



A Generic Model for Ice Growth and Ice Decrease Process

Winterwind 2015

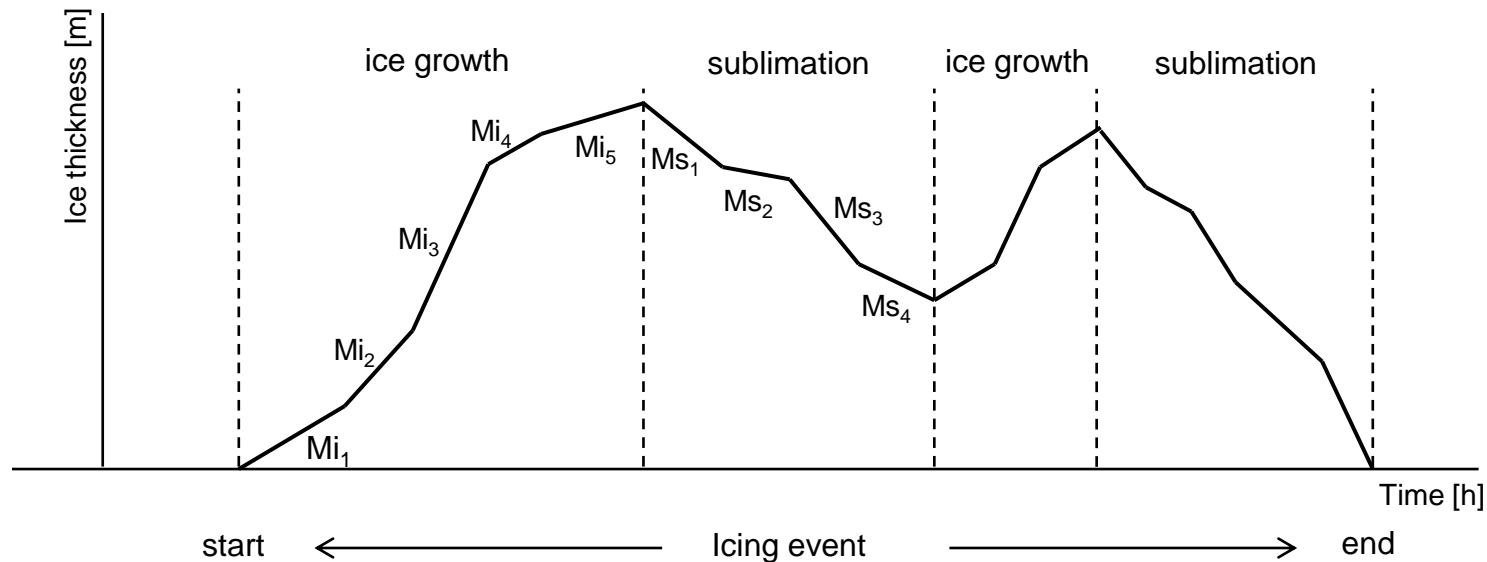
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Icing Event and Motivation



- Icing forecasts generally estimate the time periods of ice growth but not ice loss
 - Increases the uncertainty of the production estimates
- In resource assessment phase we can consider the icing intensity and the ice loads in addition to the iced up time

Model Description

■ Ice Growth

- Ice thickness growth rate
- Ice mass growth rate

■ Ice Sublimation

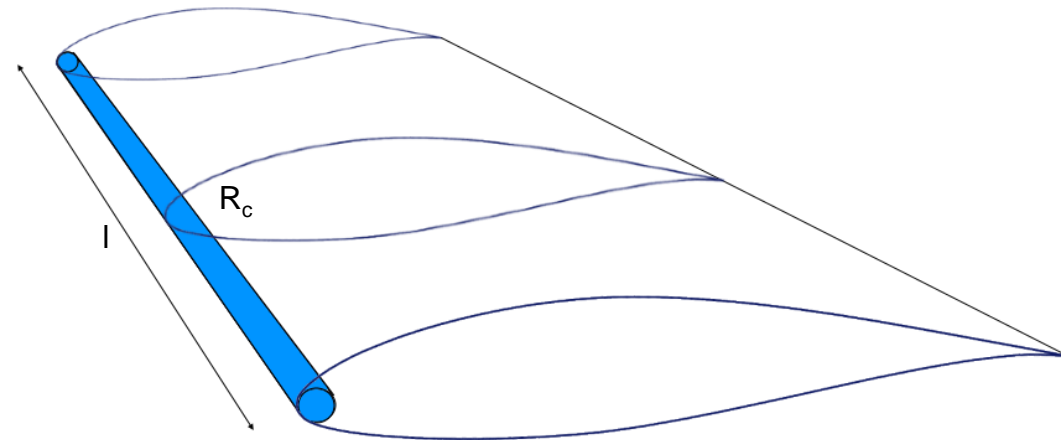
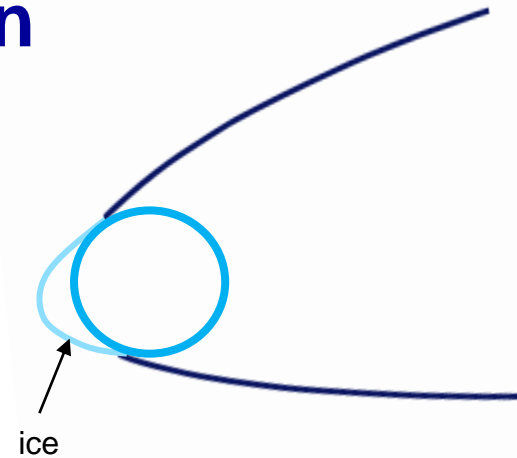
- Ice thickness decrease rate
- Ice mass loss rate

