National Aeronautics and Space Administration

Fundamental Ice Crystal Accretion Physics Studies

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Objectives

The aviation industry is experiencing numerous engine power loss events associated with high altitude convective weather that often occur in a warm tropical environment. In 2006, Mason et al. [1] suggested that flight in high concentrations of ice crystals causes ice accretion in core static components of jet engines that lead to power loss. They theorize that an optimum regime exists for ice-crystal icing which is a function of the ratio of liquid to total water content in the engine (Fig 1). The objective of this study is to examine the physical mechanisms of ice accretion on surfaces exposed to ice-crystal and mixed-phase conditions similar to those encountered during engine power-loss events.

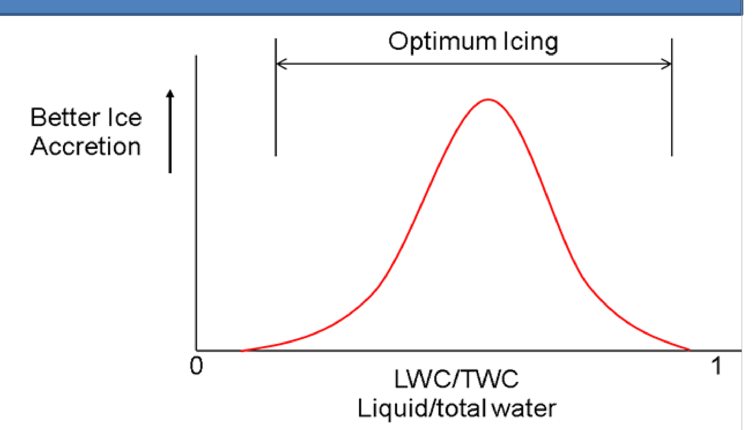


Fig. 1 Conceptual curve of ice-crystal icing for given conditions.

1. Mason, J. G., Strapp, J. W., and Chow, P. "The Ice Particle Threat to Engines in Flight," 44th AIAA Aerospace Sciences Meeting and Exhibit, 2006.

Technical Challenges

The fundamental physics of ice accretion due to ice crystals within a jet engine are not well understood. Furthermore, it is difficult to actually see into a jet engine to determine where and how icing is taking place. The engine icing problem is complex and multidisciplinary including turbo machinery aerodynamics, thermodynamics, convective and conductive heat transfer, mass transfer, as well as mixed phase flows. Simplified experiments can help uncouple these effects allowing the aviation community to understand how and under what conditions ice can accrete due to ice crystals.

Technical Approach

NASA and NRC, with sponsorship by the Federal Aviation Administration and Transport Canada, are beginning a series of experiments to examine the physical mechanisms of ice accretion on surfaces exposed to ice-crystal and mixed-phase conditions. During November 2010 and March 2011, several weeks of testing occurred at the NRC Research Altitude Test Facility, or RATFac (Fig. 3). The testing utilized a small wind tunnel, called the cascade rig (Fig. 2), which was placed inside RATFac. A single wedge-type airfoil (Fig. 4) was selected as it facilitated the study of the fundamental physics of ice-crystal icing while still retaining critical features of a compressor stator blade or guide vane. The airfoil was instrumented with thermocouples along mid-span.

