Calibration and Recent Upgrades to the Cox Icing Wind Tunnel

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A comprehensive calibration of the Cox & Company, Inc. LeClerc Icing Research Laboratory (LIRL) Icing Wind Tunnel (IWT) was recently completed. This calibration included the flow field, supercooled water spray, temperature, and ice crystal distributions. The calibration followed the newly established SAE Aerospace Recommended Practices (ARP) 5905. Increased capabilities and improvements as well as additional services have been added. This paper describes some of the processes used in the calibration, the new capabilities of the laboratory, results and some upgrades for the near future.

Nomenclature

FFT	=	*Fast Fourier Transform*
IAS	=	Indicated airspeed
IWC	=	ice water content, g/m^3
IWT	=	icing wind tunnel
K	=	empirical factor used in the calculation of LWC
LIRL	=	LeClerc Icing Research Laboratory
LWC	=	liquid water content, g/m^3
mph	=	miles per hour
PSD	=	Power Spectral Density
RTD	=	resistance temperature detector
TAS	=	true airspeed
TI	=	turbulence intensity, *%*
TS-1	=	test section-1

I. Introduction

Cox & Company, Inc. is an aerospace engineering and manufacturing company that does much of its work in the area of ice protection systems for aircraft and associated ancillary systems. The Cox Icing Wind Tunnel[1], shown in Figure 1, was designed and constructed to support Cox's own programs and as a basis for the company's research and development programs. The IWT is also available on a rental basis to other members of the icing community for their own proprietary efforts in several areas, including general icing research.

During the past few years, Cox has significantly improved the supercooled water spray distribution and uniformity, increased the operating temperature range, and added the ability to generate consistent ice crystal sprays and mixed phase icing environments that include supercooled droplets as well as glaciated particles.

During the summer of 2007, a thorough flow and spray calibration was conducted, which adhered to the SAE Aerospace Recommended Practices (ARP) 5905[2] to the maximum extent possible.

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All equipment and sensors at the IWT are calibrated on a regular schedule (generally annually) by either the Cox in-house calibration lab or by independent certified labs. The calibration includes, but not limited to RTD sensors, pressure transducers and gauges, signal transmitters and indicators, control systems, etc. The current airflow calibration includes airspeed accuracy, stability, distribution, angularity, and turbulence intensity. The supercooled spray calibration includes Liquid Water Content (LWC), cloud uniformity, and droplet sizing.

The ice crystal calibrations were conducted on a second-generation ice shaver. The new shaver was designed and fabricated to allow a more consistent control of feed rates and better spray stabilization. Calibration included mapping of the spray distribution in the main test section as well as particle size distribution. The dimensions of this section (TS-1 in Figure 1) and corresponding data are as follows:

- 28 inches (0.71 m) wide, 46 inches (1.17 m) high, and 6 ft (1.83 m) long
- Typical maximum speed of 200 mph (174 kts)
- High speed insert in TS-1 allows speeds up to 280 mph (243 kts) in a 28 inches x 24 inches (0.71 m x 0.61m) modified test section

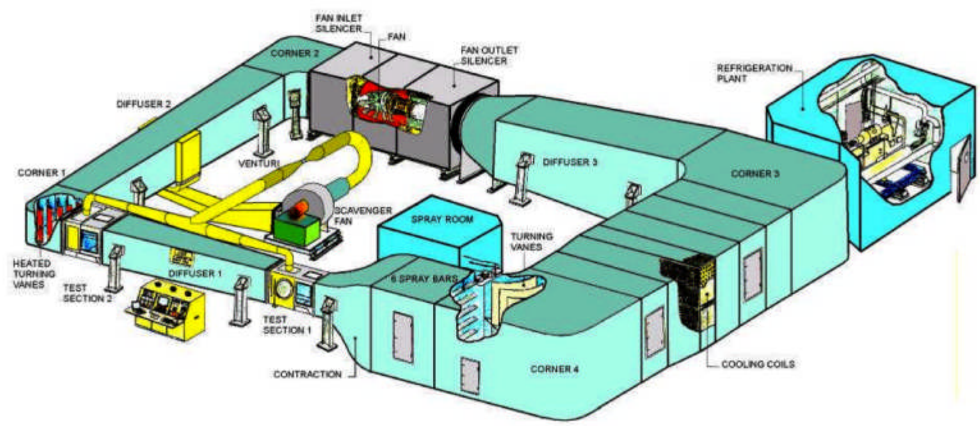

Figure 1: Layout of the Cox Icing Wind Tunnel

II. Air Flow Calibrations

The airflow angularity was measured using a seven-hole probe, and airspeed spatial uniformity was measured using an array of total pressure probes. The airspeed stability and Turbulence Intensity (TI) were measured using a TSI Constant Temperature Anemometer (CTA) Model 1750 and TSI hot-film probes model 1201-20 mounted on TSI 1150AA Probe holder. These were attached to a streamlined mount that extended across the tunnel cross-section.

Figure 2 shows a plot of the airspeed stability. These data were collected at a rate of 1024 samples per second for 30 seconds. The raw data are shown in blue. The hot film output was smoothed using Excel™ with a mild 64 point moving average. This translates into a moving average window of 0.0625 second, shown in Figure 2 as the black line. One percent error limits are also shown for reference.

The TI was measured at three airspeeds (near 75 mph, 134 mph, and 200 mph). At each airspeed, the TI was measured with the spray bar air turned off and then repeated with the air on at a pressure setting of 40 psig. The air in the spray bars can be operated at pressures higher than 40 psig, but this is seldom used. Figure 3 shows the TI as a function of airspeed. The effect of spray bar air is small at the higher speeds, but more significant at the lower speeds. In the range that most tests are conducted, airspeed higher than 125 mph, the effect of the spray bars air pressure on TI seems insignificant. Turbulence data were collected at the rate of 1024 samples/second for ten seconds. Hot-film data have been collected at lower and higher sampling rates and for longer durations, with no qualitative differences in the results.