Net Ice Thickness Growth Rate [mm/hr]
Net Ice Mass Increase Rate [kg/hr]

Leading Edge Approximation

- Turbine blade leading edge approximated by a cylinder
 - Limitation to the ice type due to the icing limits

- The whole blade discretized into blade segments with a constant leading edge radius

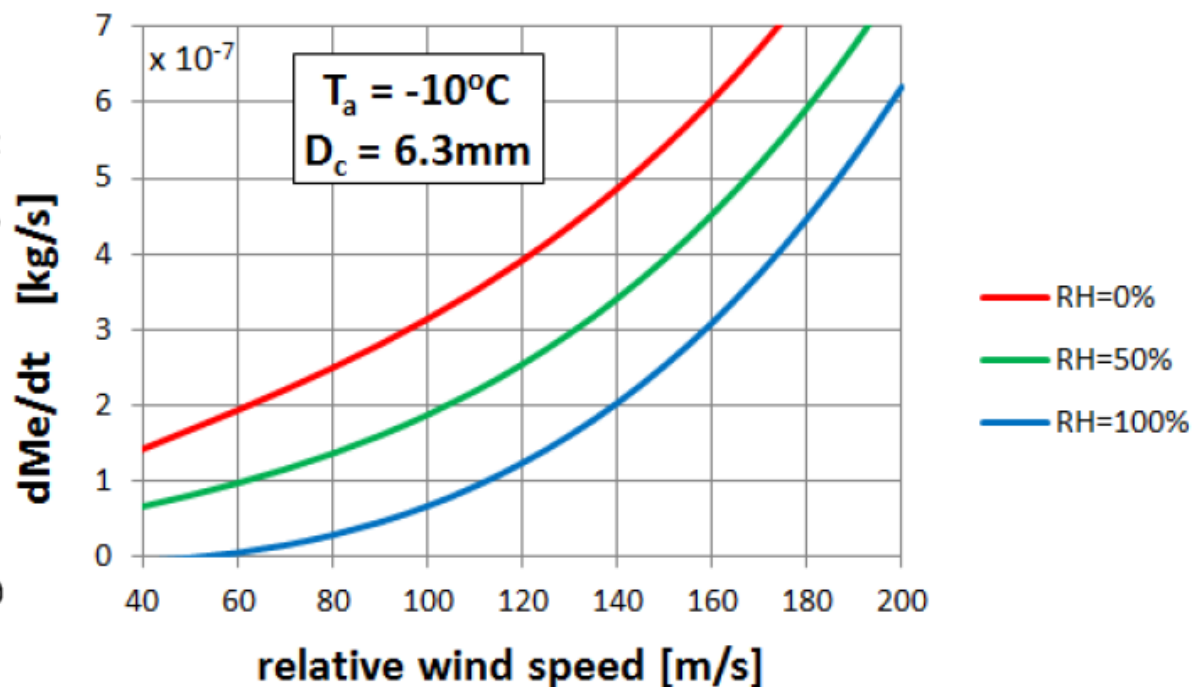
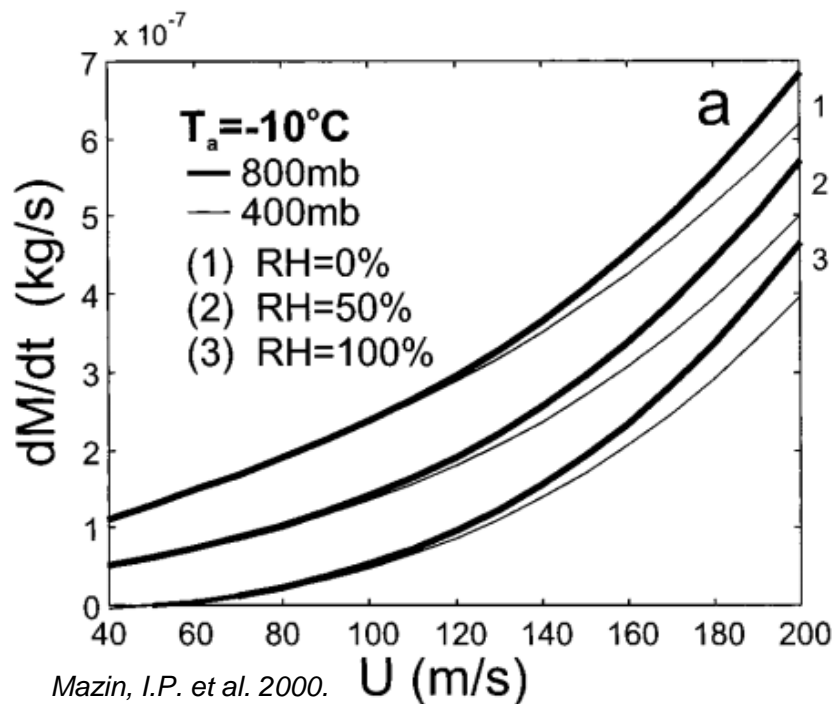