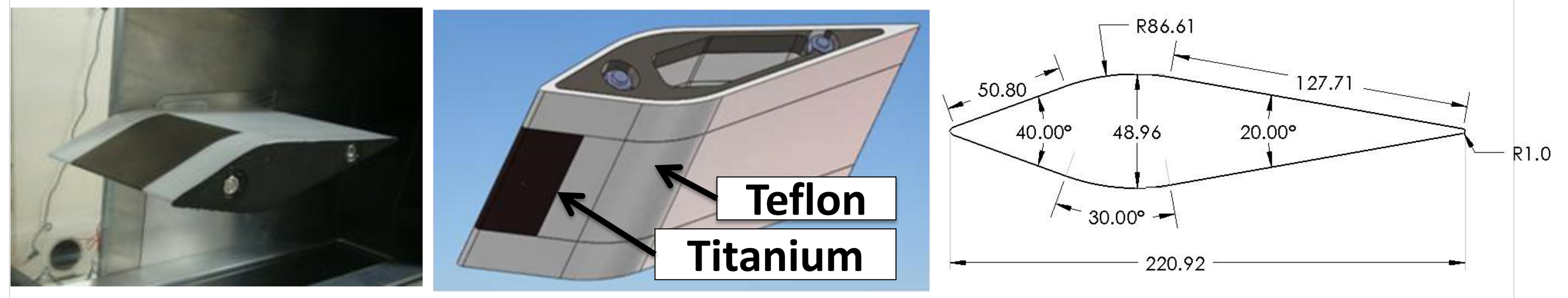


Fig. 4 Image of airfoil installed in cascade rig (left), underside of airfoil (center), dimension of airfoil in mm (right).

The Experiment

The RATFac (Fig 3.) is capable of providing ice-crystal and mixed-phase conditions with pressure variation. The test cell is divided into two sides with a cold area (right side of Fig. 3) housing the ice particle generation. The ice-crystals injection duct, the water-spray nozzle system, and the cascade-rig wind tunnel are located in the warm area (left side of Fig. 3). The warm area is often maintained well above freezing, such that it gives the desired test temperature in the cascade rig (Fig. 2) when mixed with the cold jet coming from the ice injection duct. Test points begin by initially setting the Mach number, altitude, and total temperature in the cascade rig under dry conditions after which ice and / or liquid water is added to the flow. Cameras captured high resolution image data during each test run.

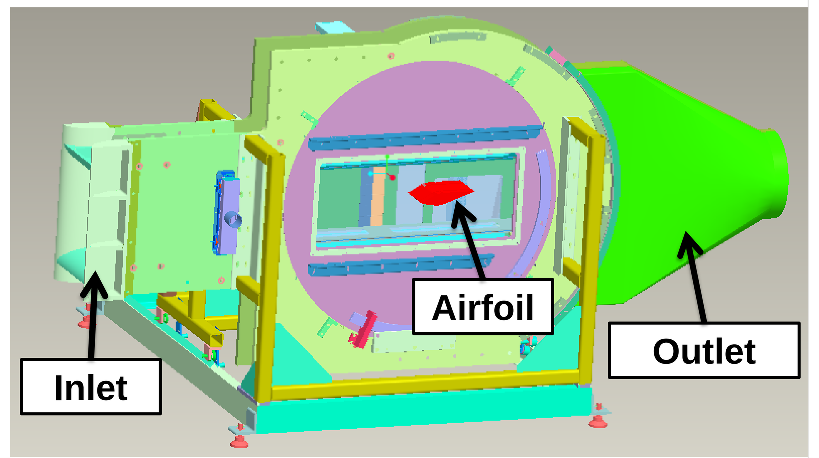
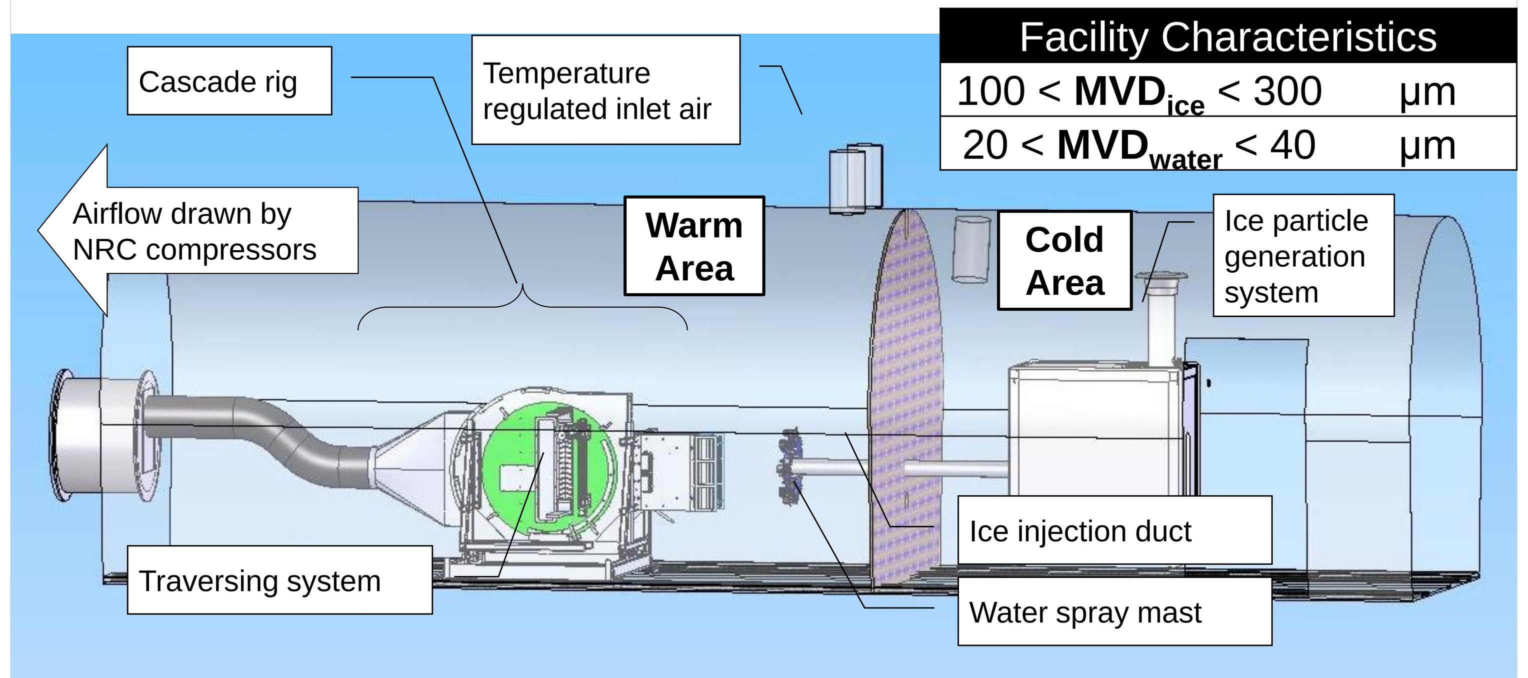


