AEROSPACE RECOMMENDED PRACTICE

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Revised 2025-01	
Superseding ARP5905	

Calibration and Acceptance of Icing Wind Tunnels

RATIONALE

This document has been revised to address areas where the committee determined it needed improvement. The original document did not specify the necessity of a test section centerline temperature calibration, and this has been added. Also, the document now contains recommendations with regard to icing wind tunnels that have altitude capability. The spray durations and recommended test matrix in 7.2.1 (previously 8.2.2) have been reworded to more accurately reflect common ice accretion test practices. Performance targets and accompanying text have been added with regard to test section calibrations (not just measurement targets). Recommendations have been added regarding the possible effects of humidity on LWC and MVD, including recommendations for facility humidity instrumentation. The original document's Appendix A (LWC instrumentation) was removed in favor of AIR6977, and its Appendix C (Guideline to Determining Derived Aerodynamic Parameters) was removed in favor of other publications that better describe wind tunnel aero-thermal calibration. A new Appendix D was added with information regarding particle size distributions.

FOREWORD

The U.S. Federal Aviation Administration established an icing plan in 1997 to respond to a need for a comprehensive program to create an awareness of in-flight icing issues and to establish documents to provide training and guidance for regulatory authorities, aircraft operators, research organizations, and aircraft manufacturers. The FAA published a 14-task plan, titled the "FAA In-flight Aircraft Icing Plan," and identified groups of people within the U.S. government and throughout the aircraft industry to address the action items contained in this plan. Task 11 of this plan called for the development of "validation criteria and data for simulation methods used to determine ice shapes on aircraft." It also indicated that this task was to include data on "wind tunnel(s), ice accretion computer codes, and icing tankers." The FAA suggested "a coordinated effort among research organizations, industry, and regulatory authorities," and individuals were asked to participate in this work. Task 11 was divided into three subtasks, and the people that participated in Subtask A were tasked with addressing criteria for the use of tankers, tunnels, and codes. Three documents were developed by the members of the Task 11.A Working Group, and these three documents were published as SAE Aerospace Recommended Practices. While each document follows a format that is appropriate to the topic, the three documents provide guidance for the application of codes (refer to ARP5903), tankers (refer to ARP5904), and tunnels (refer to ARP5905) to the icing certification or qualification process.

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https://www.sae.org/standards/content/ARP5905A/

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1. SCOPE

This SAE Aerospace Recommended Practice (ARP) provides recommended practices for the calibration and acceptance of icing wind tunnels to be used in testing of aircraft components and systems and for the development of simulated ice shapes. This document is not directly applicable to air-breathing propulsion test facilities configured for the purposes of engine icing tests, which are covered in AIR6189. This document also does not provide recommended practices for creating Supercooled Large Drop (SLD) or ice crystal conditions, since information on these conditions is not sufficiently mature for a recommended practice document at the time of publication of ARP5905A. Use of facilities as part of an aircraft's ice protection Certification Plan should be reviewed and accepted by the applicable regulatory agency prior to testing. Following acceptance of a test plan, data generated in these facilities may be submitted to regulatory agencies for use in the certification of aircraft ice protection systems and components. Certain types of tests may be appropriate in facilities with capabilities that are not as rigorously characterized by the practices defined herein, and the acceptability of these tests should be coordinated with the applicable regulatory agency.

1.1 Purpose

The purpose of this ARP is to compile, in one definitive source, commonly accepted calibration and acceptance criteria and procedures for icing wind tunnels. Wind tunnels that meet these criteria will have known icing conditions simulation capability. Each manufacturer is responsible for obtaining regulatory agency approval for using a specific facility to generate certification data in their specific certification program.

The reader is directed to the following: DTIS ADA276499, AC 20-73A, AC 29-2C, and AC 23.2010-1; and the standards for icing certification of airplanes (refer to ASTM F3120/F3120M-20 and AC 25-28) for the myriad of considerations that are inherent in defining and conducting test programs for the purpose of obtaining certification for flight into known icing conditions. This ARP provides recommended practices for the calibration of icing wind tunnels. It is not intended to substitute for the regulatory agency's latitude in selecting the combination of tests or inspections required to demonstrate compliance with regulations as described in the Aircraft Icing Handbook.

An icing facility that conforms to the recommended practices in this document provides an artificial icing test volume consistent with the capability provided by current wind tunnel technology. If results produced in a test facility are to be used in the certification process of aircraft components or ice protection systems, it should be substantiated that the facility calibration and supporting resources conform to this ARP. Also, a comparison between the facility icing condition envelopes that can be simulated and those defined by the regulatory authorities should be presented.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

AIR4906 Droplet Sizing Instrumentation Used in Icing Facilities

AIR5320 Summary of Icing Simulation Test Facilities

AIR6189 Design, Calibration, and Test Methods for Turbine Engine Icing Test Facilities

AIR6977 Water Content Instrumentation for Icing Cloud Characterization

ARP5624 Aircraft Inflight Icing Terminology

ARP5903 Droplet Impingement and Ice Accretion Computer Codes

ARP5904 Airborne Icing Tankers

ARP5905 Calibration and Acceptance of Icing Wind Tunnels

Agui, J., Struk, P., and Bartkus, T., "Total Temperature Measurements in Icing Cloud Flows Using a Rearward Facing Probe," SAE Technical Paper 2019-01-1923, 2019, https://doi.org/10.4271/2019-01-1923.

Bartkus, T., Struk, P., and Tsao, J., "Development of a Coupled Air and Particle Thermal Model for Engine Icing Test Facilities," *SAE Int. J. Aerosp.* 8(1):15-32, 2015, https://doi.org/10.4271/2015-01-2155.

Davison, C., "Development of an Altitude Evaporation Model for Icing Tunnel Control," SAE Technical Paper 2023-01-1425, 2023, https://doi.org/10.4271/2023-01-1425.

Struk, P., Agui, J., Ratvasky, T., King, M. et al., "Ice-Crystal Icing Accretion Studies at the NASA Propulsion Systems Laboratory," SAE Technical Paper 2019-01-1921, 2019, https://doi.org/10.4271/2019-01-1921.

