Journal of Wind Engineering & Industrial Aerodynamics 173 (2018) 39–52

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Effects of blade design on ice accretion for horizontal axis wind turbines

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A R T I C L E I N F O

Keywords:
Wind power
Atmospheric icing
Numerical predictions
Aerodynamics

A B S T R A C T

This paper presents a numerical study to predict ice loads on a wind turbine blade section at 80% of blade span. Air flow, droplet impingement and ice accretion simulations are conducted in FENSAP ICE. The effect of low and high liquid water content (LWC) conditions on blade thickness is presented. All NREL airfoil families used for HAWTs are examined to study blade design's effect on ice accretion. Ice shapes are numerically predicted at different atmospheric temperatures and LWC conditions. The degradation in aerodynamic characteristics due to ice formation is predicted. The numerical predictions suggest a 10%–65% reduction in lift coefficient due to ice accretion, which is highly dependent on the accreted ice shape.

1. Introduction

The installed capacity of wind turbines has expanded rapidly in recent years. However, current major issues for further development of HAWTs, such as fatigue problems associated with upscaling of turbines (Rezaeiha et al., 2017), floating offshore installations (Borg et al., 2014; Paulsen et al., 2014) and operation in harsh northern locations should be addressed to facilitate continued rapid expansion of installed capacity. Cold regions typically have abundant wind power resources making them attractive locations for wind farm installations (Reid et al., 2013). However, wind turbines installed in cold climates can experience blade icing causing significant power losses (Hochart et al., 2008), and atmospheric icing is a common cause of ice accretion on a wind turbine (Reid et al., 2013). Ice accretion on wind turbines can have significant impacts on its operation (i.e. aerodynamic performance and controlling systems), safety (i.e. site accessibility due to ice throwing) and economics (i.e., annual energy production and turbine lifespan) (Virk et al., 2012). Atmospheric icing on wind turbines occurs when super-cooled water droplets collide with the surface of the blades and freeze upon impact (Reid et al., 2013). Formed ice type is based on the atmospheric and operational conditions, including temperature, pressure, wind velocity, liquid water content (LWC), median volume diameter of droplets (MVD), rotor blade curvature, roughness, heat flux, icing event time, and collection efficiency of droplets (Battisti, 2015; Kraj and Bibeau, 2010).

Typically, ice accumulates on the turbine blades at temperatures between 0 °C and −15 °C (Virk et al., 2012; Battisti, 2015). Ice accretion mechanisms are usually classified into two different types: (i) glaze ice and (ii) rime ice (Makkonen, 2000), which are typically formed based on the atmospheric temperature range. Additionally, numerous different ice shapes can be formed, however, shape prediction is difficult due to the rapid changes in the atmospheric conditions during icing events (Fikke et al., 2006). Glaze ice usually forms transparent, horn shapes of ice and is typically caused by freezing rain/drizzle or wet icing conditions with high LWC concentrations Reid et al., 2013; Virk et al., 2012; Battisti, 2015). It is formed at temperature ranges between 0 °C and −5 °C and droplet diameter ranges from 0 μm to 500 μm. Its density is higher than rime ice, usually around 900 kg/m^3 (Reid et al., 2013; Virk et al., 2012; Cattin, 2013).

Rime ice is caused by frozen fog with smaller range of droplet sizes compared to glaze ice, ranging from 0 μm to 10 μm (Reid et al., 2013; Battisti, 2015). Rime ice usually occurs at lower temperatures below −6 °C with lower concentrations of LWC, as the temperature is well below the freezing point water droplets freezes instantaneously upon collision with object surface. Rime ice usually forms grainy and opaque ice shapes (Reid et al., 2013). Depending on droplet size, soft or hard rime can be formed. Typically, rime ice density ranges from 100 kg/m^3 to 600 kg/m^3 (Reid et al., 2013; Virk et al., 2012; Cattin, 2013). Atmospheric measurements indicated that LWC usually varies from 0 g/m^3 to 5 g/m^3. Low LWC concentrations below 1 kg/m^3 can be existed during stratiform clouds environment. In contrast to cumuliform clouds environment which are characterized by higher LWC concentrations usually higher than 1 kg/m^3 (Cober et al., 2001; Masters, 1985). LWC value is highly influenced by elevation and atmospheric temperature. The relationship between LWC, MVD and temperature was experimentally evaluated showing that LWC decreases as the droplet size increases (Jeck, 2002). LWC value decreases with altitude and temperature.