Sublimation of Ice on a 2D Cylinder

- Based on the steady-state heat balance equation integrated over the cylinder covered with ice
- Numerical analysis used to determine the surface temperature and the mass of sublimating ice per unit time
- The required input for the sublimation rate [mm/hr]:
 - Relative humidity
 - Air temperature
 - Air pressure
 - Relative wind speed
 - Nose radius and the length of the blade segments

Model Validation for Ice Loss Rate

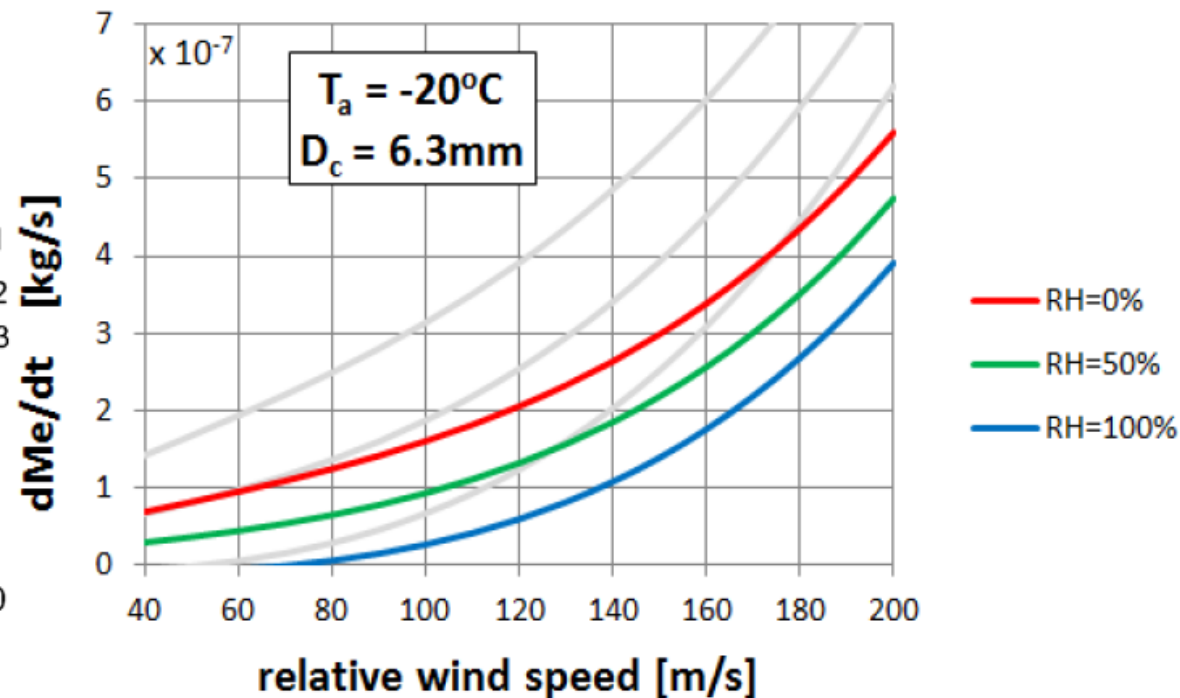
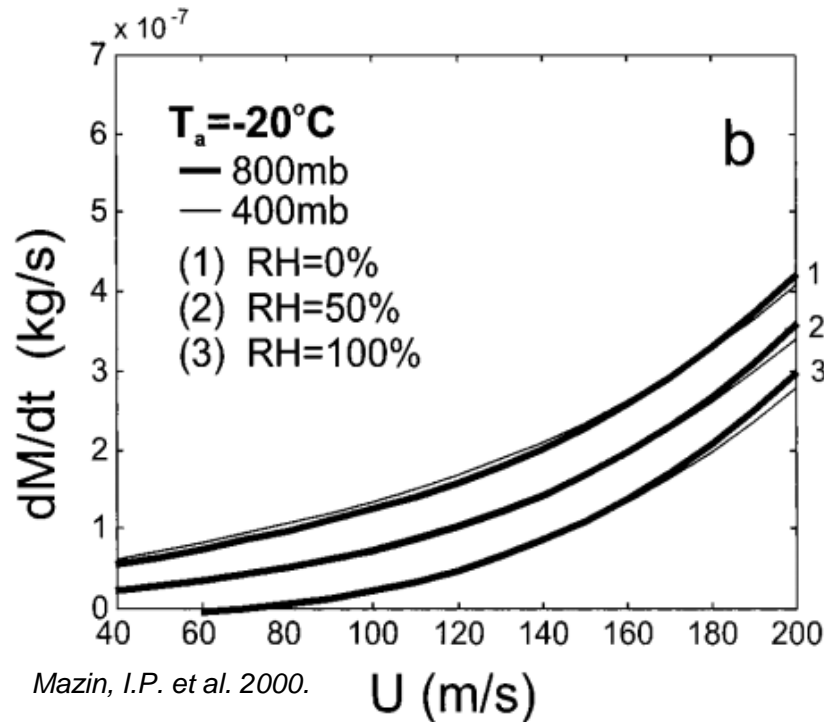
- $R_c = 6.3\text{mm}$, $l = 25.4\text{mm}$, $MVD = 20\mu\text{m}$, $LWC = 0$
- Assumes cloud free air and smooth cylinder surface (ice roughness neglected)



Mazin, I.P. et al. 2000.

