Simulated Ice Growth on a Blade Profile and Representative Cylinders

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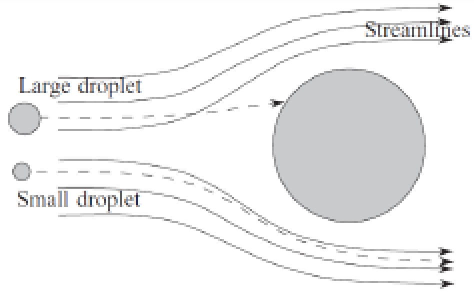
Background

- Makkonen model

$$\frac{dM}{dt} = \alpha_1 \alpha_2 \alpha_3 \cdot w \cdot A \cdot V$$

α_1 represents collision efficiency

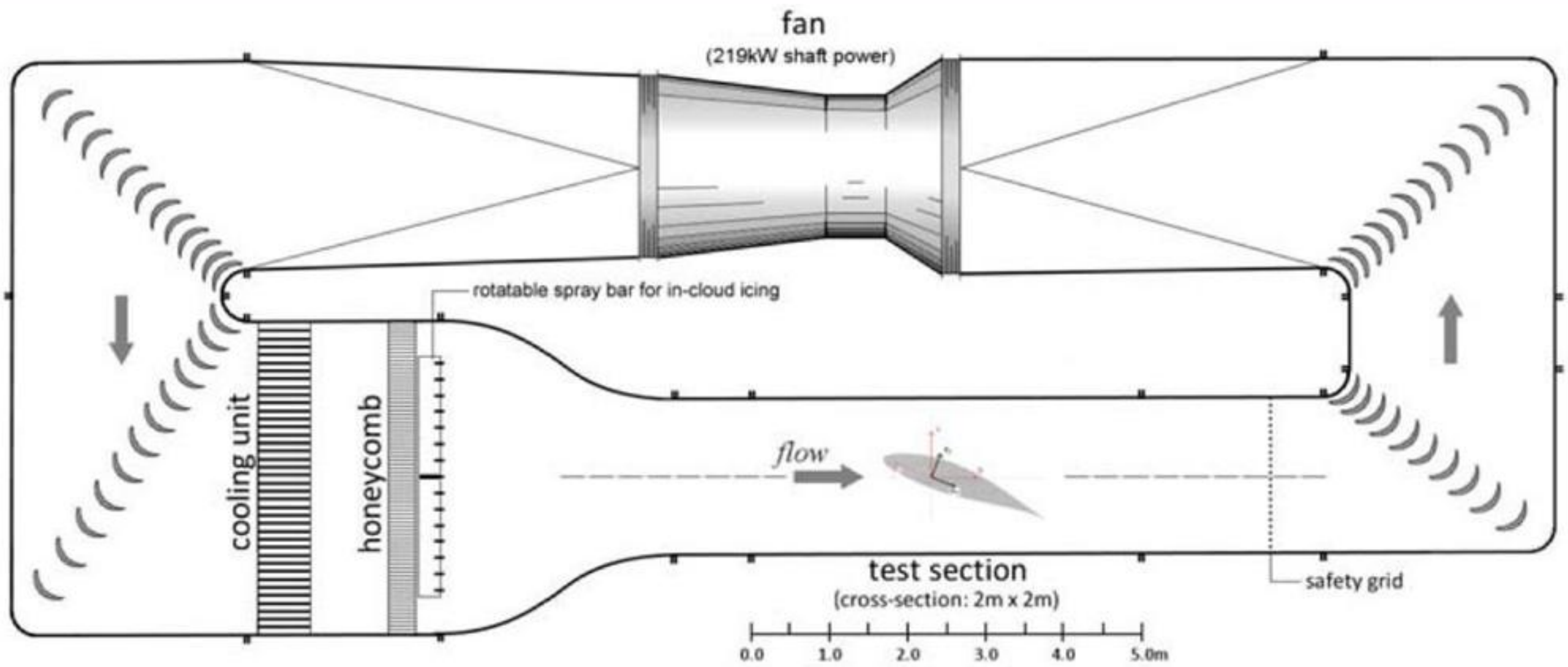


Homola, M. C., T. Wallenius, L. Makkonen, P. J. Nicklasson, and P. A. Sundsbø, 2010: The relationship between chord length and rime icing on wind turbines. Wind Energy, 13, 627–632, doi:10.1002/we.

