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

Dr Hui Hu

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.
ISU Research Center for Icing Physics and Anti-/De-icing Technology

Aircraft icing
Rotocraft icing
Aer-engine icing
Wind turbine icing
Solar panel icing
Powerline icing

NDE, MEMS sensors for in-flying icing detection
Experimental aerodynamics & wind tunnel testing
CFD & multiphase modeling
UAS/MAV, Rotorcraft, wind turbine, power lines
Super-hydrophobic coatings and surface engineering
System design and MDO for anti-/de-icing strategy
Aero-structure designs for icing mitigation & protection.
Smart materials, Micro & Nano Mechanics

Center for Icing Physics & Anti-/De-icing Technology
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 form 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.
• **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:** \( W \times L = 0.4m \times 0.4m \) (16 in \( \times \) 16 in)
  - **Velocity:** \( V_\infty = 5 \sim 100m/s \)
  - **Temperature:** \( T_\infty = 20 \degree C \sim -25 \degree C \)
  - **Droplet size:** \( d = 10 \) to \( 100 \mu m \)
  - **Liquid Water Content:** \( LWC = 0.05 \sim 10 g/m^3 \)

• The large LWC range allows ISU-IRT tunnel to be run over a range of conditions from dry rime icing to wet glaze icing.
**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:** $D = 10 \sim 50 \mu m$

Picture of the test section in the icing wind tunnel

Quantification of Transient Surface Water Runback Process over an Airfoil Surface by using a Novel Digital Image Projection (DIP) technique

- Test Conditions
  - Angle of attack of the airfoil: $\alpha \approx 0.0$ deg.
  - Temperature of the wind tunnel: $T \approx 20^\circ$C.
  - The liquid water content (LWC): $LWC = 5.0 \text{ g/m}^3$
  - Frame rate for Image acquisition: $f = 30$ Hz

Airflow velocity $V_\infty = 15\text{ m/s}$

Airflow velocity $V_\infty = 20\text{ m/s}$

Airflow velocity $V_\infty = 25\text{ m/s}$
Quantification of Glaze Ice Accretion Process over a Airfoil Surface

**Test Conditions**
- **Oncoming airflow velocity**: $V_\infty \approx 35$ m/s
- **Angle of attack of the airfoil**: $\alpha \approx 5$ deg.
- **Airflow Temperature**: $T \approx -8$ °C.
- **Liquid water content (LWC)**: $LWC = 3.0$ g/m³
- **Image acquisition rate**: $f = 150$Hz, 10X replay
Glaze Ice Accretion over a NACA0012 Airfoil

- $V_\infty = 20 \text{ m/s}$
- $T_\infty = -8.0 \degree \text{ C}$
- $\alpha = 5 \degree$
- $LWC = 1.1 \text{ g/m}^3$

- $V_\infty = 40 \text{ m/s}$

- $V_\infty = 60 \text{ m/s}$

(Waldman R. and Hu H., 2015, Journal of Aircraft)
Ice accretion feature extraction and dynamics measurements of a NACA0012 airfoil

Extracting rivulet features from icing video sequence

Tracking ice growth, film runback, and rivulet runback

(Waldman R. and Hu H., 2015, Journal of Aerocraft)
Unsteady Heat Transfer Process over an Ice Accreting Airfoil Surface

Test Conditions:
- Airflow temperature: -4 & -8 °C
- Wind speed: 20, 40, 60 m/s
- LWC in airflow: 0.3, 1.0, 3.0 g/m³
- Angle of Attack: -5°

Experimental setup for IR thermal imaging

Wind Speed: 40 m/s
Temperature: -8 °C
LWC: 1.0 g/m³

ΔT (°C): 0.0 0.3 0.7 1.0 1.4 1.8 2.1 2.4 2.8 3.1 3.5

- Glaze ice accreting process
  \( V_\infty = 40 \text{ m/s}; T_\infty = -8.0 \degree \text{ C}; \text{LWC} = 1.0 \text{ g/m}^3 \)

- Rime ice accreting process
  \( V_\infty = 40 \text{ m/s}; T_\infty = -8.0 \degree \text{ C}; \text{LWC} = 0.30 \text{ g/m}^3 \)

Wind Speed: 40 m/s
Temperature: -8 °C
LWC: 0.3 g/m³

ΔT (°C): 0.0 0.3 0.7 1.0 1.4 1.8 2.1 2.4 2.8 3.1 3.5
**Problems**

- Ice accretion cause imbalance and even be suck into the core if shedding that *cause power loss*.
  - “*Power loss*” of the engine including surge, stall, flameout, or roll back that results in *unstable* operation.
- Internal ice causes blockage of the piping system.
- More than 100 jet engine power-loss events since 1990.