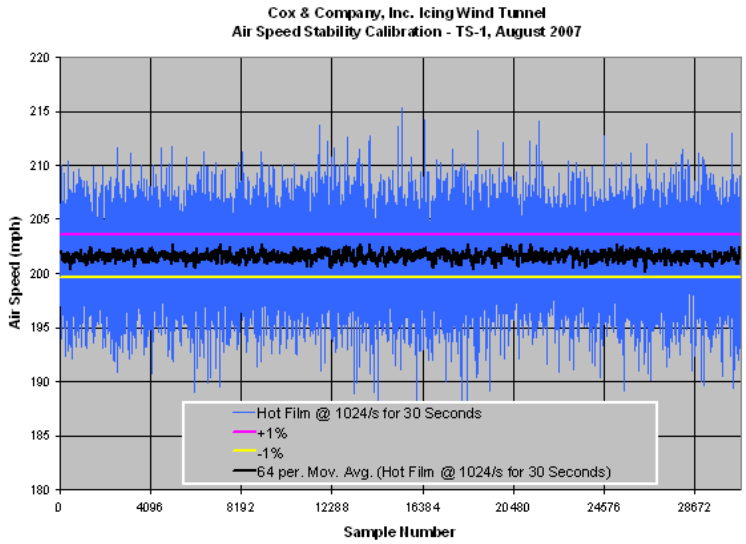

Figure 2: Hot film output over 30 seconds showing stability of the airspeed control

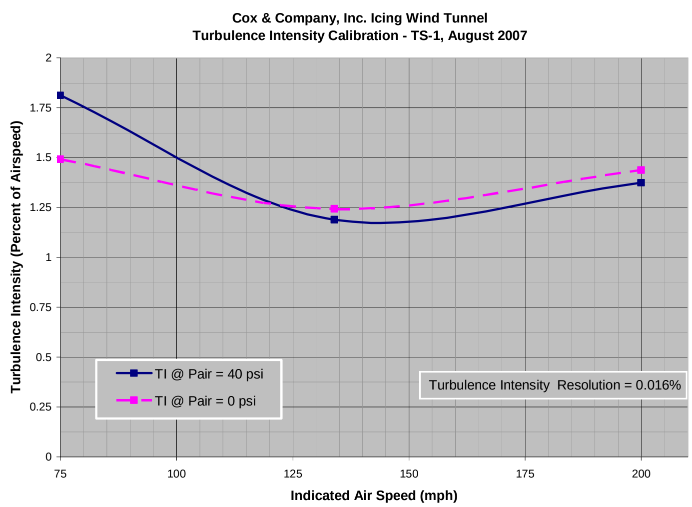

Figure 3: Turbulence Intensity with and without spray bar air

The 30-second data collected for airspeed stability were passed through an FFT filter to compute frequency domain information. Figure 4 shows the results of the FFT analysis, and Figure 5 shows the power spectral density. It appears that there is no significant energy that stands out at any particular frequency.

Visible in both plots are spikes at 230.5Hz, 331Hz and 461Hz. The 230.5Hz and 461Hz spikes seem to be related to the main fan, but the large spike at 331Hz is undetermined. These are high frequency and low energy perturbations and as such are expected to have a negligible effect on the flow and spray.

A conical head 7-hole probe from Aero-probe Corporation was used for flow angularity measurements. The probe head is 0.125 inch in diameter and is 6 inches long. There is one total pressure hole centered at the tip and 6 holes evenly distributed around the circumference on the cone. The roll and velocity errors for the probe are 0.1453º, 0.2493º, and 0.3139 m/s (0.7 mph)with corresponding standard deviations of 0.1514º, 0.2648º and 0.2758 m/s (0.6 mph), respectively. A Scanivalve Digital Sensor Array model DSA-3017 pressure transducer was used to measure the pressures off the probe. This is a self-contained temperature compensated electronic pressure scanner, which has 16 channels available for reading pressures. The 1.0 psid unit has an accuracy of 0.05% FS (Full Scale), i.e. 0.0005 psid, and can be scanned at a rate of 7.8 times per second. Data for flow angularity were collected at the rate of 7.8 Hz for 100 scans, i.e. ~13 seconds, and averaged. The flow angularity results are shown in Figure 6. Note the cone angle error bars; approximately 0.15º. Both deviations for Alpha (pitch) and Beta (sideslip) are fairly low and are generally negligible for most icing tests.