- Collision efficiency function of:
  - mass
  - velocity
  - drag force

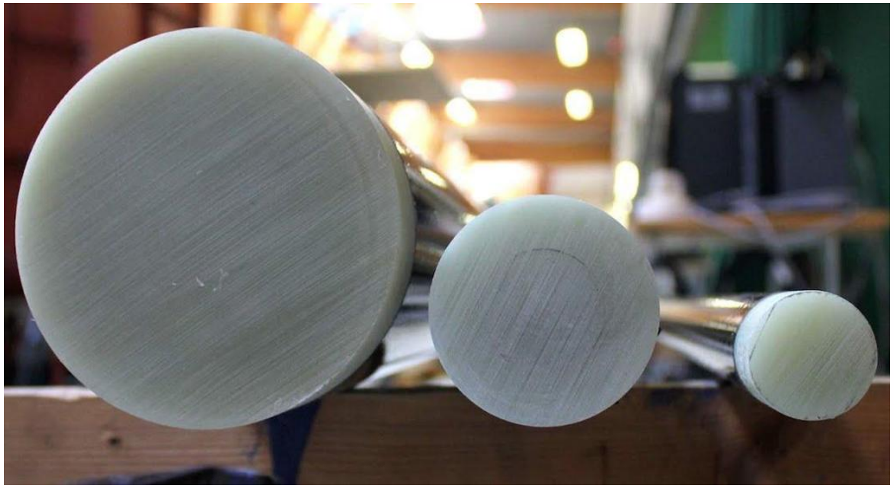
- Makkonen model uses an empirical function
  - Cylindrical object
  - Small diameter

Climatic Wind Tunnel



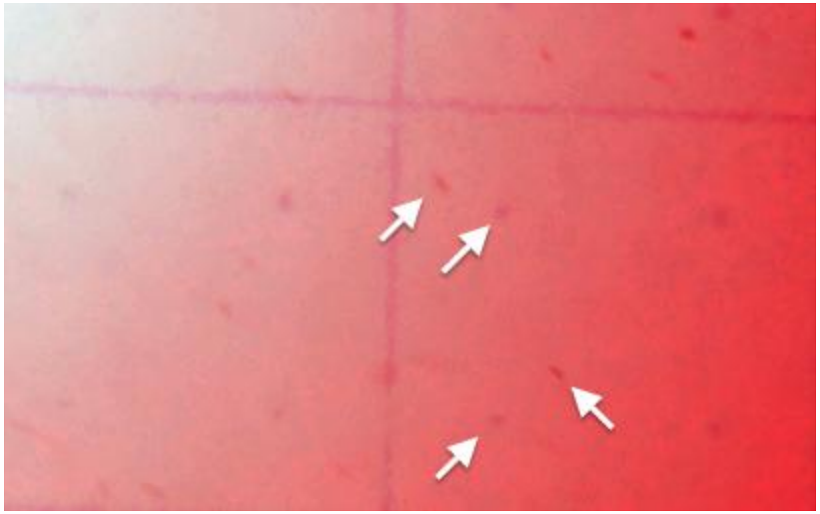
Experimental Design

- Foam NACA 0015 Airfoil
  - Leading edge (d) - 3.2 cm
  - Chord - 38 cm
  - Thickness - 5.7 cm
- Fiberglass Cylinders
  - Leading edge (d) - 3.2 cm
  - Thickness - 5.8 cm
  - 2x thickness - 10.5 cm

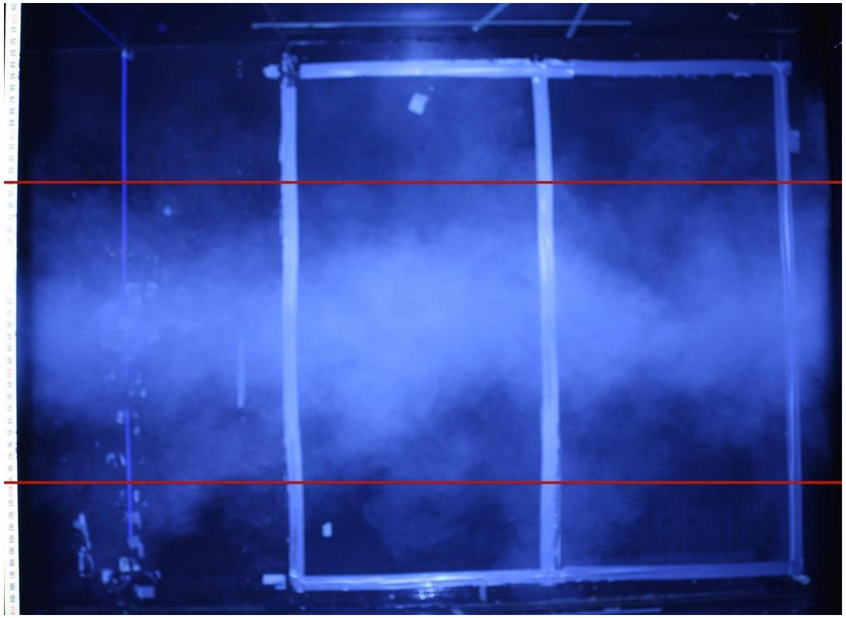


Uncertainty in MVD

- Estimated using backlight photography
  - backlight often too dim
  - Unable to capture droplets from spraybar
- Used pump sprayer to estimate droplet size
- Nozzle manufacturer specified MVD of 15 μm for our settings