Whalen, M., and Matheis, B., "Effect of Icing Environment and Humidity on Reference Air Data Parameters in an Icing Tunnel," SAE Technical Paper 2019-01-1929, 2019, https://doi.org/10.4271/2019-01-1929.

2.1.2 AIAA Publications

Available from American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344, Tel: 703-264-7500, www.aiaa.org.

AIAA G-045-2003 Guide to Assessing Experimental Uncertainty – Supplement to S-071A-1999

AIAA R-093-2003 Calibration of Subsonic and Transonic Wind Tunnels

AIAA S-071A-1999 Assessment of Experimental Uncertainty with Application to Wind Tunnel Testing

Bencic, T.J., Fagan, A.F., Van Zante, J.F., Kirkegaard, J.P. et al. (June 2013). *Advanced Optical Diagnostics for Ice Crystal Cloud Measurements in the NASA Glenn Propulsion Systems Laboratory*. 5th AIAA Atmospheric and Space Environments Conference. Available at https://doi.org/10.2514/6.2013-2678.

Henze, C.M. and Bragg, M.B. (1999). Turbulence Intensity Measurement Technique for Use in Icing Wind Tunnels. *Journal of Aircraft, 36*(3), 577-583. https://doi.org/10.2514/2.2473.

Struk, P.M., King, M.C., Bartkus, T.P., Tsao, J.C., et al. (June 2018). *Ice Crystal Icing Physics Study using a NACA 0012 Airfoil at the National Research Council of Canada's Research Altitude Test Facility*. 2018 Atmospheric and Space Environments Conference. Available at https://doi.org/10.2514/6.2018-4224.

Van Zante, J.F., Bencic, T.J., and Ratvasky, T.P. (June 2016). *Update on the NASA Glenn Propulsion Systems Lab Ice Crystal Cloud Characterization (2015)*. 8th AIAA Atmospheric and Space Environments Conference. Available at https://doi.org/10.2514/6.2016-3897.

Van Zante, J.F. and Rouse, B.M. (June 2014). *NASA Glenn Propulsion Systems Lab: 2012 Inaugural Ice Crystal Cloud Calibration Procedure and Results*. 6th AIAA Atmospheric and Space Environments Conference. Available at https://doi.org/10.2514/6.2014-2897.

2.1.3 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM F3120/F3120M-20 Standard Specification for Ice Protection for General Aviation Aircraft

2.1.4 Code of Federal Regulations (CFR) Publications

Available from United States Government Publishing Office, 732 North Capitol Street, NW, Washington, DC 20401, Tel: 202-512-1800, www.gpo.gov.

14 CFR Part 25 Airworthiness Standards: Transport Category Airplanes"

14 CFR Part 29 Airworthiness Standards: Transport Category Rotorcraft"

2.1.5 Department of Defense Technical Publications

Available from Defense Technical Information Center (DTIC), 8725 John J. Kingman Road, Fort Belvoir, Virginia 22060-6218, Tel: 800.225.3842, https://Discover.DTIC.mil.

Schulz, R.J. (1998). *Second Report for Research and Modeling of Water Particles in Adverse Weather Simulation Facilities*. AEDC-TR-97-03.

Willbanks, C. and Schulz, R. (1973). *Analytical Study of Icing Simulation for Turbine Engines in Altitude Test Cells*. AEDC-TR-73-144.

2.1.6 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

AC 20-73A Aircraft Ice Protection

AC 23.2010-1 FAA Accepted Means of Compliance Process for 14 CFR Part 23

AC 25-28 Compliance of Transport Category Airplanes with Certification Requirements for Flight in Icing Conditions

AC 29-2C Certification of Transport Category Rotorcraft

2.1.7 NACA Publications

Available from National Technical Information Service, 5301 Shawnee Road, Alexandria, VA 22312, Tel: 1-888-584-8332 or 703-605-6050, www.ntis.gov.

DTIS ADA276499 Aircraft Icing Handbook (Update), Volume 2, Chapter V, Section 4.0, Testing to Demonstrate Compliance

NACA Report No. 1135 (1953). *Equations, Tables and Charts for Compressible Flow*. NASA Ames Research Center.

2.1.8 NASA Publications

Available from NASA Technical Services, NASA STI Program STI Support Services, Mail Stop 148, NASA Langley Research Center, Hampton, VA 23681-2199, Tel: 757-864-9658, Fax: 757-864-6500, http://ntrs.nasa.gov/.

Ide, R.F. (1990). *Liquid Water Content and Droplet Size Calibration of the NASA Lewis Icing Research Tunnel*. NASA/TM - 102447.

Ide, R.F. and Sheldon, D.W. (2008). *2006 Icing Cloud Calibration of the NASA Glenn Icing Research Tunnel*. NASA/TM - 2008-215177.

Rinehart, D.A. and Johnson, A.M. (2020). *Full Aerothermal Characterization of the 6- by 9-Foot Icing Research Tunnel (2019 Test)*. NASA/CR - 20205005811.

Timko, E.N., King-Steen, L.E., Van Zante, J.F., and Acosta, W.J. (2021). *NASA Glenn Icing Research Tunnel: 2019 Cloud Calibration Procedure and Results*. NASA/TM - 20205009045.

2.1.9 Other Publications

Barlow, J.B., Rae, W.H. Jr., and Pope, A. (1999). *Low-Speed Wind Tunnel Testing* (3rd ed.). John Wiley and Sons.

Coleman, W.H and Steele, W.G. Jr. (1989). *Experimentation and Uncertainty Analysis for Engineers*. John Wiley and Sons.

Jørgensen, F.E. (2005). *How to Measure Turbulence with Hot-Wire Anemometers - a Practical Guide*. Dantec Dynamics. Available at https://www.dantecdynamics.com/wp-content/uploads/2020/08/pratical-guide-how-to-measure-turbulence.pdf.

Langmuir, I. and Blodgett, K.B. (1946). *A Mathematical Investigation of Water Droplet Trajectories* (U.S. AAF Technical Report 5418).