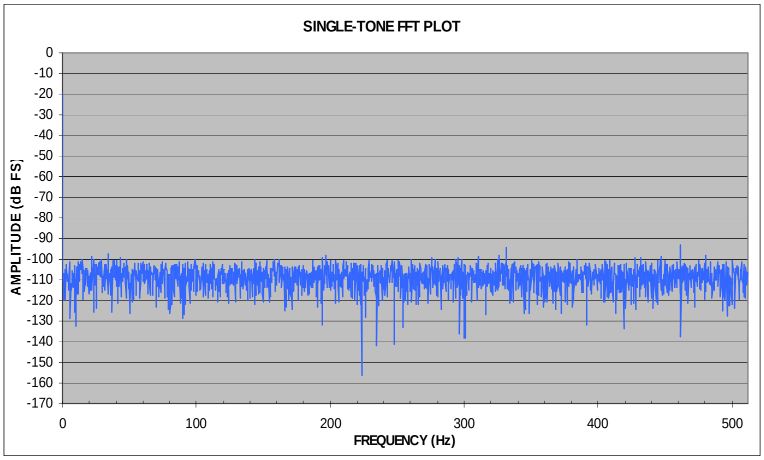

Figure 4: FFT results of hot film data

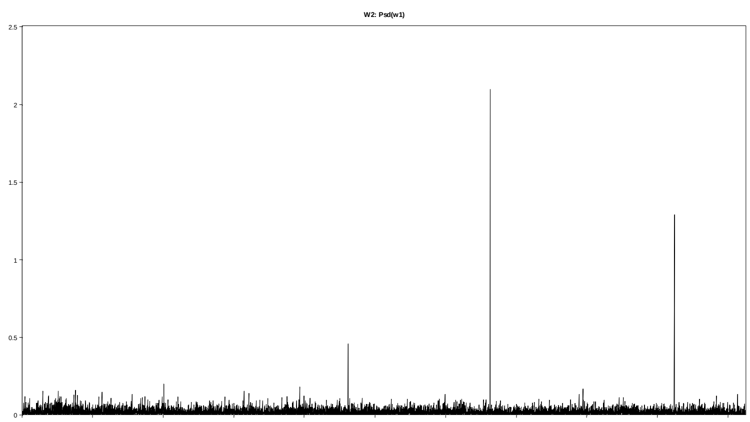

Figure 5: PSD results of hot film data

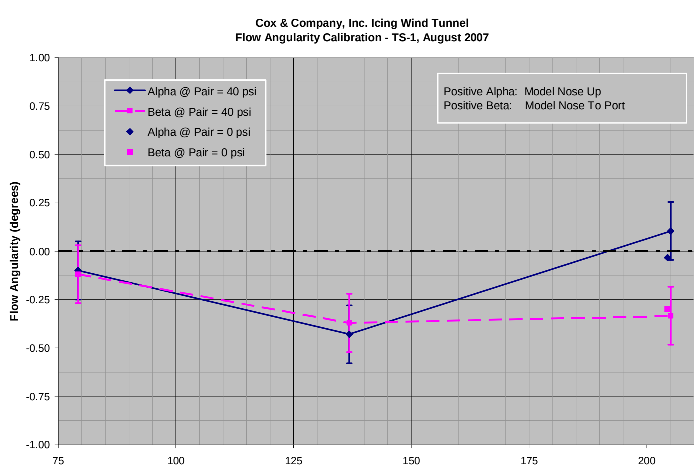

Figure 6: Flow angularity measurements

Airflow in closed wind tunnels is rarely ever uniformly distributed. This is because the flow along the inside wall has to travel a shorter distance than does the flow along the outer wall. Furthermore, the wall friction/boundary layer retards the flow along the walls. The use of flow smoothing screens for improved flow uniformity is not practical in an icing tunnel. In an open loop tunnel, which is not common in year-round operating icing tunnels, a screen could be installed upstream of the spray bars. But the benefits are insignificant due to the flow disturbances produced by the spray bars.

The velocity distribution can be presented as a contour map of the flow variations in a plane perpendicular to the flow direction near the middle of the tunnel main test section. The distribution presented in this way is an indication of the uniformity of the airspeed across the Test Section.

The flow distribution was measured through the use of a total pressure grid installed in Test Section-1. This total pressure grid is similar to an icing grid. There were 31 total pressure tubes distributed on this grid. These were read using the Scanivalve Digital Sensor Array DSA-3017 pressure transducer. Figure 7 shows the distribution at IAS of 82 mph and 161 mph. The view is looking upstream from the test section towards the spray bars located in the settling chamber.

These plots show variations in miles per hour. In terms of percentage of average airflow, at the lower airspeed of 82 mph, the maximum variation seems to be about ±1.2%, while at the higher speed the maximum variation appears less than ±0.5%. Note that in these plots, the corners are fictitious since there are 6-inch fillets in the tunnel corners, and the values were averaged from nearby measured grid location values.

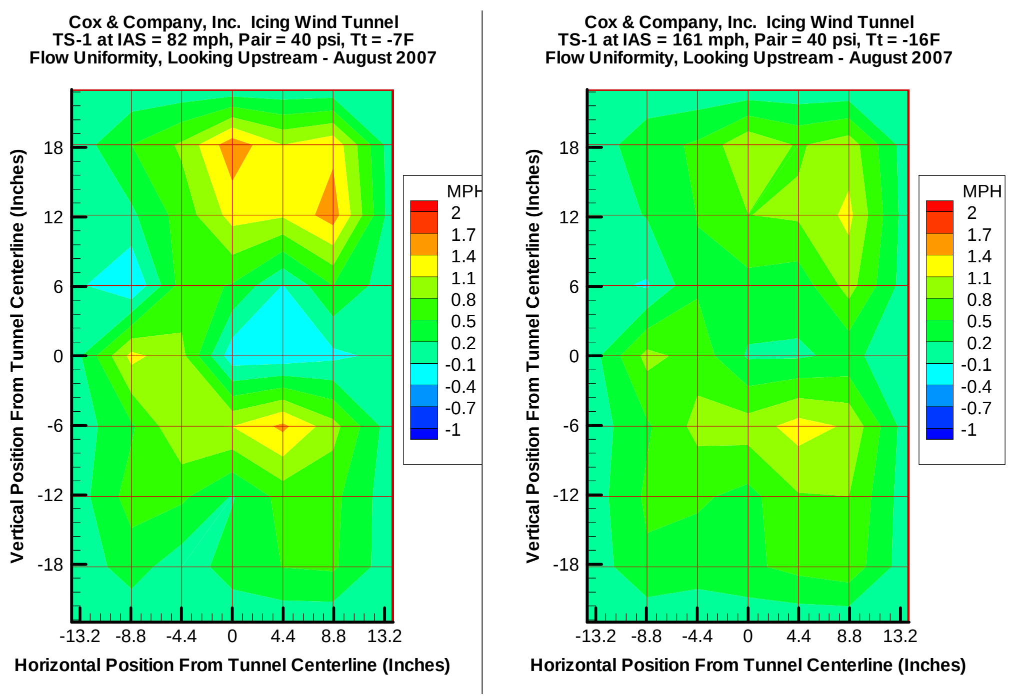

Figure 7: Flow uniformity at an IAS of 82 mph and 161mph

III. Temperature Uniformity

The same grid that was used for airspeed uniformity measurements was also used to measure temperatures across Test Section-1. Thirty-one (31) thermocouples were installed on the grid, one for each grid intersection. Each thermocouple was isolated from the grid using non-conductive tape. In addition, each thermocouple was positioned slightly off the surface to minimize any errors in the measurement of the local total air temperature due to heat conduction from the aluminum grid structure. The thermocouples were calibrated at multiple temperatures in a freezer and an error curve was generated for each thermocouple as a function of temperature. This error was inclusive to the thermocouples as well as the data acquisition signal conditioners. The final data were then corrected using these error curves.