Uncertainty in LWC

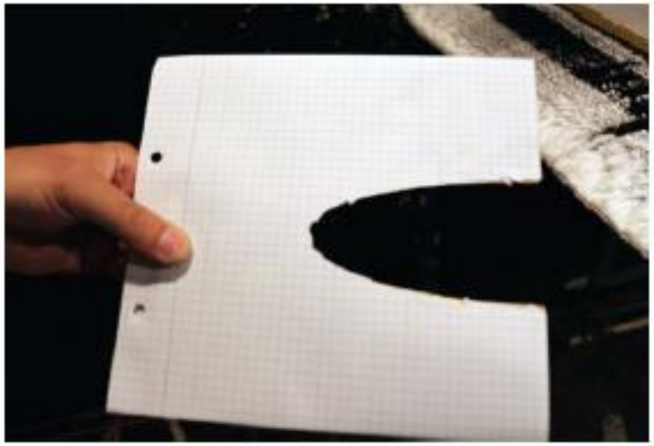


- Measured mass of water during experiment
- Calculated cloud height from photos
  - Dependent on wind speed
- Estimated LWC by fitting normal distribution along cloud height (1.3 g/m^3)

Ice Growth
Airfoil 4° angle of attack

Ice Growth
58mm Cylinder

Capturing the ice profile

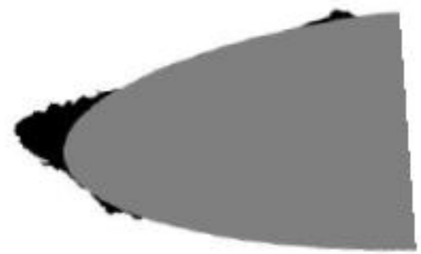


(a) Cut-out with heat gun

(b) Spraypaint

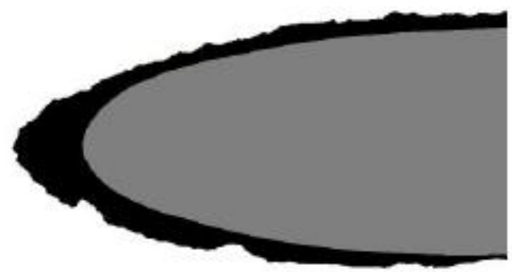
Capturing the ice profile

(a) 58mm cylinder contour 10 m/s



(b) Airfoil at 4 degree AOA 15 m/s

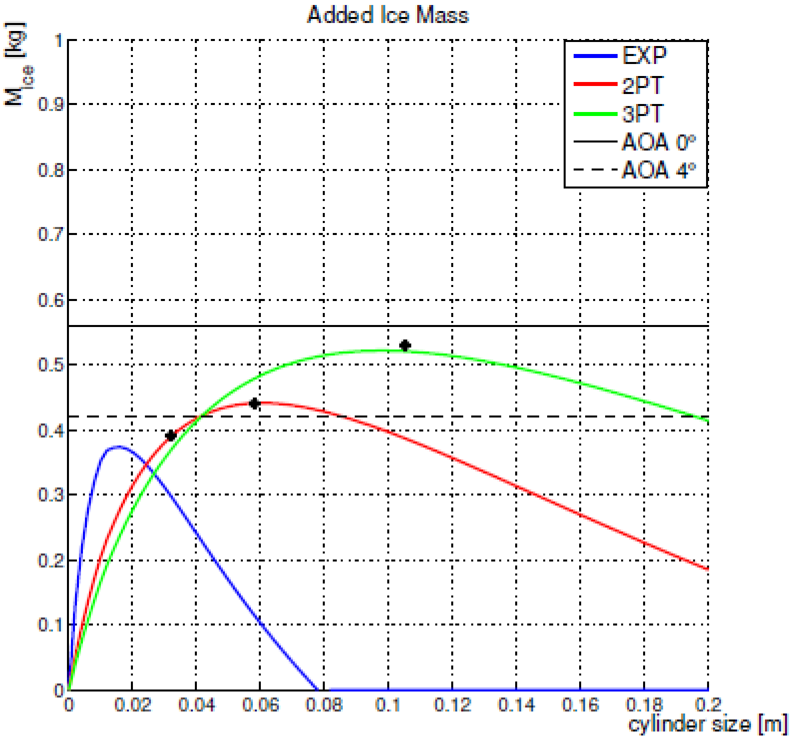
(c) Airfoil at 0 degree AOA 10m/s



(d) Airfoil at 0 degree AOA 15m/s

Empirical fit

- MVD & LWC do not match
  - Error at larger diameters
  - Errors in estimation
- No curves match 0° AOA airfoil (solid line)
- 2 of the curves pass through the 4° AOA airfoil (dashed line)



Fitting method	MVD	LWC
# 1 - EXP	15	1.3
# 2 - 2PT	30	0.4
# 3 - 3PT	39	0.3

Conclusion

- Empirical fit may not hold for larger cylinders
  - Observed ice not shown to decrease with increasing diameter for diameters tested
- Using Cylinders to represent airfoils
  - Proposed modification to Makkonen equation
  - d = leading edge for calculating α_1
  - d = airfoil thickness for area calculation
- Future tests
  - Test against validated LWC and MVD
  - Test using larger cylinders
  - Test at higher wind speeds

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