, the values are lower than the reference one. Ice accretion can be the responsible of that. If most of the amount os the ice accretes to the front part of the airfoil, ice mass will create a moment in the same direction that the wind speed is tryign to rotate the airfoil.

To be able to know how much the ice affect the lift, drag and torsion a percentage comparison has been made and it is shown in Table 4.8.

	Percentage loss [%]					
AoA[0]	Lift	Drag	Torsion			
0	81.038	-472.8	39.225			
4	47.069	-58.971	56.5484			
8	41.395	71.631	62.453			
12	31.671	94.384	-28.183			

Table 4.8: Percentage losses of the lift, drag and torsion in glaze ice tests

The minus sign in Table 4.8 does not correspond to a loss, but to a gain in the drag or in the torsion. In the first case an enormous gain in the drag force can be observed. This is due to the ice accretion in the tip of the blade that modifies all the aerodynamics of the blade and increases the resistance to the wind speed.

After all tests a static measurement was taken in order to know the amount of ice accreted on the blade. The results are shown in Table 4.9

AoA $[^{0}]$	0	4	8	12
Ice mass [kg]	4.311	5.002	5.470	2.490

Table 4.9: Ice mass created

It has to be said that during the last test one big piece of ice brakedown right after the test and before the ice mass test, and that is why the value of the ice mass was so low. In order to have a reliable value the test was repeated and the results were very similar to the previous ones except of course for the ice mass, that the value is shown in equation 4.1.

$$m_{ice} = 6.53 \quad Kg \tag{4.1}$$

From Figure 4.8 to 4.11 different glaze ice shapes from the different tests can be examined. As in the precious case with rime ice tests, the ice shapes have been taken as close to the middle of the airfoil as possible trying to not to measure the center of the impact of the water cloud from the nozzle in the spray bar. As closer to center of the impact of the water cloud impact, the ice shape is bigger and the ice shape obtained from there is no relevant. The idea is to measure an area were the water cloud impacts the airfoil at the wind speed without the addition of the air pressure comming from the spray bar.

In many cases the stagnation point can be seen and analyzed.



(a) Glaze ice shape with (b) Glaze ice shape with $AoA = 0^0 \qquad \qquad AoA = 0^0$

Figure 4.8: Glaze ice shapes with $AoA=0^{0}$



(a) Glaze ice shape with (b) Glaze ice shape with (c) Glaze ice shape with $AoA = 4^0$ $AoA = 4^0$ $AoA = 4^0$

Figure 4.9: Glaze ice shapes with $AoA=4^{0}$



(a) Glaze ice shape with (b) Glaze ice shape with (c) Glaze ice shape with $AoA = 8^0$ $AoA = 8^0$ $AoA = 8^0$

Figure 4.10: Glaze ice shapes with $AoA = 8^{\circ}$



(a) Glaze ice shape with (b) Glaze ice shape with $AoA = 12^0$ $AoA = 12^0$

Figure 4.11: Glaze ice shapes with $AoA=12^{0}$

And in Figure 4.12 the real ice on the airfoil can be seen. Some of the main properties of the ice can be observed like the transparency. Different properties as the high adhesion factor was checked. This type of ice was much harder to remove it from the blade in comparison with the rime ice.



(a) Glaze ice shape with $AoA = 0^0$ (b) Glaze ice shape with $AoA = 4^0$



4.1.3 Data comparison with SNU

Students from SNU are developing a program able to predict the ice shape obtained in an airfoil under any climate condition. All previous cases have been sent to them in order to calibrate their software. It was needed due to the uncertainty round the MVD parameter and the LWC.

Table 4.10 shows all the tests done and also sent to SNU to compare results.

Accretion Time	AoA	Chord length	Air Speed	Air Temperature	LWC	MVD
[min]	[⁰]	[m]	[m/s]	$[^{\mathrm{o}}\mathrm{C}]$	$[g/m^3]$	$[\mu m]$
10	0	0.38	10	-5	0.25	20
10	0	0.38	25	-4	0.25	20
10	0	0.38	10	-1	0.25	20
10	0	0.38	25	-1	0.25	20
10	4	0.38	10	-1	0.25	20
10	4	0.38	10	-4	0.25	20

Table 4.10: New test conditions for NACA 0015

In these tests some conditions have changed compared to the previous ones. Wind speed has a lower value, the idea behind this decision was to try to have a better mix between the water and the air in the water cloud produced by the spray bar. The turbulence intensity is lower in this case and the water cloud width is bigger, so it is expected to have a better ice uniformity on the airfoil.