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https://doi.org/10.1016/j.jweia.2017.11.024
Received 28 June 2017; Received in revised form 23 November 2017; Accepted 25 November 2017

Nomenclature

ρ	Density (kg/m^3)
V	Velocity (m/s)
T	Temperature (K)
m	Mass flow (kg)
d	Droplet diameter (μm)
A	Surface area (m^2)
p	Static pressure (Pa)
μ	Dynamic viscosity (kg/m·s)
E	Internal energy (J)
H	Enthalpy (J/kg)
α	Local water volume fraction (kg/m^3)
β	Collection efficiency
C	Chord length (m)
C	Coefficient
F	Force (N)
K	Droplet inertia parameter
τ_{ij}	Shear stress tensor
g	Gravity vector (m/s^2)
F_r	Froude number
R_e	Reynolds number
L	Latent heat (J/kg)
Q	Heat flux (W/m^2)
σ	Stefan-Boltzmann constant ($\sigma = 5.67 \times 10^{-8}$ W/m^2·K^4)
ε	Solid emissivity
n	Surface normal vector
X_{Offset}	Offset distance (m)
T_{Max}	Maximum thickness (m)
X_{Mean}	Average distance (m)

Subscripts

a	Air
d	Droplet
f	Fluid
$evap$	Evaporation
s	Solid
∞	Reference
Rec	Recovery
h	Water film height
l	Lift
d	Drag
U	Upper
L	Lower

Abbreviations

LWC	Liquid water content
MVD	(Droplet) Median volumetric diameter
CFD	Computational fluid dynamics
HAWTs	Horizontal axis wind turbines
NREL	National Renewable Energy Laboratory
AoA	Angle of attack

The most common solvers applied to investigate icing on wind turbines are LEWICE (Ruff and Berkowitz, 1990), TURBICE (Marjaniemi et al., 2000; Makkonen et al., 2001) and FENSAP ICE (Hé et al., 2003; Habashi et al., 2001). LEWICE is 2-D an ice accretion code developed by NASA Glenn Research Center. The code applies a time-stepping procedure code to predict ice accretion shape. The flow field calculations are computed using Douglas Hess-Smith 2-D panel code. Then the obtained solution is used to calculate the trajectories of particles and the impingement points on the body. The icing model is then used to predict the ice growth rate and shape (Ruff and Berkowitz, 1990). Turbine Blade Icing Model (TURBICE) is a two-dimensional ice accretion simulation program. It was developed to predict icing on wind turbine blades. TURBICE uses panel methods to calculate potential flow field around the blade. The program uses Lagrangian technique for droplet trajectories and impingements calculations. The program is capable of calculating collision efficiencies and locating the droplet impingement locations along the blade surface. The program can estimate the amount of energy required for heating to prevent ice accretion on blade surface (Ruff and Berkowitz, 1990; Makkonen et al., 2001). FENSAP ICE is a 3-D premier in-flight icing simulation solver. The solver simulates flow field, droplet impingements, ice shapes and predicting anti/de-icing heat loads using a built in CFD modules. It uses 3D Navier-Stokes and energy equations for flow field calculations and 3-D Eulerian model for droplet calculations (Hé et al., 2003; Habashi et al., 2001).

Ice accretion on wind turbines can greatly degrade the aerodynamic performance and reduce the power production by up to 60% at lower wind speeds (Reid et al., 2013). In a study on icing of large wind turbines, the results indicated that ice growth can be greatly influenced by combined changes in blade design (i.e., size and profile) and relative velocity at each blade section (Virk et al., 2012).

Furthermore, ice accretion was observed to be more at blade sections near the tip compared to root section, where both blade thickness and chord length are minimized (Virk et al., 2012). A study by Homola (Virk et al., 2010a) indicated that ice growth in terms of ice rate and accretion shape is highly influenced by angle of attack of fluid flow. A study of icing on small wind turbines identified that blade rotation can lead to large ice accumulation at blade sections near the tip and at the leading edge of a blade section (Bose, 1992a; Fu and Farzaneh, 2010).

Ice accumulation along the blade is highly affected by variation of centripetal and gravity forces along blade span sections which can cause highly irregular ice shapes (Fu and Farzaneh, 2010; Bose, 1992b). The rate of ice accretion increases with water droplet size (Homola et al., 2010) and atmospheric temperature significantly influences ice shape. Streamlined ice shapes are formed at lower temperatures and horn ice is formed at higher temperatures (Homola et al., 2010). Glaze ice conditions can produce higher power loss compared to rime ice conditions, due to the greater ice thickness and shape of glaze ice (Reid et al., 2013). An investigation of ice accretion on four different wind turbines sizes indicated that rime ice conditions are less severe for large wind turbines compared in terms of ice mass and thickness (Virk et al., 2010b; Homola et al., 2010). The most severe icing problems are typically from glaze ice conditions during freezing rain and drizzle (Bose, 1992a), which can produce higher losses in lift coefficient than rime ice conditions (Hudecz et al., 2013).

Limited data is available on airfoil profile's effect on ice accretion, in terms of ice quantity and shape, as well as the effect on aerodynamic performance. To further examine ice accretion impacts on wind turbines, numerical studies are performed to determine the connection between icing parameters and blade designing parameters. In this paper, ice accretion on wind turbines is investigated in terms of the following:

- Airfoil type of the NREL airfoil families of S801 to S835 (inclusive)
- Blade thickness of 50%–150% of airfoil blade for NREL S809
- The effect of ice accretion on aerodynamic performance (lift and drag) for different icing conditions

Studying blade design parameters such as blade thickness is useful to investigate ice accretion physics at different locations along the blade span, as typical turbine designs often have varying airfoil curvature/thickness from the blade's root to tip. Lastly, the effect of different ice shapes, caused by differing icing conditions, on aerodynamic performance provides important insights for wind turbine design and