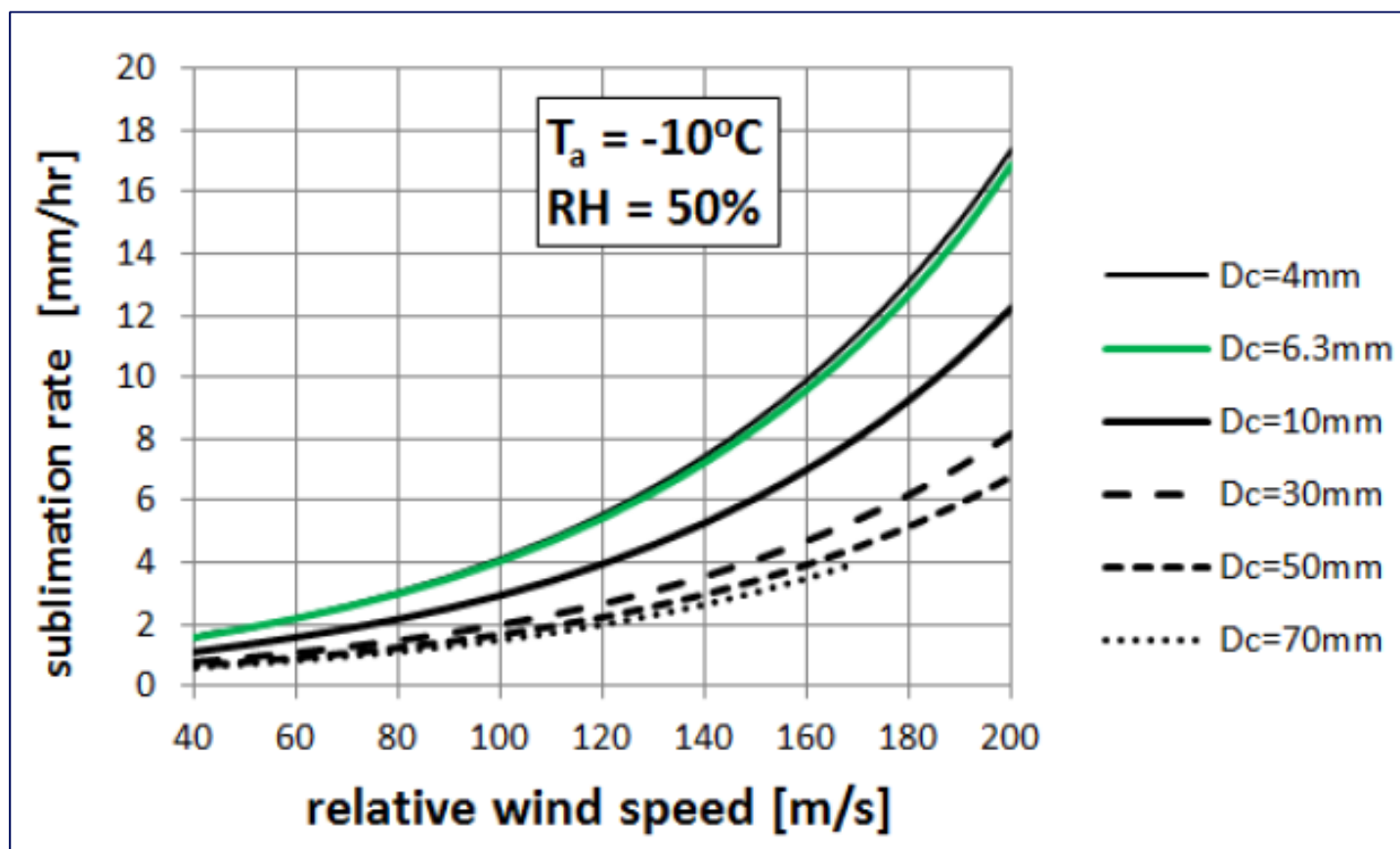
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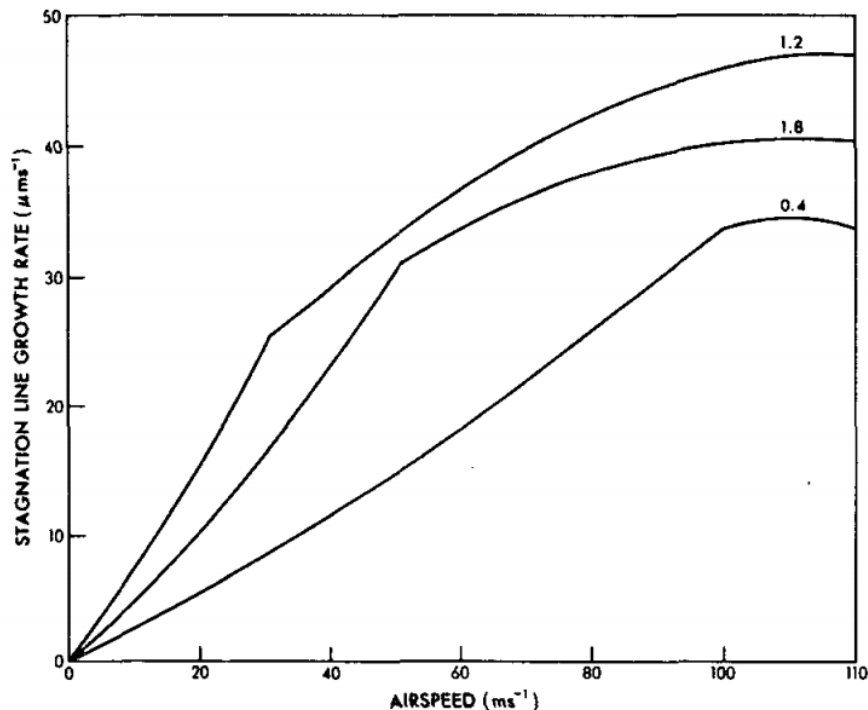
Ice Thickness Decrease Rate and Cylinder Diameter Effect