Figure 8 shows the results at warm and cold temperatures at a TAS of 75 mph. In the warm case of 23ºF, there seems to be a maximum variation of ±1ºF (0.6ºC), while at the colder condition of -19ºF the variation seems to be much higher: ±1.8ºF (1ºC). Both of these plots show a definite warm spot near the tunnel floor. Outside this warm area, there is very good temperature uniformity. This might be associated with the lower cooling coils upstream of the settling chamber. A new set of coils is planned in an upcoming upgrade as discussed later.

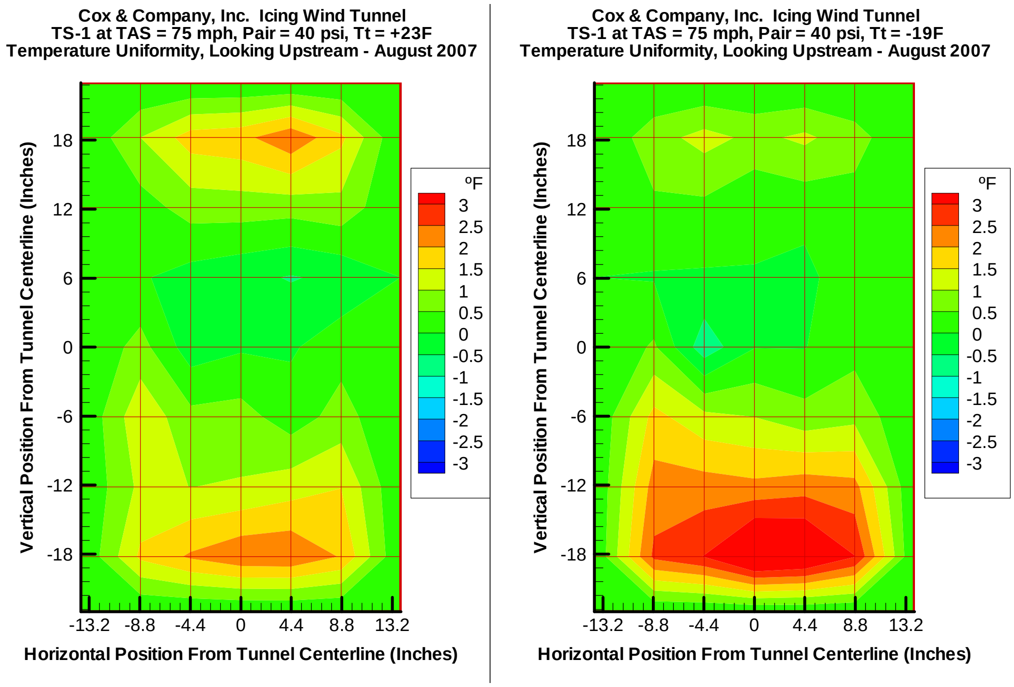

Figure 8: Temperature uniformity at +23F and -19F, TAS = 75 mph

Figure 9 shows warm and cold temperature results at a TAS of 150 mph. At the warm case of 27ºF, there is a maximum variation of ±1.2ºF (0.7ºC). At the colder condition of -17ºF the variation is almost the same, ±1.5ºF (0.8ºC), although the distribution is different. As before, the colder temperature plot shows a definite warm spot near the floor of the tunnel. Outside of this warm area, the flow has very good temperature uniformity.

IV. Super-cooled Spray Uniformity

A grid similar to the one used to map the previously shown flow and temperature uniformities was used to map the spray LWC uniformity in the test section. The grid for spray uniformity is made up of 7 vertical and 9 horizontal aluminum bars, each with a rectangular cross section of 1.5 inch streamwise by 0.1875 inch thickness. A drawing of this grid is shown in Figure 10. The grid completely fills Test Section-1.

The spray uniformity calibration was conducted at a TAS of 150 mph, a total temperature of 5ºF, drop size of MVD = 20 µm, and a nominal LWC = 0.422 g/m^3 (average of 6 cells near the center of the test section in Figure 10). The ice accretion was measured at 72 points on the grid using a digital caliper, and the data was recorded directly into a computer. The ratio of the local LWC to the nominal value is presented in the contour plot shown in Figure 11. This illustrates a cloud uniformity that is within 10% of the nominal value over a large portion of the test section away from the side walls, ceiling, and floor.