Another factor is the accretion time, it has been reduced to try to have time to do more tests and to have more data to compare. What it is behind the tests is the time that the tunnel needs to cold down and then to heat up to melt all the ice accreted on the airfoil. As the airfoil is made of wood, extreme care must be taken in removing the ice adhered on its surface, so as not to damage the aerodynamics of the NACA profile so it can affect the rest of the tests.

As it can be seen in Table 4.10 the MVD selected for this tests is 20 μ m. To be able to obtain this value a combination of air pressure and water pressure in the nozzle is needed, thanks to the manufacturers information the correct values correspond to a water pressure of $P_{water} = 3.6bar$ and $P_{air} = 2.1bar$. It has to be highlighted that the possibilities of getting this MVD value are very huge, but as the system in the CWT has a P_{water} fixed to 3.6 bar, the only possible value for the air pressure is 2.1 bar.

The results of the lift, drag and torsion of these tests are shown in Table 4.11.

Accretion Time	AoA	Wind Speed	T_{air}	Lift	Drag	Tosion	
[min]	[⁰]	[m/s]	[^o C]	[N]	[N]	[Nm]	lest Number
10	0	10	-5	4.397	1.114	1.215	408
10	0	25	-4	11.119	2.356	3.246	412
10	0	10	-1	3.802	1.028	1.087	406
10	0	19	-1	21.757	5.851	6.565	410
10	4	10	-1	23.773	0.7	1.249	414
10	4	10	-4	23.295	0.612	1.226	416

Table 4.11: Results for new test conditions

From Table 3.2 some conclusion can be obtained and evaluated. An increase in the wind speed causes a big change in the lift, in the drag and also in the torsion values. However when the wind speed is the same but the temperature changes no big difference between lift, drag and torsion are observed. It has to be highlighted that one test has a different wind speed, this was caused due to technical problems with the cooling system that was not able to reach the desired wind speed at the needed temperature.

The problem is that the higher the wind speed in the CWT, the more difficult is to reach a lower temperature. When the fan is at high speeds, it releases energy into the system and this energy heats up the tunnel. Also the flow in the tunnel rubs with the walls heating up them and also rising the temperature in the tunnel.

It is expected that the amount of ice in these cases is much lower than in the glaze and in the rime ice test due to the accretion time. The results are shown in Table 4.12.

Accretion Time	AoA	Wind Speed	T_{air}	Ice mass
[min]	$\left[^{\Omega} \right]$	[m/s]	$[^{0}C]$	[kg]
10	0	10	-5	0.436
10	0	25	-4	0.908
10	0	10	-1	0.366
10	0	19	-1	1.029
10	4	10	-1	0.54
10	4	10	-4	0.542

Table 4.12: Ice mass

It can be observed that the higher the wind speed the higher the ice mass is obtained on the airfoil. The higher the wind speed, the more water droplets that impact to the airfoil surface and so the more that freezes on it.

Also if 3rd and 5th cases are compare, it can be analyzed that changing the angle of attack from 0 to 4 increases the contact surface were the water droplets impacts on the airfoil and so the amount of ice accreted on it is bigger.

From Figure 4.13 to 4.18 all the ice shapes obtained from these tests can be seen.



Figure 4.13: Test 408 ice shape



(a) Test 412 ice shape (b) Test 412 ice shape

Figure 4.14: Test 412 ice shape



(a) Test 406 ice shape (b) Test 406 ice shape

Figure 4.15: Test 406 ice shape



(a) Test 410 ice shape (b) Test 410 ice shape (c) Test 410 ice shape Figure 4.16: Test 410 ice shape



(a) Test 414 ice shape

(b) Test 414 ice shape (

(c) Test 414 ice shape

Figure 4.17: Test 414 ice shape



(a) Test 416 ice shape (b) Test 416 ice shape

Figure 4.18: Test 416 ice shape

Figure 4.19 shows the comparison between the empirical and the simulated results. It is obvious that there are some big difference between them. These difference can be due to the uncertainty of the LWC value and the MVD value. Also some other physical phenomenons, as the PhDs have said, are missing in the model and that is the reason why the ice shapes are not exactly the same.