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

Cain, G., Yurczyk, R., Belter, D., and Chintamani, S., "Boeing Research Aerodynamic/Icing Tunnel Capabilities and Calibration," SAE Technical Paper 940114, 1994, https://doi.org/10.4271/940114.

2.2.2 AIAA Publications

Available from American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344, Tel: 703-264-7500, www.aiaa.org.

Steen, L., Ide, R., and Van Zante, J. (June 2016). *An Assessment of the Icing Blade and the SEA Multi-Element Sensor for Liquid Water Content Calibration of the NASA GRC Icing Research Tunnel*. 8th AIAA Atmospheric and Space Environments Conference. Available at https://doi.org/10.2514/6.2016-4051.

2.2.3 Department of Defense Technical Publications

Available from Defense Technical Information Center (DTIC), 8725 John J. Kingman Road, Fort Belvoir, Virginia 22060-6218, Tel: 800.225.3842, https://Discover.DTIC.mil.

Chintamani, S., Delcarpio, D., and Langmeyer, G. (1996). *Development of Boeing Research Aerodynamic Icing Tunnel Circuit*.

Aerodynamics of Wind Tunnel Circuits and their Components (1996). AGARD-CP-585.

Quality Assessment for Wind Tunnel Testing (1994). AGARD Advisory Report No. 304.

2.2.4 National Research Council Canada Publications

Available from National Research Council Canada, 1200 Montreal Road, Building M-58, Ottawa, Ontario K1A 0R6, Tel: 613-993-9101, https://nrc.canada.ca/en.

Stallabrass, J.R. (1978). *An Appraisal of the Single Rotating Cylinder Method of Liquid Water Content Measurement* (Report LTR-LT-92). National Research Council Canada.

2.2.5 Other Publications

Bradshaw, P. (1971). *An Introduction to Turbulence and its Measurement*. Pergamon Press Ltd. https://doi.org/10.1016/C2013-0-02451-6.

Finstad, K.J., Lozowski, E.P., and Gates, E.M. (1988). A computational investigation of water droplet trajectories. *Journal of Atmospheric and Oceanic Technology, 5*, 160-170.

2.3 Symbols

γ	Ratio of specific heats
ρ_{ice}	Density of ice
ρ_w	Density of water
τ_C	Thickness of the iced grid at the center location
τ_{grid}	Thickness of grid in the uniced condition
τ_{ice}	Thickness of ice
$\tau_{ice\ R}$	Relative thickness of ice
$\tau_{(x,y)}$	Thickness of the iced grid at each (x,y) location
ω_a	Air mass flow rate
ω_w	Water flow rate
ω_{wB}	Bulk water flow rate
A	Flow area
a	Speed of sound

$C_{d\ a}$ Air discharge coefficient

$C_{d\ w}$ Water discharge coefficient

$C_{d\ w/a}$ Discharge coefficient based on difference of water and air pressures

C_f Water flow coefficient

C_0 Intercept constant

D Nozzle approach diameter

d_o Nozzle orifice diameter

H_1, H_2, H_3 Icing grid locations (horizontal)

K Unit conversion factor

K_A Liquid water content calibration constant for constant tunnel velocity

K_e Calculated nozzle correlation parameter

K_v Liquid water content calibration constant for constant spray bar air pressure

LWC Liquid water content

LWC_B Bulk liquid water content

LWC_b Icing blade liquid water content

LWC_C Tunnel centerline liquid water content

LWC_e Facility calibration predicted liquid water content

$LWC_{(x,y)}$ Liquid water content calculated at icing grid location (x,y)

M Freestream Mach number

MVD Median volumetric diameter

P_a Spray bar air pressure

PSD Particle size distribution

P_S Freestream static pressure

$P_{S\ dwn}$ Static pressure downstream of orifice

$P_{S\ up}$ Static pressure upstream of orifice

P_T Freestream total pressure

P_w Spray bar water header pressure

$\Delta P_{w\text{-}a}$ Spray bar water to air differential pressure

R Gas constant

RTD Resistance temperature detector

T_S Absolute freestream static air temperature

T_T Absolute freestream total air temperature

T_{Ta} Nozzle total air temperature

t Time

V Freestream velocity (i.e., true airspeed)

V_{TS} Test section freestream velocity (i.e., true airspeed)

V_1, V_2, V_3 Icing grid locations (vertical)

3. FACILITY DESCRIPTION

This ARP is intended to cover a variety of icing wind tunnel types from refrigerated closed-circuit facilities to open air freejet facilities. AIR5320 also presents information on icing test facilities.

3.1 Example Closed-Circuit Facility

An example facility consists of a closed-circuit, refrigerated wind tunnel with a constant area test section. A variable speed fan motor provides for a variation in the test section air velocity. Refrigeration is obtained via a heat exchanger placed upstream of the settling chamber, adequately sized to provide the required test section temperature setting. The facility has a settling chamber that may be fitted with honeycomb flow straighteners and screens and a contraction section with sufficient area ratio to provide for good airflow quality in the test section. Water spray bars located in the settling chamber and their associated controls provide the water droplet spectrum and liquid water content (LWC) required for the test conditions. The water used in the spray bar system is normally heated and treated (e.g., deionized) in order to avoid freeze-out and fouling of the water spray atomizing nozzles, respectively. An example of a typical closed-circuit refrigerated facility is shown in Figure 1.