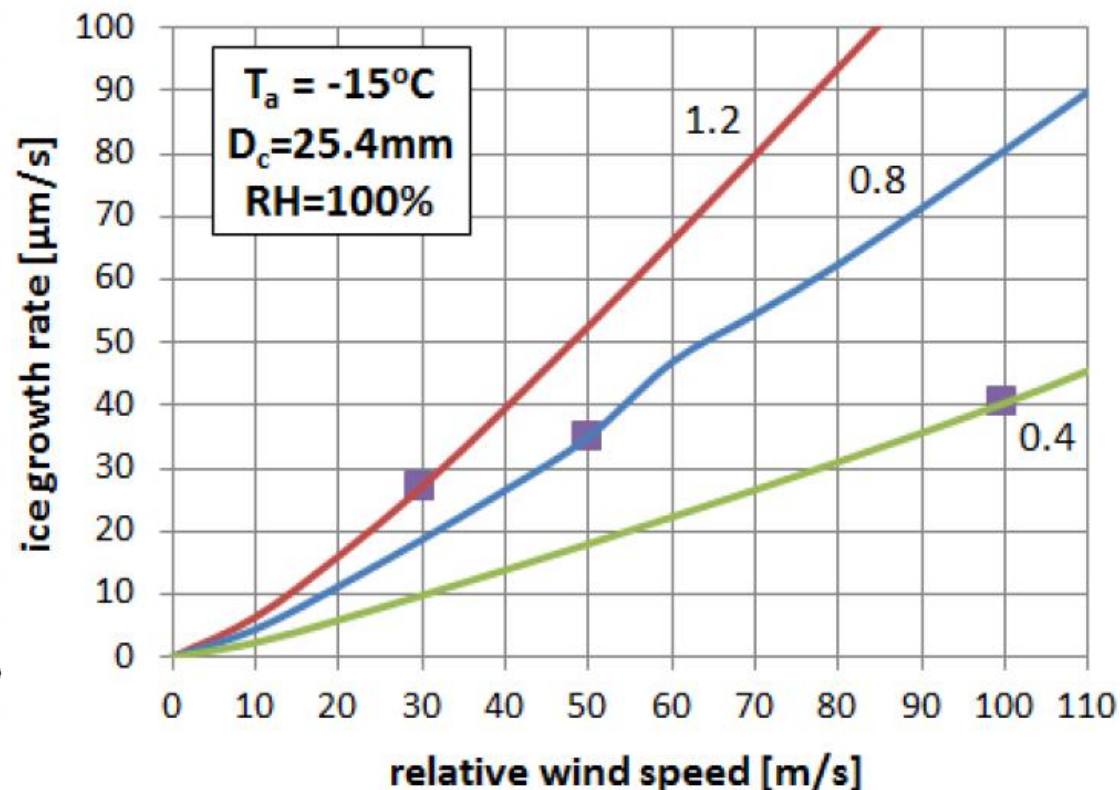
Ice Growth on a 2D Cylinder

- Simplified ice growth model as compared to comprehensive ice accretion models such as TURBICE
 - Simple and fast, yet accurate for cylinder approximation
- Ludlam limit as a key parameter for determining the ice type and thus the freezing fraction calculation method
- The required input for the ice growth rate [mm/hr]:
 - Relative humidity
 - Air temperature
 - Relative wind speed
 - Liquid water content
 - Median volume droplet size
 - Nose radius and the length of the blade segments