Fig. 2 NRC Cascade Rig



Facility Characteristics	
100 < **MVD**$_{ice}$ < 300	μm
20 < **MVD**$_{water}$ < 40	μm

Fig. 3 Experiment layout in the NRC RATFac facility

Test Matrix from November 2011 Testing

Two weeks of testing were performed in November 2010: the first for aerodynamic testing and the second for icing. The table below shows the primary variables controlled and range of values used during the November tests. In March 2011, two additional test weeks occurred with the addition of a facility capability to measure and control the relative humidity in the test section are currently under analysis.

Controlled Parameter	Unit
5 ≤ **TAT** ≤ 15	°C
6.5 ≤ **P**$_{TOT}$ ≤ 13.5	PSIA
0.2 ≤ **M** ≤ 0.3	
0 ≤ **IWC** ≤ 20	bulk, g/m³
0 ≤ **LWC** ≤ 3	g/m³

Legend
TAT Total Air Temperature
P$_{TOT}$ Total Pressure
M Mach Number
IWC Ice Water Content
LWC Liquid Water content
MVD Median Volumetric Diameter

Reference: Paper 2011-38-0018, SAE 2011 Intl. Conference on Aircraft & Engine Icing & Ground Deicing, Chicago, Illinois, June 13-17, 2011

Results

Ice accretions with different characteristics were observed at different pressures. For the low pressure (6.5 psia) tests, the ice developed over a large portion of the forebody pressure surface and was well adhered in all cases where accretion was observed. In several cases, continuous leading-edge ice growth was observed. Fig 5. below shows a top-down view (left) and front perspective view (right) of the airfoil exposed to a mixed-phase spray at the conditions shown. In this case, the leading-edge ice growth thickness was in excess of 0.6" at mid-span over a period of 3 minutes. Such widespread deposits were never observed in the tests at the highest pressure tests, where accretions never covered the entire test surface and were usually limited to a small area around the leading edge. The bottom (suction) surface was typically ice-free in the tests at high pressure, but not at low pressure. Generally, the larger accretions observed at low pressure were accompanied by lower surface temperatures.