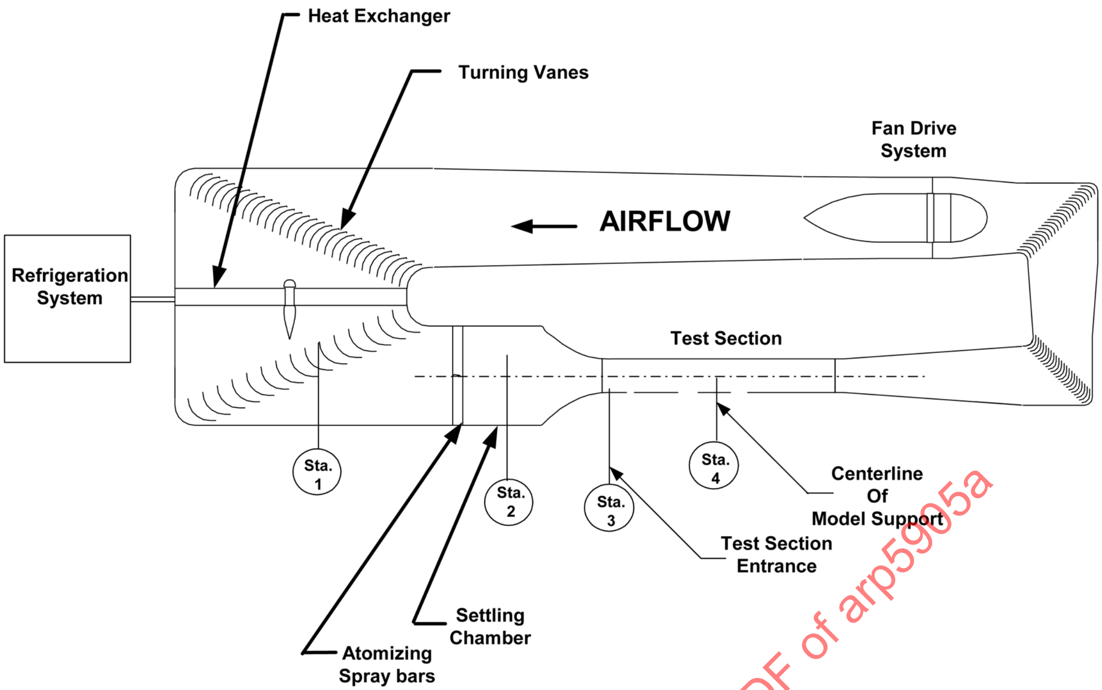

Figure 1 - Example of typical closed-circuit, refrigerated icing tunnel

3.2 Considerations for Open-Circuit Wind Tunnels and Facilities with Alternate Configurations

Another example facility is an open-circuit refrigerated wind tunnel, typically used for engine testing. Such facilities are briefly addressed here but are described in greater detail in AIR6189. The NRC Canada 3 m x 6 m icing wind tunnel is an example of this type of facility and is shown schematically in Figure 2. In this facility, cold air is supplied at the inlet and driven by a fan through a series of flow conditioning screens in the settling chamber to straighten the flow and improve the velocity distribution. The flow is accelerated as it passes through a bell mouth or other contraction device and is conducted via a straight duct to the test section, where the test article is typically placed. The icing water spray is injected upstream of the test section. The flow then discharges through the diffuser along with any engine combustion products. Generally, the flow in such (engine test) facilities does not meet the detailed flow angle and turbulence criteria cited in Section 4.

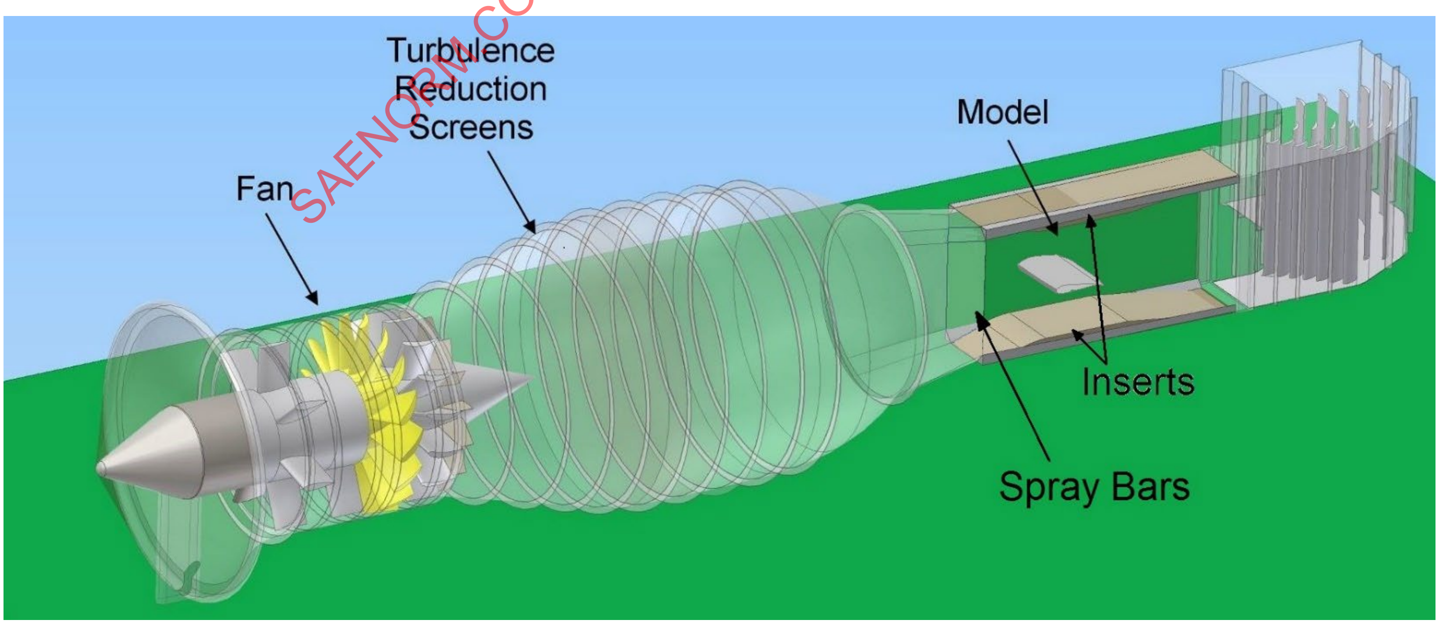

Figure 2 - Example of a non-recirculating icing wind tunnel

It should be pointed out that in some instances an open-circuit facility is adapted to specific tests and does not have a static configuration (i.e., is not permanently configured as an icing facility). This is also the case for other icing facilities (e.g., climatic chambers and tunnels with removable contractions or test sections), which have alternate facility configurations that make a full calibration unfeasible. Consequently, these facilities are not consistently configured for the routine calibrations cited below and generally do not have the same characterized flow quality as a closed-circuit facility. Typically, spray nozzles are flow calibrated and characterized for droplet size, but they are installed in an adaptable array for generation of a specific cloud. To overcome these facility constraints, these facilities typically calibrate the flow and cloud either prior to a specific test or during the test. These calibrations are then adequate only for the specific test and do not constitute a general facility calibration. However, these calibrations should use the practices established in this document.