Figure 4.19: Comparison between empirical and simulated results

4.2 Cylinders results

Unfortunately due to external problems the parts were not ready to do any measurements, not even to obtain the reference values. The comparison and the analysis of the Magnus effect remains pending for a future research.

Chapter 5

Problems, conclusions and further studies

5.1 Problems

In this section some problems presented through this research are going to be presented and some solutions are going to be explained to improve future researches.

• Wall effect

In order to obtain higher wind speeds and save energy in the fan, the wind tunnel is provided with a narrowing in the test section. If the amount of fluid, in this case air, remains constant through the close-circuit and a narrowing is provided, this leads to an increment of the wind speed in the test section. The problem comes when the spray bar is right before the narrowing, causing the water cloud produced by the nozzles at the ends of the spray bar to mix and became just one leading to an increment in the amount of water droplets that impact the arifoil per cm. And therefore obtaining a measure that is not reliable. From Figure 5.1 a comparison between an ice shape obtained in the middle of the airfoil and another one obtained next to the wall is shown.



(a) Ice shape obtained in (b) Ice shape obtained the middle of the airfoil next to the wall.

Figure 5.1: Wall effect

• Ice homogeneity

Through this research it has been said that the higher the wind speed the less ice homogeneity on the airfoil. There are several solutions that can deal with this problem. The simplest one is to build 2 more spray bars and place them in the position where their nozzles cover the space of the old one. In such a way that there is no gaps between nozzles and so, the water cloud would be uniform.

Another solution is to place a honeycomb right after the spray bar. This honeycomb modifies the turbulent intensity after the nozzles and cause a better mixing between the wind created by the fan and the water cloud.

Another solution is to check the distance between the spray bar and the airfoil, the bigger the distance, the higher the mixing between the water cloud and the wind. In that case the system has more time to stabilize and so to have a better water cloud. From Figure 5.2 gaps between the water cloud produced by the nozzles can be seen.



Figure 5.2: Gaps in the water cloud at high wind speeds

• Metal plat

The only possible way to measure the ice shapes is thanks to the metal plat that is shown in Figure 5.3.



(a) Side view of the metal plat(b) Metal plat place in the airfoilFigure 5.3: Metal plat

This metal plat can be slightly deform due to the icing conditions and also has to break some ice to be able to be placed in position to take measurements. Sometimes this caused large blocks of ice to come off the airfoil lossing the chance to have more than 2 ice shapes.

5.2 Conclusions

Throughout this research the importance of studying the ice effects on wind turbine blades and how much they influence their aerodynamics, their structure and, consequently, their mechanical properties have been verified.

Also, it has been possible to verify the properties of the different types of ice, as well as the climatological conditions necessary for these types to be obtained. Characteristics such as adhesion, hardness and visual appearance have been checked. As expected, ice has caused a reduction in the lift coefficient round 40% in glaze ice and even more in rime ice. Regarding drag coefficient it is curious why in some cases there is a gain, which was expected, but in some other cases the ice modifies the surface in such way where the resistance to air is lower and so the drag coefficient.

Another factor tested was the capability of the facilities to maintain the cold climate conditions. During tests the temperature was fluctuating all of the time and to reach low temperatures at high wind speeds was really difficult. The cooling system has to be checked every two tests to verify that there is no condensation in the tubes that may cause ice inside the system when cooling down the tunnel.

5.3 Further studies

Further studies can be done by improving aspects that in this reseach were out of control.

- LWC In this research there was no possibility to control the LWC value, parameter that it is extremely important to take into account when the calculations are done.
- MVD The only way to control the MVD value was through the manufacturers information, but some changes in the CWT are needed to be done in order to be able to control this value on-site at any time.
- Rotating cylinders

Rotating cylinders tests are pending. As the rotating cylinders set-up is completely done, it would be interesting to to verify the importance of the Magnus effect on different diameter cylinders.

Part II

Technical drawings

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