Model Validation for Ice Growth Rate

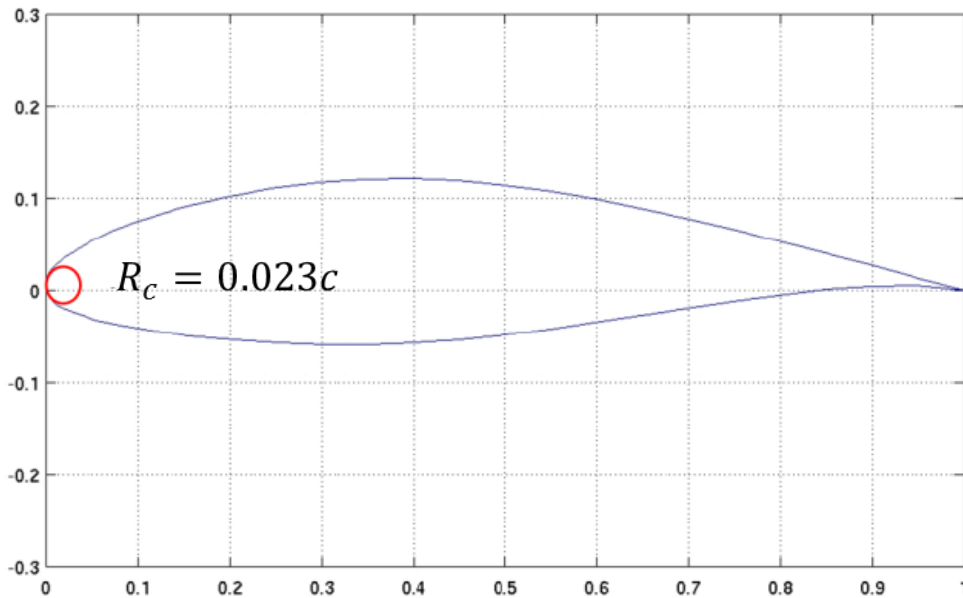


Lozowski, E.P. et al. 1983

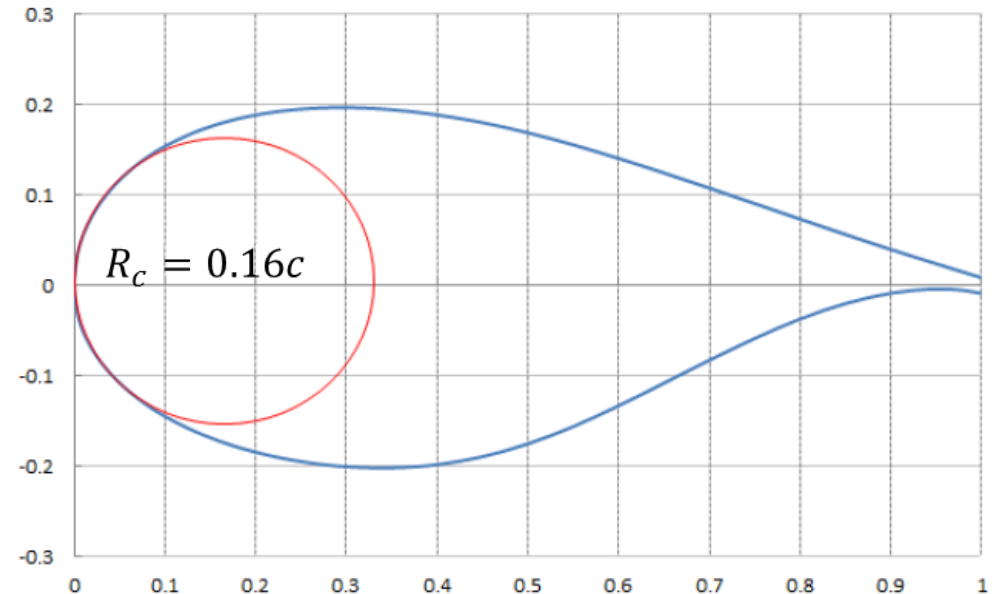


- Growth rates averaged over a cylinder
- $F = 1$ for these calculations, thus comparison is valid for rime ice cases only