4. FACILITY PERFORMANCE TARGETS

Icing testing should be performed in facilities having measured, defined, and documented aerothermodynamic flow qualities, icing cloud qualities, and calibrated instrumentation. The facility should be calibrated in accordance with the time frames in Section 6 and the procedures in Section 7. The test section aerothermodynamics and icing cloud characteristics should be within the range of performance targets listed in Table 1 over the area of the uniform icing cloud. The uniform icing cloud is defined as the area of the test section over which the LWC does not vary by more than ±20% from the test section centerline LWC value for a given airspeed and water droplet size MVD.

Table 1 - Test section performance targets[(1)]

	Measurement Instrumentation Maximum Uncertainty	Tunnel Centerline Temporal Stability[(2)]	Spatial Uniformity[(3)]	Limit Value[(4)]	Test Section Calibrations (see Section 7)[(5)]
Aerothermodynamic Parameters					
True Airspeed[(6)(7)]	±1%	±2%	±2%	N/A	±1%
Total Air Temperature below -30 °C[(8)]	±2 °C	±2 °C	±2 °C	N/A	±2 °C
Total Air Temperature Between -30 and +5 °C[(8)]	±0.5 °C	±0.5 °C	±1 °C	N/A	±0.5 °C
Flow Angularity	±1.0°	N/A	±2°	±3°	N/A
Pressure Altitude	±50 m	±50 m	N/A	N/A	±50 m
Flow Turbulence					
(P_a-Off or minimum)[(9)]	±0.25%	N/A	<2%	2%[(11)]	N/A
(P_a-On at maximum)[(10)]	±0.25%	N/A	<2%	5%[(11)]	N/A
Cloud Parameters					
Liquid Water Content[(12)]	±10%	±20%	±20%	N/A	±10%
Median Volume Diameter[(13)]	±20%	±10%[(14)]	N/A	N/A	±20%
Relative Humidity	±3%	N/A	N/A	N/A	[(15)]

(1) These performance targets are for an empty test section and apply for otherwise uncorrected parameters (i.e., deviations from above may be allowed if the flow quality is sufficiently known to locally correct the conditions and/or results).

(2) Temporal stability is the time variation of the measurement over the duration of the test point (e.g., cloud exposure per 14 CFR Parts 25 and 29, Appendix C conditions) for each parameter. Temporal stability should be assessed at the geometric center (x,y,z) of the test section. The minimum time interval for establishing temporal stability is 30 seconds.

(3) Spatial uniformity is the recommended maximum allowable deviation of a temporal average at any point within the uniform icing cloud area relative to the temporal average at the centerline.

(4) Limit is the recommended maximum allowable value of any single measurement at any point within the uniform icing cloud area.

(5) Test section calibration relationships are required to relate facility instrument data to test section parameters measured at centerline during facility calibration (see Section 7). It is recommended that the calibration relationships align with the measured test section values within the limits specified in this column. This applies to airspeed, air temperature, altitude, liquid water content, and median volumetric diameter.

(6) In this document, airspeed is understood to be true airspeed, not indicated airspeed.

(7) For airspeed less than 40 m/s, instead of ±1% use ±0.4 m/s.

(8) Table 1 recommends total temperature performance targets rather than static temperature performance targets. This is because total temperature is a measured value, and most ground testing facilities control to total temperature. Static temperature, however, is a calculated value (refer to AIAA R-093-2003) and thus has greater potential for error. Further discussion can be found in the notes following Table 2.

(9) (P_a-Off) designates the spray nozzle atomization air is not flowing. If the operations are such that the facility never collects test data with air pressure completely off, they may instead run this test at the minimum air pressure at which the facility collects data.

(10) (P_a-On) designates the spray nozzle atomization air is set at the maximum pressure that may be used during regular facility testing. If hydraulic atomization nozzles are used, ignore this entry. Further information on measured effect of nozzle air pressure on turbulence intensity can be found in Henze and Bragg (1999).

(11) The flow turbulence intensity is defined in Chapter 10 of Jørgensen (2005).

(12) For LWC less than 0.2 g/m^3, use uncertainty of 0.02 g/m^3 instead of ±10%.

(13) For MVD less than 15 µm, use uncertainty of ±3 µm instead of ±20%.

(14) See 7.2.3 on time intervals for MVD measurements.

(15) This document gives no specified recommendation to measure the humidity values in the test section and correlate/calibrate it to the sensor measurement(s) that exist elsewhere within the facility (see 5.1.3). However, changes in humidity values can affect MVD and LWC values and may also have an effect on cloud uniformity. Facilities should either ensure that their humidity levels are consistent enough to not greatly impact these values or should be able to account for differences in their calibration that may be caused by the changes in humidity to maintain the parameter accuracy values specified in Table 1.

Accuracy and uncertainty are determined by a statistical process whereby measured data is analyzed by acceptable means. Wind-tunnel-specific assessment of data uncertainty is discussed in AIAA S-071A-1999 and AIAA G-045-2003. A textbook treatment on the topic of statistical method for the assessment of data uncertainty can be found in Coleman and Steele (1989). Temporal stability is defined as the variation of the parameter over the run. Uniformity is the spatial variation of the parameter over the cross-sectional area of the uniform icing cloud. The limits in the spatial uniformity column of Table 1 are applicable for parameters that are characteristics of a facility design and generally are not controlled.