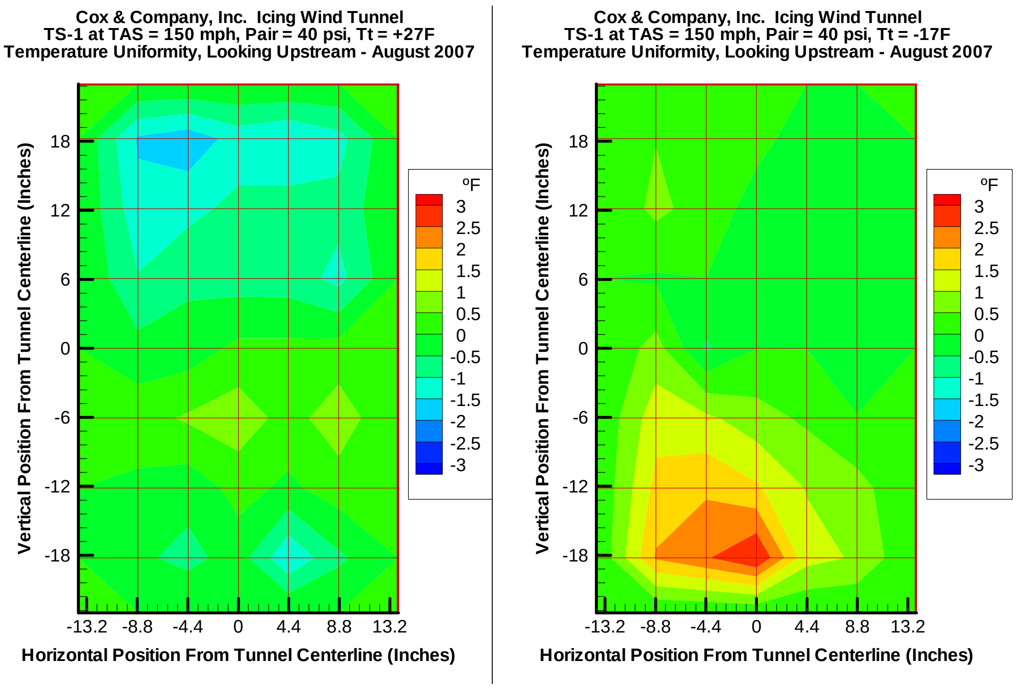

Figure 9: Temperature uniformity at +27°F and –17°F, TAS = 150 mph

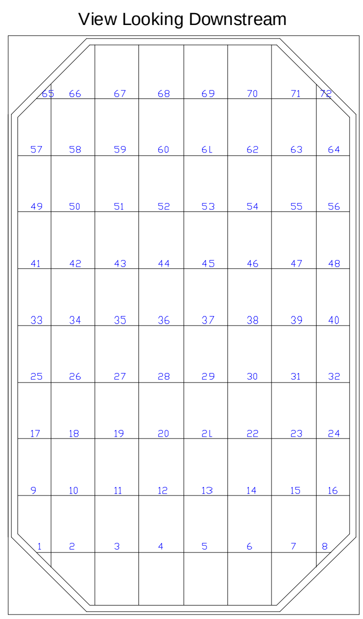

Figure 10: Drawing of icing grid with 72 measurement points

Most icing tests are conducted near the center of the test section. To illustrate a typical cloud uniformity case, a horizontally mounted wing section example was considered.. Figure 12 illustrates the case of rime ice accretion, and Figure 13 illustrates the case of glaze ice accretion in a high LWC environment. The wing section is 2D with no sweep. These photographs taken during representative icing tests, show that the spray is uniform and consistent to within 4 inches of the side walls. Within 4 inches from the walls, LWC drops almost linearly to a very low value next to the side walls.

