Lecture # 15: Aircraft and wind turbine icing and anti-/de-icing

Dr Hui Hu
Dr Rye M Waldman
Department of Aerospace Engineering, Iowa State University
Ames, Iowa 50011, U.S.A
Introduction

Ice accretion on wings
Atmospheric moisture freezes on wings
  • Accreted ice modifies airfoil shape
  • Increases drag
  • Can lead to stall
  • Costly to remove

Conditions determine ice type (glaze vs rime)
  • Liquid water content (LWC)
  • Temperature
  • Airspeed
  • Geometry
  • Surface chemistry
Wind Turbine Icing and Anti-/De- Icing

- Wind turbine icing represents the most significant threat to the integrity of wind turbines in cold weather.
  - Change airfoil shapes of turbine blades.
  - Cause imbalance to the rotating system.
  - Shedding of large chunk of ice can be dangerous to public safety.
  - Cause errors to anemometers to estimate wind resource.

- Some thermal de-icing systems could consume up to 70% of the total power generated by the wind turbine on cold days.
Basic icing problem

LWC, D, T

Shin & Bond, 1994

Tsao & Lee, 2012

Rothmayer, 2003
Glaze ice is the most dangerous type of ice.

Glaze ice forms much more complicated shapes and are difficult to accurately predict.

Glaze ice is much more difficult to remove once built up on aircraft wings or wind turbine blades.
The ISU Icing Research Tunnel (ISU-IRT), originally donated by UTC Aerospace System (formerly Goodrich Corp.), is a research-grade multi-functional icing wind tunnel.

The working parameters of the ISU-IRT include:

- **Test section:** 16 inches by 16 inches by 6 ft
- **Velocity:** up to 60 m/s;
- **Temperature:** down to -30 °C;
- **Droplet Size:** 10 to 100 micrometers;
- **Liquid Water Content (LWC):** 0.05 ~ 20 grams/cubic meter.

The large LWC range allows ISU-IRT tunnel to be run over a range of conditions from rime ice to extremely wet glaze ice.
Wind-driven Water Runback Flow over a NACA 0012 Airfoil

Experimental conditions:

- Incoming flow velocity: \( V_\infty = 10 \sim 20 \) m/s
- Water flow rate: \( Q = 1.0 ml / min \)
- Spray droplet size: \( D = 10 \sim 50um \)
Micro-sized Water Droplets Impinging onto a NACA-0012 Airfoil

- **Test Conditions**
  - Angle of attack of the airfoil: $\alpha \approx 0.0$ deg.
  - Temperature of the wind tunnel: $T \approx 20$ °C.
  - The liquid water content (LWC): $LWC = 5.0$ g/m³
  - Frame rate for Image acquisition: $f = 30$ Hz

- Airflow velocity $V_\infty = 15$ m/s
- Airflow velocity $V_\infty = 20$ m/s
- Airflow velocity $V_\infty = 25$ m/s
Glaze Ice Accreting Process over a NACA0012 Airfoil

Test Conditions

- Oncoming airflow velocity: \( V_\infty \approx 20 \text{ m/s} \)
- Angle of attack of the airfoil: \( \alpha \approx 5 \text{ deg.} \)
- Temperature of the wind tunnel: \( T \approx -8 \circ C \)
- The liquid water content (LWC): \( LWC = 3.0 \text{ g/m}^3 \)
- Total recording time: \( t = 110 \text{ seconds} \)

Frame rate for Image acquisition, \( f = 150\text{Hz}, 10X \text{ replay} \)

Upper surface

Lower surface

Videos of ice accretion

\( V_\infty \)

\( \alpha \approx 5.0 \text{ deg.} \)
Glaze Ice Accreting Process over a NACA0012 Airfoil

- $T_\infty = -8.0 \, ^\circ C$;
- $\alpha = 5 \, ^\circ$;
- $LWC = 1.1 \, g/m^3$

- $V_\infty = 20 \, m/s$
- $V_\infty = 40 \, m/s$
- $V_\infty = 60 \, m/s$

(Waldman R. and Hu H., 2015, Journal of Aircraft)
IR Thermometry to Quantify the Unsteady Heat Transfer Process