Case Study – NREL 5MW Reference Turbine



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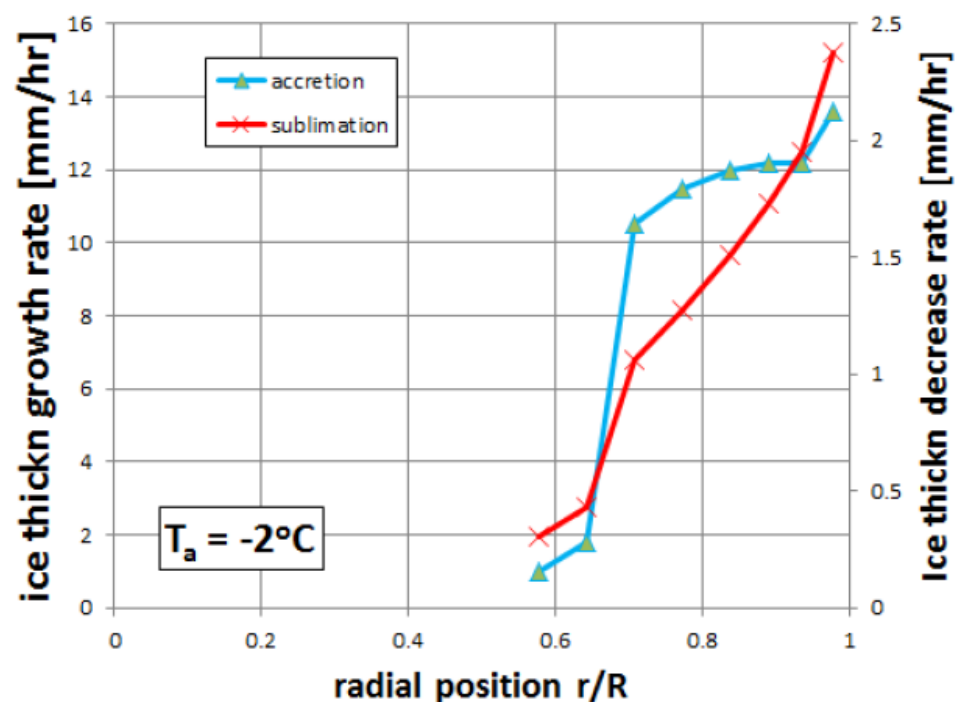
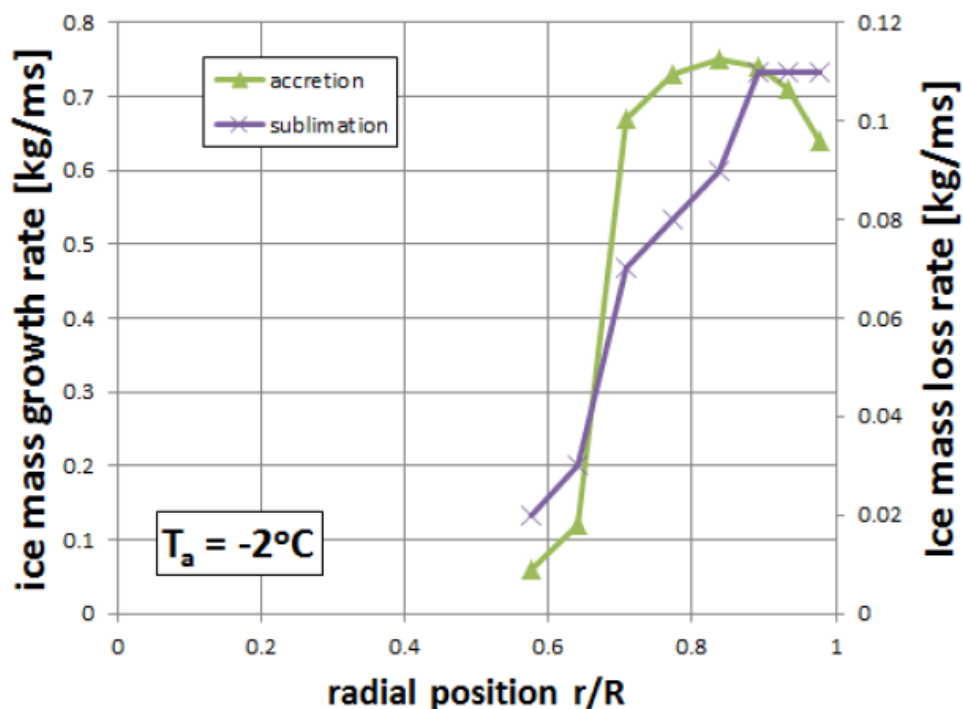


DU40

- 15 blade segments approximated by LE cylinder
- Wind speed 10 m/s, corresponding rotor speed 11.4 RPM
- Ice roughness taken into account