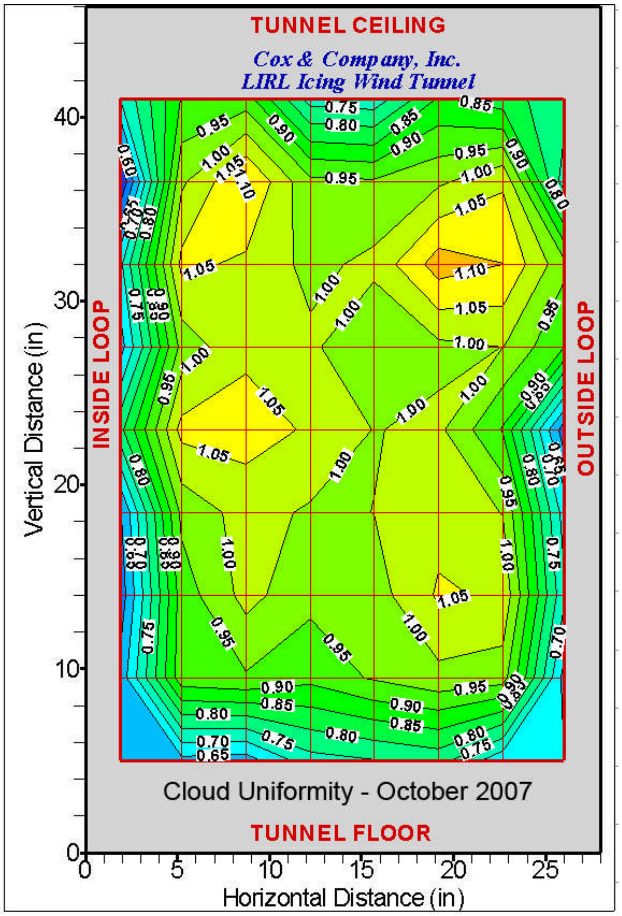

Figure 11: Spray Uniformity in TS-1

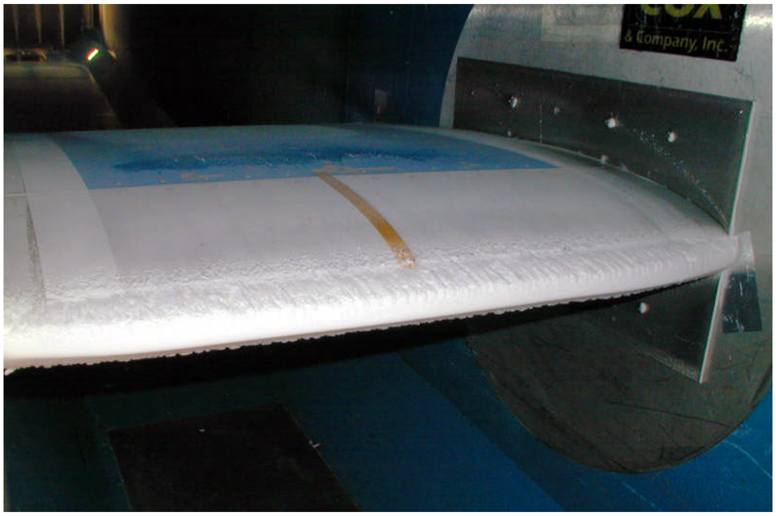

Figure 12: Rime ice spray uniformity across an airfoil model

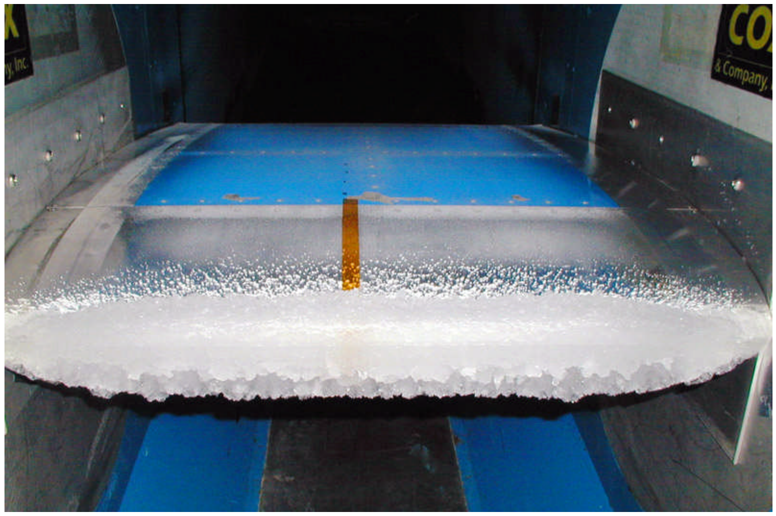

Figure 13: Glaze ice spray uniformity across an airfoil model

V. Ice Crystal Developments

Beginning in approximately 2003, Cox has done considerable developmental work in the simulation of ice crystals and mixed phase icing environments in the tunnel as well as testing of articles (probes and heated wings) in those conditions [3,4]. Some of the development work was supported by NASA SBIR Phase I & II grants. The work has resulted in the development of a liquid spray based snow-gun system as well as an ice shaver system. The snow gun system has seen limited use because of earlier problems with complete freeze-out of the droplets. In 2006, some modifications were made to this system that resulted in complete or very near 100% freezing of the atomized droplets. The snow-gun system was not included in the calibration because of lack of time and resources, as well as due to much less usage compared to the ice shaver system.

Alternatively, the Cox ice shaver system has seen considerable use in the past few years and is capable of covering a significant portion of the British Standard BS-2G requirements for ice crystals and mixed phase testing for air data probes. The big challenge with this system is to create properly sized crystals and to deliver them to the model at the proper temperature and velocity. Another challenge is to measure the actual IWC and the distribution of the ice crystals.

Figure 14 shows contour plots of the IWC distribution resulting from dispersion of the shaved ice crystals at a TAS of 175 mph for the current lowest and highest shaving rates. Slower and faster shaving rates can be accomplished, but the consistency is not as reliable as the range shown in Figure 14.. The plots indicate that the distribution is bell-shaped where the concentration of ice particles falls off from the high values near the test section centerline fairly quickly to a low value near the walls. The distributions shown were obtained through a combination of analysis and measurements taken using a Nevzorov LWC/IWC probe , and other instruments used by NASA Glenn, Environment Canada, and Science Engineering Associates, during testing of existing and new icing probes[5,6].

Ice crystal testing can be conducted over the full temperature and airspeed envelopes of the tunnel. The duration of the shaved ice runs at the high tunnel speeds can range from about 7.5 minutes at the highest shaving rate to more than thirty (30) minutes at the lowest shaving rate. Consideration is being made to double the IWC capability to meet recent requests of the meteorological community in light of known effects on engine stall/flame-out at high altitudes where high IWC concentrations are suspected. The current capability meets current commercial customers needs.

Figure 15 shows a representative ice particle size distribution produced with the ice shaver. The image on the left side is obtained from a 2D gray probe laser droplet measuring system. Shown on the right side is a particle size distribution taken during one of the representative ice shaver runs.

Figures 16 show a Nevzorov probe and an OAP instrument mounted on the standard mount in Test Section-1 of the LIRL Icing Wind Tunnel during ice crystal spray calibration.