In addition to the non-controlled performance parameters found in Table 1, the facility operator should also document the time to achieve spray bar system (both air and water pressure) stability. This performance feature of an icing wind tunnel does not lend itself to definition in Table 1. However, it is an important performance characteristic to document, as the operator has the responsibility to ensure that time to achieve a stable icing cloud is consistent with (generally much less than) the icing spray duration for a given test point. The spray can be considered “stabilized” when the temporal variations in air and water pressure values are small enough that the temporal variances in LWC and MVD are less than ±20% and ±10%, respectively, of their mean values (see Table 1). The operator should know the time required to stabilize the spray bar system to within ±2 seconds. If a test point requires a very short spray duration (i.e., less than 10 seconds), the spray stabilization time may comprise a substantial portion of the test time. In such cases, the facility operator may need to work with the test conductor to determine possible accommodations and/or corrections as needed. One example accommodation is to have a retractable shield over the test article that can be removed quickly after the spray is stabilized or, conversely, to insert the test article into the cloud after spray is stabilized.

5. INSTRUMENTATION

All instrumentation (sensors, transducers, and data acquisition systems) used in the facility for monitoring facility operation and for determining the aerothermodynamic and icing cloud properties should be traceable to the applicable national standards setting agency (National Institute of Standards and Testing, United States; National Research Council, Canada; Servizio di Taratura, Italy; etc.) and should be calibrated at least annually or in accordance with each facility-operator organization’s processes and procedures.

Standard instruments should be used for pressure and temperature measurements in the facility as well as the test section. This will enable the tunnel operator to vary the fan and heat exchanger controls to maintain the velocity and temperature in the test section within the set tolerance limits. Calibration relationships are generally built by relating test section measurements (see 5.2) to measurements from the facility-mounted instrumentation (see 5.1) using procedures described in Section 7.

5.1 Facility Instrumentation

The following sections provide information on the minimum instrumentation set for measuring tunnel total pressure, static pressure, total temperature, and humidity. Special care should be used in the selection of the instrumentation for an icing tunnel due to the icing conditions that will exist. Typically, heated probes are used to avoid measurement contamination due to ice buildup. Additionally, this section gives recommendations for the spray bars that create the liquid water spray.

5.1.1 Tunnel Temperatures

Two types of temperatures are commonly used to define the air temperature. Total temperatures are generally measured and used along with Mach number, M (determined from the measured total and static pressure that are described in 5.1.2), to determine the static temperatures, which are used as the defining temperature for icing conditions. Static temperature is also used to calculate the velocity of the tunnel. The equations used to determine static temperatures are described in NACA Report No. 1135, Equations 44 and 43, which are also given in Equations 1 and 2:

$$\frac{P_S}{P_T} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma}{\gamma - 1}} \quad \text{(Eq. 1)}$$

$$\frac{T_S}{T_T} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-1} \quad \text{(Eq. 2)}$$

where:

γ = ratio of specific heats

M = freestream Mach number

P_S = freestream static pressure

P_T = freestream total pressure

T_S = absolute freestream static temperature

T_T = absolute freestream total temperature

5.1.1.1 Total Temperature Probe

A total temperature probe is commonly located in the settling chamber near Station 1 of Figure 1; that is, downstream of the heat exchanger but upstream of the spray bars. It is recommended to install the total temperature probe upstream of the spray bars so that it does not need to be heated. A flow-through temperature probe that allows airflow to pass over the sensing element is recommended. In the settling chamber, since airspeed is generally low, recovery error corrections are generally not needed but can be performed. Temperature measurements inside a cloud in the test section are not generally part of the recommended practice of this document, but if a facility wants to attempt this (see 5.1.3.1), they will need to use a self-heated probe like that shown in Figure 3, and they will need to be familiar with the manufacturer's recommendations regarding the necessary temperature corrections, which may include recovery error, deicing heater error, and self-heating error.

Figure 3 - Example of total temperature probe

5.1.2 Tunnel Pressures

Two types of pressure measurements are required for determining the Mach number at the measurement location: total pressure and static pressure. These may be used to determine Mach number (see Equation 1). Mach number may then be used in combination with test section static temperature to determine velocity by using Equations 29b and 30 in NACA Report No. 1135, which are also given in Equations 3 and 4:

$$a = \sqrt{\gamma R T_S} \qquad \text{(Eq. 3)}$$

$$M = \frac{V}{a} \qquad \text{(Eq. 4)}$$

where:

a = speed of sound

R = gas constant

V = freestream velocity (i.e., true airspeed)

V = V_{TS} (freestream test section velocity) if the pressure and temperature values used to obtain it are the test section pressure and temperature values (see 7.1.2)

Individual total and static pressure probes or a combined pitot-static probe may be used for pressure measurements. Aircraft-type probes, similar to that shown in Figure 4, are generally used. Facility pressure probes need to be heated to avoid measurement contamination due to ice buildup. Further recommendations regarding pressure instrumentation for wind tunnel testing can be found in Chapters 4 and 6 of Barlow et al. (1999).

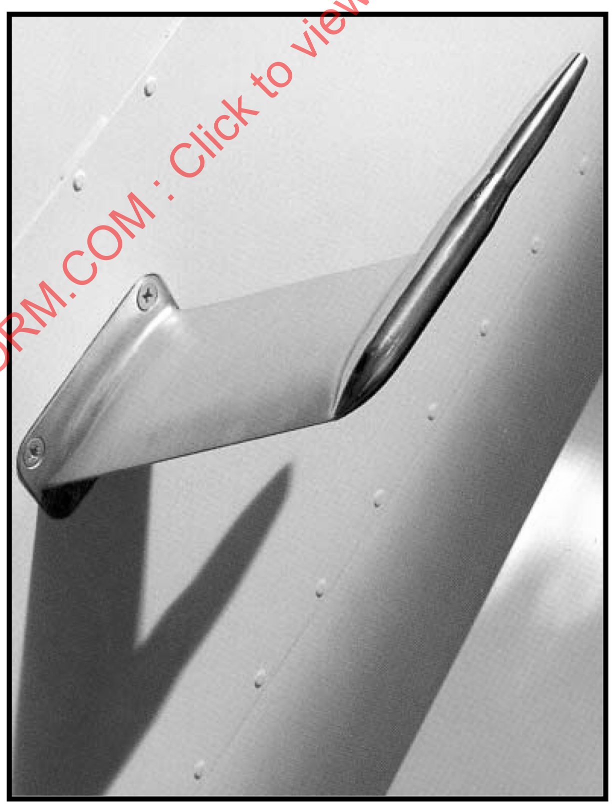

Figure 4 - Example of total pressure probe

5.1.2.1 Total Pressure

Total pressure, P_T, may be measured in the settling chamber upstream of the test section (see Station 2 in Figure 1) using a total pressure probe (see Figure 4) or upstream of the test article in the constant area of the test section (see Station 3 in Figure 1) using a pitot-static probe, in accordance with standard wind tunnel practice. Facility pressure probes need to be heated to avoid measurement contamination due to ice buildup.