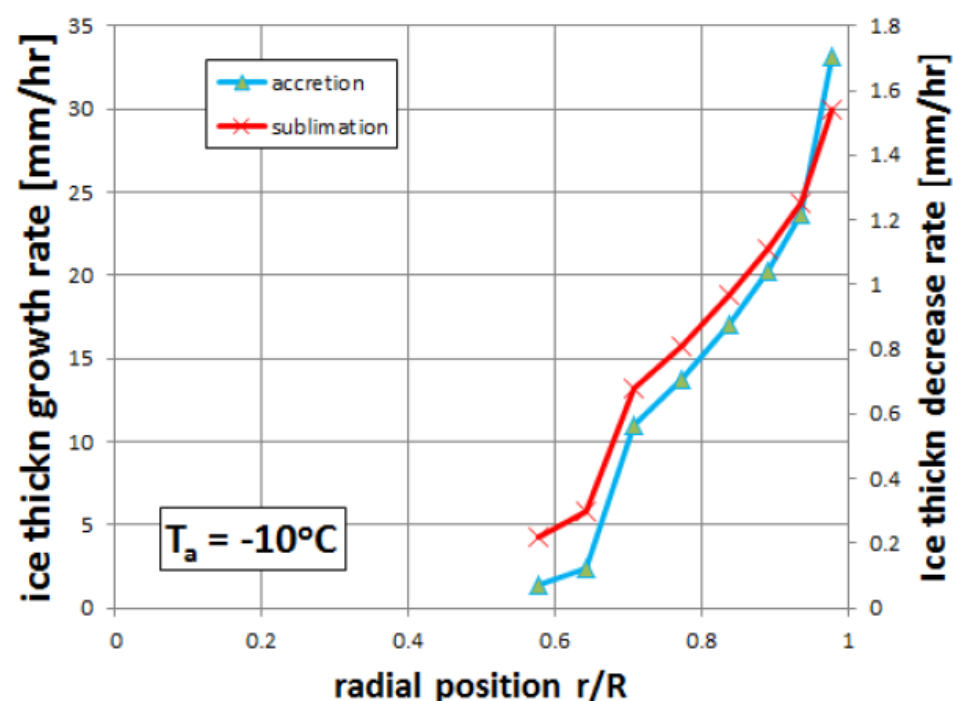
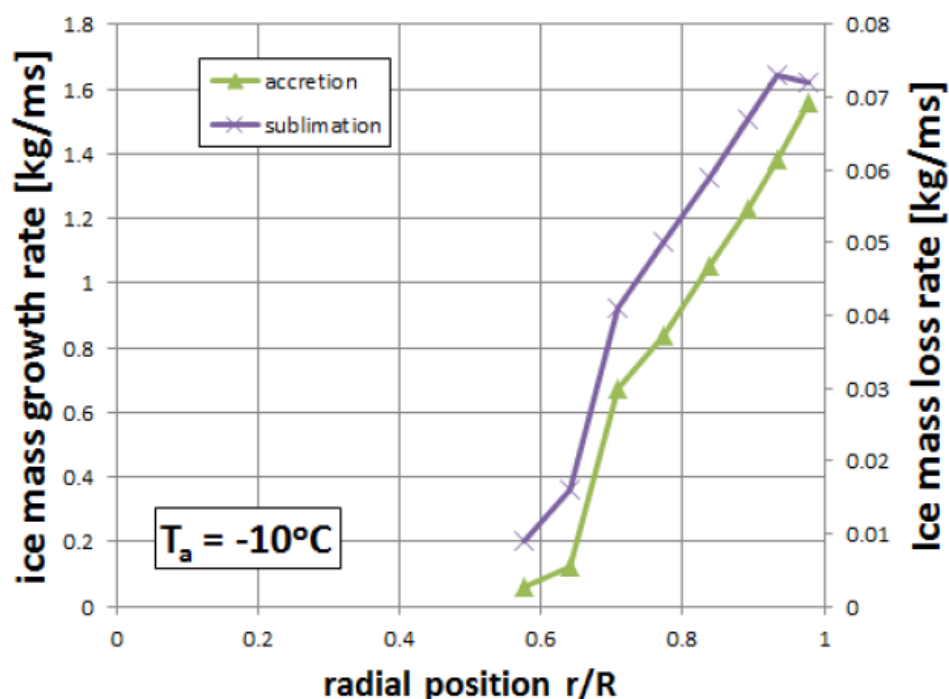
Case Study – NREL 5MW Reference Turbine

$LWC = 0.2 \text{ g/m}^3$, $RH = 97\%$, $T_a = -2^\circ\text{C}$, $MVD = 20\mu\text{m}$, $P_a = 100\text{mbar}$

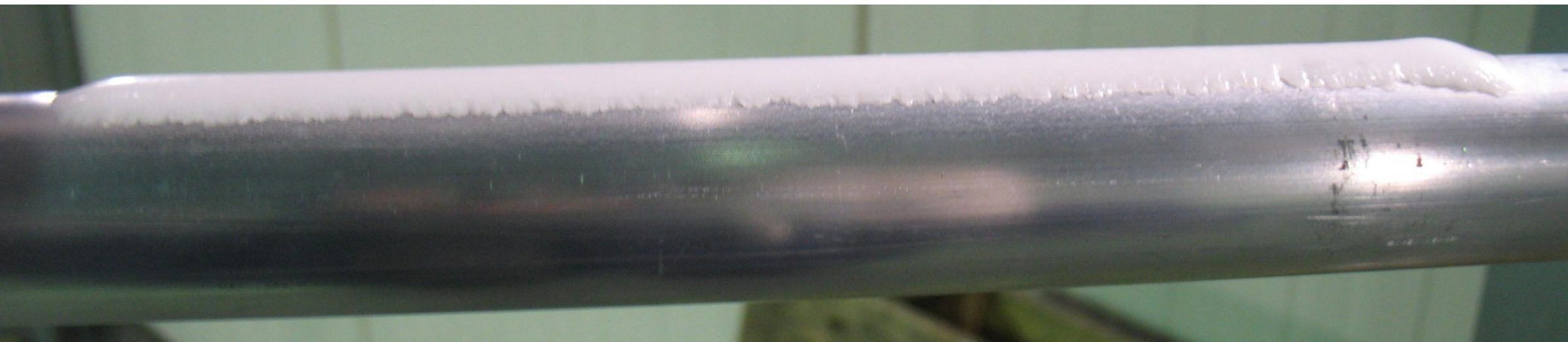


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VTT Icing Wind Tunnel Experiments



Future work



- Analysing the data from the wind tunnel experiments
- Continue validation
- Include wind erosion and melting models
- Power loss estimation



Thank you!

Questions?



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