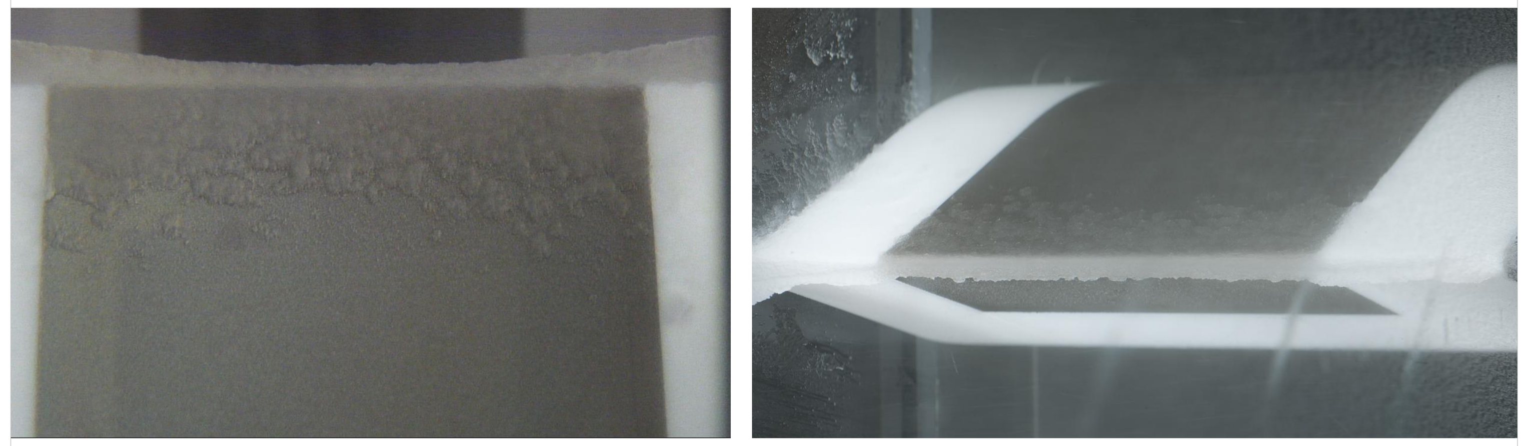


Fig. 5 Ice accretions at M=0.2, P$_{TOT}$=6.5 PSIA, TAT=12.5°C, LWC=1 g/m³, IWC=5 g/m³ after approximately 100 seconds of spray.

Summary & Future Work

Preliminary observations supported the hypothesis that wet bulb temperature (T_{wb}) is a key parameter. The icing behavior at low and high pressure appeared to be correlated with T_{wb} which was above freezing in all of the tests at 13.5 PSIA and below freezing in all of the tests at lower pressure. Since T_{WB} is defined as the temperature of an adiabatic wet surface in air, freezing of water on such a surface can be expected for a local T_{WB} < 0° C. Reduced air pressure increases evaporation and thereby reduces T_{WB}, so the potential for evaporation-enhanced freezing increases as air pressure decreases. The large (adhered) ice accretions that were observed in the low-pressure tests would undoubtedly cause the aerodynamic performance of a compressor stator or guide vane to degrade significantly, and could significantly damage downstream components if shed from the blade. The authors believe that it is important to get a better understanding of the conditions under which these large accretions can occur, and in particular the role of wet-bulb temperature or, more generally, evaporative cooling. Wet-bulb temperature was the focus of the March 2011 tests and results from those experiments are currently under analysis.

NASA Aviation Safety Annual Technical Meeting, St. Louis, MO, May 10 - 12, 2011