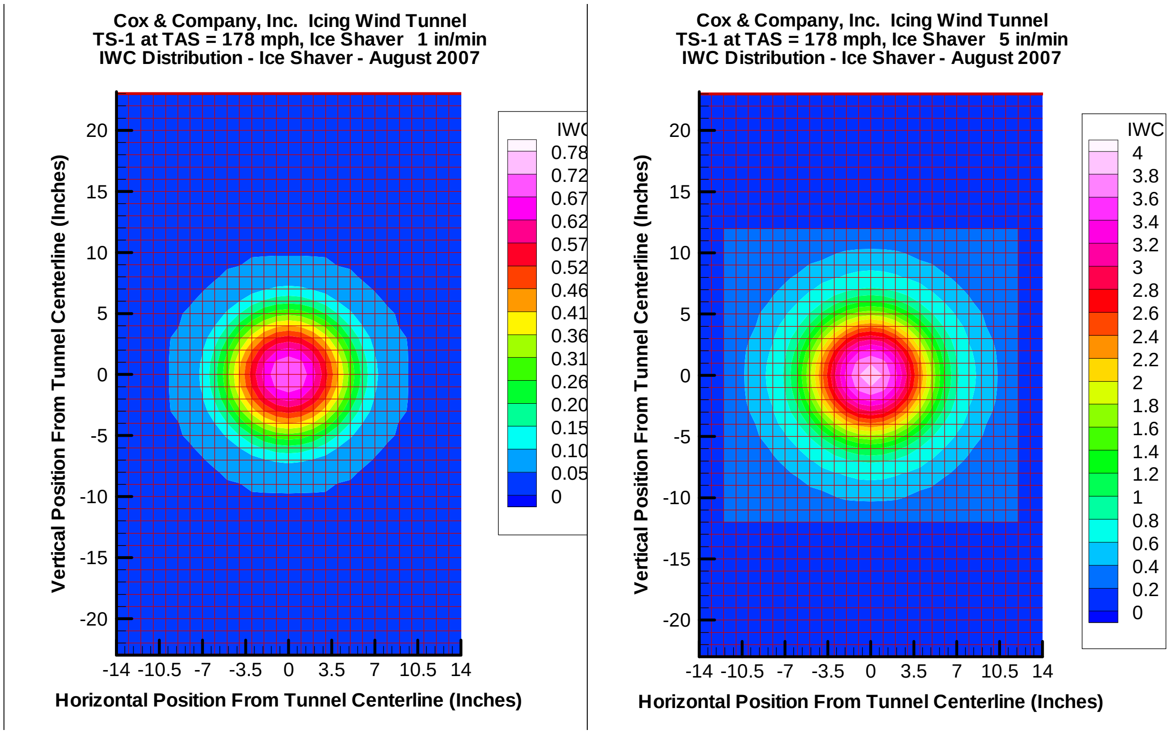

Figure 14: Shaved ice crystal distribution at TAS = 178 mph
(Data courtesy of Walter Strapp, EC)

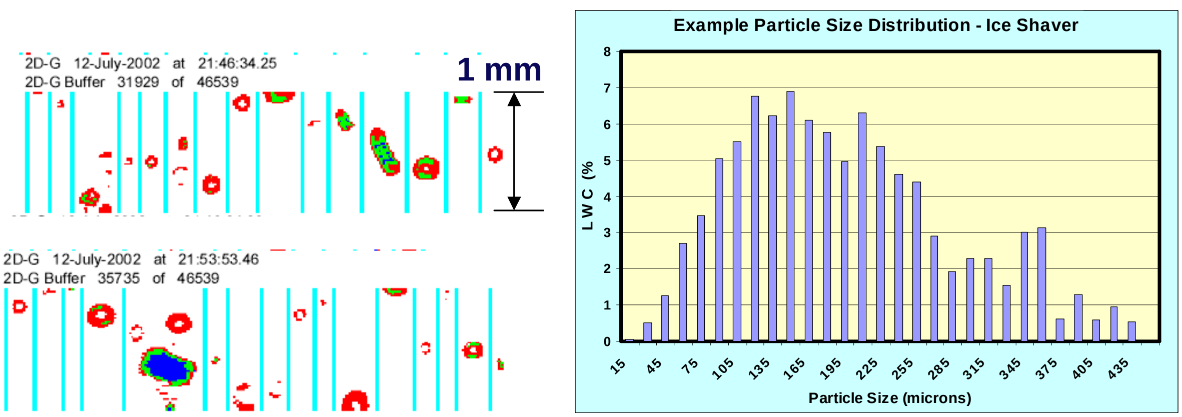

Figure 15: Sample of shaved ice crystals (OAP-2D gray) and size distribution

VI. Supercooled Drop Size Calibration

The first droplet sizing calibration was conducted in April 1998, a year following the inception of the tunnel. This calibration was performed using two PMS laser probes: FSSP (Forward Scattering Spectrometer Probe) and OAP (Optical Array Probe). Final drop sizing was obtained by combining data from the FSSP and the OAP since they covered the small drop and large drop ranges, respectively. In years 2000 and 2003, the calibration was repeated using the Malvern Spraytec laser system. Results were within 3 microns for drop sizes below about 25 microns. Above that, the Malvern seemed to under-predict the results, or the PMS over-predict the drop sizes.

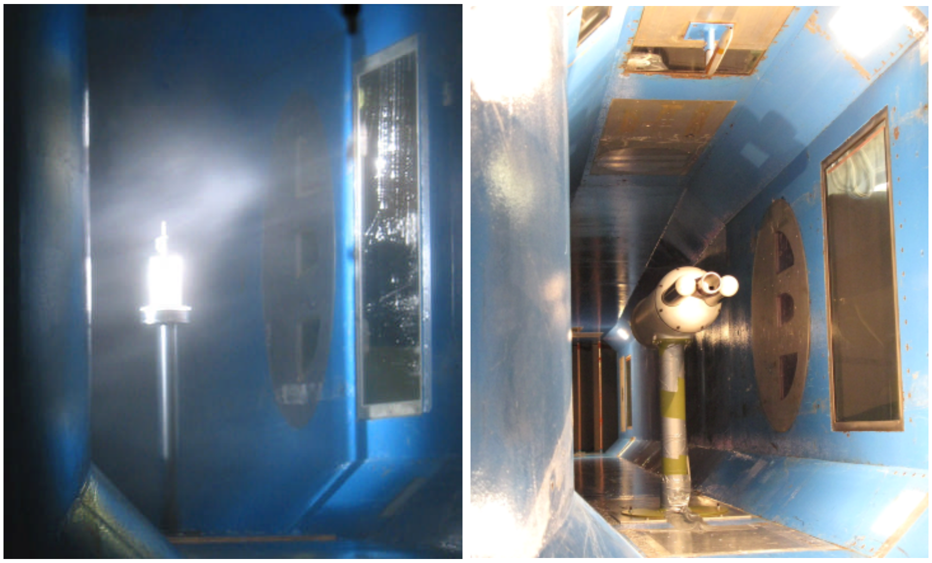

Figure 16: Nevzorov and OAP in Test Section-1 of the LIRL Icing Wind Tunnel

Recent calibrations were conducted during the summer of 2007, but data reduction was not completed in time for this paper. However, preliminary results from a few points of the recent calibration and those from previous calibration indicate that the Cox drop sizes are near 3 microns larger than those produced/measured at the NASA Glenn Icing Research Tunnel for the MOD-1 nozzles under the same air and water pressure settings. This close agreement was expected since Cox uses the same type of nozzles and the same spray bar concepts. Figure 17 illustrates the range of LWC at different airspeeds and drop sizes that can be simulated in Test Secction-1 of the Cox IWT.