---

*An engine core icing event hit an AirBridge Cargo-operated Boeing 747-8F on July 31, 2013.*
Aero-engine Icing experimental setup

Research Facilities
- ISU Icing Research Tunnel.
- PCO 1200hs imaging camera.
- NI USB-6218 DAQ System.
- Crmagnetics CR5410-50 current transducer.
- BK PRECISION 1692 power supply.

The process of icing events over the spinners of aero engine fan.
- The ice shape and features on the spinners.
- The influence of icing on rotation speed (RPM) and power input \( (P=U*I) \) of the motor.
Aero-engine icing and Anti-/De-icing

- Aero-engine icing event hits an AirBridge Cargo-operated Boeing 747-8F on 07/31/2013 to cause power loss.

Icing on the inlet and spinner of aero-engines

Source: Boeing

Conical

Conical (1D)

Elliptical

Elliptical (1D)

Conical (1D)
Aero-engine ice accretion on different spinner cone geometries

- Conical \((1D_s)\)
- Elliptical \((1D_s)\)
- Conicalpical \((1D_s)\)

\(U=15 \text{ m/s}, T= -5^\circ C, LWC=2 \text{ g/m}^3, R_0=2500\text{rpm}\)
Bio-Inspired Ice Phobic Coatings for Aircraft Icing Mitigation

Barthlott & Neinhuis (1997): The Lotus Effect

- Lotus-leaf-inspired Super-Hydrophobic Surface (SHS)
- Pitcher-plant-inspired Slippery Liquid-Infused Porous Surfaces (SLIPS)

(Hu et al. AIAA paper, 2017)
Surface Chemistry: Effects of Hydrophobicity of the Airfoil Surface on the Impingement of Water Droplets

\[ T_\infty = -5 \, ^\circ C, \quad V_\infty = 20 \, m/s, \quad MVD = 40 \, \mu m, \quad LWC = 2.5 \, g/m^3 \]

\[ T_\infty = -5 \, ^\circ C, \quad V_\infty = 40 \, m/s, \quad MVD = 40 \, \mu m, \quad LWC = 2.5 \, g/m^3 \]

With Super-hydrophobic Surface coating

Without Super-hydrophobic Surface coating

With Super-hydrophobic Surface coating

Without Super-hydrophobic Surface coating
Effects of Hydrophobicity of the Impact Ice Accretion Process

- Uncoated Hydrophilic surface

\[
\frac{F_{cap, \text{enamel}}}{F_{cap, \text{SLIPS}}} \approx 3
\]

- Petcher-plant-inspired SLIPS

\[
\frac{F_{cap, \text{enamel}}}{F_{cap, \text{SHP}}} \approx 15
\]

- Lotus-leaf-inspired SHS

\[
T_\infty = -4^\circ C; \quad V_\infty = 30 \text{ m/s}; \quad \text{MVD} = 40 \mu\text{m}; \quad \text{LWC} = 4.0 \text{ g/m}^3
\]

\[
\text{SHS (Superhydrophobic)} \quad \text{uncoated (hydrophilic)} \quad \text{SLIPS (Wong et al., 2011)}
\]
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

\[ U_{\infty} [\text{m/s}] = 0.9388F - 0.3756 \]
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 ($\alpha = -2^\circ - 20^\circ$) without icing.
Lift, drag, and moment measurements during the icing process for $\alpha = 5^\circ$.
Lift, drag, and moment measurements vs angle of attack ($\alpha = -2^\circ - 20^\circ$) 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:
  \[ C_L = \frac{L}{\frac{1}{2} \rho U^2 s c} \]
  \[ C_D = \frac{D}{\frac{1}{2} \rho U^2 s c} \]
  \[ C_M = \frac{M}{\frac{1}{2} \rho U^2 s c^2} \]