5.1.2.2 Static Pressure

Static pressure, P_S, may be measured in the test section upstream of the test article in the constant area of the test section, Station 3, using a static pressure probe (see Figure 5), a pitot-static pressure probe, or a sidewall pressure tap in accordance with standard wind tunnel practice. Tunnel attributes should be considered to select the most appropriate P_S measurement method. Facility pressure probes need to be heated to avoid measurement contamination due to ice buildup; facilities that use sidewall pressure taps should be aware this may be an issue. Sidewall static pressure taps should be far enough upstream of the test section that model blockage won't impact measurement. Further considerations regarding sidewall static pressure taps near the wind tunnel test section can be found in Chapter 6 of Barlow et al. (1999).

Figure 5 - Example of static pressure probe

5.1.3 Humidity

Several test section parameters may be influenced by variations in humidity, including liquid water content (LWC) and drop size (both size distribution and MVD). This is true for both open- and closed-circuit facilities. Closed-circuit facilities often experience a near constant humidity (often near saturation) after a number of sprays of liquid water into the airstream. Such facilities should be aware of how much (spray) time it takes to reach near saturation, i.e., when LWC and MVD values remain constant and consistent with expected values. It is recommended that closed-circuit facilities measure the dew/frost point temperature at a plane just upstream of the water injection plane.

Since open-circuit tunnels are more likely to have drier air, evaporation is expected to occur between the injection location and the measurement plane and can thus have a significant impact on the measurement plane parameters (e.g., LWC and MVD). Thus, open-circuit facilities should monitor humidity closely in order to improve LWC and MVD prediction at the measurement plane. It is recommended that open-circuit facilities measure the relative humidity at a plane just upstream of the water injection plane and at the desired LWC measurement plane in order to facilitate a prediction of the impact on LWC due to any evaporation of the injected liquid water. If open-circuit facilities opt to only measure humidity just upstream of the injection plane and use that to predict humidity at the test section, these predictions should be validated by testing at a range of humidity, airspeed, and (if applicable) air pressure values. Facilities should also note that humidity measurements have been found to vary with sensor location in the same measurement plane. Some options for analysis tools that can be used to predict humidity changes and humidity effects on icing tunnel air and water properties are discussed in Schulz (1998) and Bartkus et al. (2015). Another analysis tool from NRC-Canada is discussed in Davison (2023).

There are several measurement technologies available to determine humidity in an airstream. One such technology is a chilled mirror dew/frost point measurement system. Correct determination of humidity via chilled mirror measurement systems may be somewhat cumbersome and involved to perform correctly. The resulting accuracy of a laboratory-grade chilled mirror measurement system on dew or frost point, however, is typically on the order of ±0.1 °C. The measured dew/frost point temperature is then applied with other required airstream measurements, such as static temperature, to determine the corresponding stream relative humidity. While chilled mirror systems can be very accurate, they have very long response times that are not always suitable in dynamic environments. Capacitive solid-state relative humidity sensors may also be employed to measure relative humidity directly. It is highly recommended, however, to ensure that the calibration of a capacitive humidity sensor is performed in the operating range, both pressure and temperature, for which it is expected to perform its measurement. It has been shown that there can be excellent correspondence between chilled mirror determined relative humidity and capacitive measurement system determined relative humidity. A third technology is IR absorption, which measures specific humidity (mass of water/mass of dry air). It is independent of pressure and temperature and has a very fast response time on the order of seconds. The facility operator should select the best technology for their particular application.

5.1.3.1 Potential Humidity Effects on Air Temperature Inside a Cloud

Some wind tunnel users have reported changes in test section air temperature compared to the pre-spray value if there is a substantial amount of either evaporation or condensation between the spray bars and the test section. Measurements presented in Struk et al. (2019), Agui et al. (2019), and Struk et al. (2018) showed a significant decrease in air total temperature at the test section in low-humidity environments due to the effect of the thermal energy exchange that happens as the water particles evaporate. Furthermore, Whalen and Matheis (2019) reported seeing air temperatures increase when relative humidity near the spray bars is high, particularly when test section altitude is high, liquid water content is high, and tunnel airspeed is high (higher speed means lower static air temperature, meaning less capacity for the air to hold water vapor). If a test is likely to be affected by a few degrees difference in air temperature and the test fits either of the above combinations of conditions, then test conductors may want to consider trying to measure if there is a temperature difference caused by the cloud in a high/low humidity environment. However, it should be noted that there is currently no publicly available instrumentation that can measure the air temperature inside a cloud of supercooled liquid water drops to the accuracy levels that are given in Table 1, and the temperature deltas that are measured may be on a similar order of magnitude as instrumentation accuracy.

5.1.4 Spray Bar Instrumentation and Heating

The liquid water content (LWC) and droplet size (MVD) of the tunnel icing cloud are primarily a function of water mass flow rate delivered to the spray system nozzles and the air pressure supplied to atomize the water. It is assumed that nozzles used are the mixing type; that is, both air and water are supplied. Typical practice is to calibrate the spray system by relating measurements of LWC and droplet size MVD observed in the tunnel test section to air and water pressure (or flow rate) settings maintained at the spray bars. Once calibrated, it is assumed that particular settings will repeatably deliver an icing cloud of the same LWC and droplet size MVD. Increased confidence in the stability of the calibration is obtained by following established/appropriate maintenance procedures, such as nozzle cleaning, and periodic visual check inspections of individual nozzle spray patterns.