**Experimental Conditions:** \( V_\infty = 35 \text{ m/s} \); \( T_\infty = -8.0 \, ^\circ\text{C} \); AOA = 5 \, ^\circ; \ LWC = 0.30 \, \text{g/m}^3

![Image of rime ice accretion](U40_LWC030_T08 (deg C))

- Rime ice accretion
- E
- D
- C
- B
- A

**Experimental Conditions:** \( V_\infty = 35 \text{ m/s} \); \( T_\infty = -8.0 \, ^\circ\text{C} \); AOA = 5 \, ^\circ; \ LWC = 3.0 \, \text{g/m}^3

![Image of glaze ice accretion](U40_LWC300_T08 (deg C))

- Glaze ice accretion
- E
- D
- C
- B
- A

Ingrmn airflow
Hydrophilic, Hydrophobic and Superhydrophobic

- a). drop on a smooth surface;
- b). Wenzel state;
- c). Cassie–Baxter state;
- d). combined state.

*Measured* $\theta = 67$ [deg]

*Measured* $\theta = 104$ [deg]

*Measured* $\theta = 170$ [deg]

- Hydrophilic; $\theta < 90^\circ$
- Hydrophobic; $90^\circ < \theta < 150^\circ$
- Superhydrophobic; $\theta > 150^\circ$

Lotus leaves
Surface Chemistry: Effects of Hydrophobicity of the Airfoil Surface on the Impingement of Water Droplets (Weber number ~ 800)

Acquired at 12K FPS, replay at 400X slower

Without Super-hydrophobic Surface coating

With Super-hydrophobic Surface coating

Normal impact

45 degree slope
Surface Chemistry: Effects of Hydrophobicity of the Airfoil Surface on the Impingement of Water Droplets

- $T_\infty = -5^\circ C$, $V_\infty = 20$ m/s, MVD = 40 μm, LWC = 2.5 g/m$^3$
- $T_\infty = -5^\circ C$, $V_\infty = 40$ m/s, MVD = 40 μm, LWC = 2.5 g/m$^3$
Effects of Surface Hydrophobicity on Surface Water Transport and Ice Accretion Process

- Surface engineering to change the surface hydrophobicity of the airfoils/wings for wind turbine anti-/de-icing applications

Coated side has little ice

Untreated side is glazed by ice

Anti-icing coating test on wind turbines

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Lab 13: Aerodynamic force measurement on an icing airfoil

Objective:
The objective of this lab is to measure the aerodynamic forces acting on an airfoil in a wind tunnel using a direct force balance. The forces will be measured on an airfoil before, during, and after the accretion of ice to illustrate the effect of icing on the performance of aerodynamic bodies.

ISU Icing Research Tunnel velocity calibration

\[ U_\infty \text{[m/s]} = 0.9388 \times F - 0.3756 \]
Lab 13: Aerodynamic force measurement on an icing airfoil

What you will be given for your experiment:
• Icing wind tunnel
• A NACA 0012 airfoil model
• A force/torque transducer
• A data acquisition system
• A digital inclinometer

What your experiment needs to produce:
Lift, drag, and moment measurements vs angle of attack (α = -2° – 20°) without icing.
Lift, drag, and moment measurements during the icing process for α = 5°.
Lift, drag, and moment measurements vs angle of attack (α = -2° – 20°) after the airfoil has accumulated ice.
Lab 13: Aerodynamic force measurement on an icing airfoil

What results you will produce from the experiment data:
• The lift, drag, and moment coefficients vs angle of attack for the NACA 0012 airfoil with uncertainty bounds for both the uniced and iced conditions.
• Time history of the apparent lift, drag, and moment coefficients during the icing process.

Beware!
• Lift and drag must be derived from the force transducers local Normal and Tangential force components:
  e.g., \( L = F_N \cdot \cos(\alpha) - F_T \cdot \sin(\alpha) \)

• Coefficients are normalized by density, wind speed and geometry:
  \( C_L = \frac{L}{\frac{1}{2} \rho U^2 sc} \)
  \( C_D = \frac{D}{\frac{1}{2} \rho U^2 sc} \)
  \( C_M = \frac{M}{\frac{1}{2} \rho U^2 sc^2} \)

Force transducer–wing model configuration