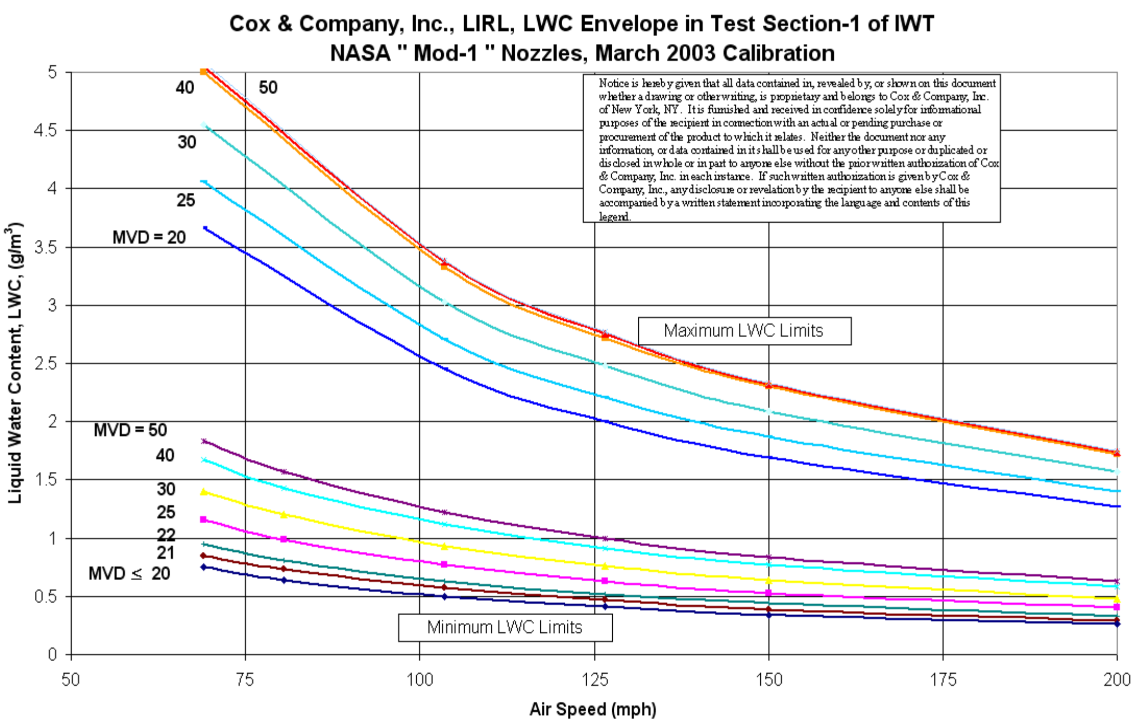

Figure 17: Supercooled Cloud Envelope in Test Section-1 of the LIRL Icing Wind Tunnel

VII. Near Future Upgrades

By the end of year 2008, Cox & Company, Inc. will relocate its facility, including the IWT, from downtown Manhattan in New York to a close suburb. This has opened up an opportunity for upgrades and improvements that would have otherwise caused an undesirable shutdown of the tunnel for a few months. The following provides a partial list of planned upgrades:

- Significantly upgraded heat exchanger for better temperature distribution, temperature stability, and reliable temperature control near freezing point where interest has grown to study runback water formation and its effects
- Upgraded refrigeration compressor central controller and local high fidelity temperature controller
- More powerful main fan motor to better maintain the higher airspeeds, specially with large ice accretions on models that produce high drag, thus loss of airspeed
- Better spray water and spray bar temperature control for very high pressure sprays (usually high LWC)

Most systems will also be converted to higher voltages and will be operated more efficiently and smoothly using variable frequency drives (VFD). These and other smaller detail and procedural changes are designed to improve the operation of the tunnel and increased consistency of all sub-systems.

This move and major upgrades will require a full tunnel calibration. The lessons learned during the current calibration effort will be applied to increase the fidelity of measurements as well as icing simulation capabilities. It is expected that the next calibration effort will be completed by early February 2009 at the new facility site.

VIII. Concluding Remarks

The Cox & Company, Inc. Icing Wind Tunnel has been recently calibrated and improved with additional simulation capabilities, specifically of ice crystals and mixed phase icing conditions. The calibrations included the conventional flow parameters such as airspeed, temperature, angularity, and turbulence, in addition to icing-tunnel specific parameters such as droplet distribution and ice accretion uniformity. All calibrations were conducted to the maximum extent possible in accordance with SAE Aerospace Recommended Practices (ARP) 5905. The generosity of other members of the Icing Community and Cox's customers in this subject area is acknowledged. The data presented herein is a representative subset of the total data collected during the calibration.

References

[1]Al-Khalil, K., Salamon, L. and Tenison, G., "Development of the Cox Icing Research Facility," AIAA 98-0097, 36th AIAA Aerospace Sciences Meeting, Reno, NV, 1998.

[2]SAE Aerospace Recommended Practice (ARP) document ARP 5905, "Calibration and Acceptance of Icing Wind Tunnels," September 2003.

[3]Al-Khalil, K., Irani, E. and Miller, D., "Mixed Phase Icing Simulation and Testing at the Cox Icing Wind Tunnel," AIAA-2003-0903, 41st AIAA Aerospace Sciences Meeting, Reno, NV, 2003.

[4]Al-Khalil, K. "Assessment of effect of mixed-phase icing conditions on thermal ice protection systems," Department of Transportation, Federal Aviation Administration, Office of Aviation Administration, Rep. No. DOT/FAA/AR-03/48, May 2003.

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