5.1.4.1 Instrumentation Application

Typically, a number of spray bars are positioned upstream of the tunnel test section in the settling chamber, equally spaced and spanning the chamber horizontally; see Figure 1 (tunnel schematic). A number of nozzles are usually installed in each spray bar at locations determined to provide the desired spray coverage and uniformity.

Dedicated instrumentation should be used for each spray bar to monitor and control the water and air delivered. Care should be taken in spray bar and plumbing design to assure that air and water pressure drops between the first and last nozzles in the bar are not significant enough to result in different spray characteristics.

Instrumentation to monitor the spray parameters and provide information for controls (e.g., water and air pressures, flow rates, and temperatures) should be located as close to the spray bar inlet as practical. Once the spray system is calibrated, the location of instrumentation should not be changed. This is especially true for water pressure measurement instrumentation, where a change in elevation could result in an appreciable offset of measured pressure.

5.1.4.2 Measured Parameter Alternatives

There are three commonly used methods for controlling spray bar nozzle performance. No particular alternative is preferred over the other but are rather nozzle design dependent. Alternative 1 is to measure spray bar air and water pressure independently. Alternative 2 is to monitor air pressure and the differential pressure between water and air. This alternative is typically more convenient and direct than alternative 1 as the nozzle MVD output is usually expressed as a function of differential pressure.

Alternative 3 is to monitor air pressure and water flow rate. Flow rate may be measured with a rotameter, turbine flow meter, or similar device. As with transducers used to measure pressure, meter selection should consider accuracy and resolution requirements over the intended operating range.

5.1.4.3 Spray Bar Air and Water Heating

Air and water delivered to the nozzles usually must be heated to prevent freezing of water in the lines and to prevent freeze-out of droplets. The air-droplet mixture experiences a decrease in temperature as it expands upon release from the nozzle. Heating the air and water prior to release compensates for this temperature drop. The concern with insufficient heating is that a portion of the water may freeze out, lowering the LWC such that pressure or flow settings established during calibration result in less LWC than assumed.

It is therefore recommended that spray bar air and water be heated and that temperatures be monitored. Monitoring instrumentation should be accurate to ±2 °C (±3.6 °F). Temperatures required may vary among facilities and even within a facility depending on the icing condition being produced. Air and water need not be heated to the same temperature. Typical heated temperatures range from 45 to 100 °C (113 to 212 °F), with temperatures at the high end of the range more likely to be needed at higher nozzle air pressures. Appendix A gives a recommended test procedure for determining the correct air and water temperature settings to minimize freeze-out and also check for sufficient droplet supercooling. For further understanding of test section particle temperature, it is recommended that an analysis of droplet temperature for the particular test condition and facility geometry be conducted using methods similar to Willbanks and Schulz (1973) and/or Schulz (1998).

5.1.4.4 Instrumentation Accuracy

The spray bar instrumentation should be selected and operated such that the root sum square (RSS) error contribution from instrumentation equates to less than 2.5% uncertainty in the LWC produced and less than 3.5% uncertainty in the droplet distribution median volume diameter (MVD) produced.

There are a number of suitable approaches for instrumenting spray bars, so selection of instruments and error budgeting among them can vary considerably. Each facility should analyze and select instrumentation that is most appropriate.

5.2 Calibration Instrumentation

The instrumentation described herein is to be used for calibration described in Section 7 and does not imply required usage during testing.

For aero-thermal calibration, standard wind tunnel instrumentation probes should be used to measure the total temperature, total pressure, static pressure, and flow angularity distributions. These probes should be suited to handle the range of conditions described in Tables 2A and 2B, with uncertainty values within those described in Table 1. Aero-thermal calibration is typically conducted with the cloud off (at a range of nozzle air pressures described in Tables 2A and 2B).

5.2.1 Pressure Calibration Instrumentation

A pressure survey device (e.g., an array, or a rake similar to the one shown in Figure 6) may be used during the aerodynamic calibration for measurement of velocity and flow angularity. Each facility is responsible for designing a survey device suitable for that facility that can be used to meet the recommendations specified in Section 7. The probes should be calibrated for the operating range of the facility, and they should be able to achieve the measurement uncertainty recommendations in Table 1 for airspeed and flow angularity. If the facility controls altitude, the probes should also be able to achieve the recommended pressure altitude uncertainty specified in Table 1.

The pressure measurements from test section centerline location are to be used for calibration relationships indicated by the last column of Table 1 (see 7.1.2). The additional measurement locations are used to determine spatial distribution of parameters indicated in Tables 1 and 2.

AIAA R-093-2003 is a good resource for the aero-thermal calibration of subsonic wind tunnels, although it is targeted toward non-icing wind tunnels.

Figure 6 - Example of pressure calibration rake

5.2.2 Temperature Calibration Instrumentation

A temperature calibration survey device (e.g., a rake, or an array similar to the one shown in Figure 7) should be used during the thermodynamic calibration for measurement of total temperature distribution. Each facility is responsible for designing a calibration survey device suitable for that facility that can be used to meet the recommendations specified in Section 7. A temperature calibration array is recommended over a rake or a traversing system because test section temperature distributions may distort as the test day progresses and simultaneous measurements are more likely to capture the overall temperature distribution. A characterization array removes any uncertainty caused by the additional variables introduced by operating a characterization rake multiple times in varying locations. The simultaneous nature of data collected with a characterization array provides a significantly more complete understanding of flow uniformity. If a characterization rake or traversing system is used, an emphasis on data normalization, settling times of facility and characterization instrumentation, and conditional accuracy are recommended.

Figure 7 - Example of total temperature calibration array

Total temperature sensors using either copper/constantan wires (Type T), chrome/alumel wires (Type K) or platinum RTDs should be used in the calibration survey device. RTD's have higher accuracy, but if thermocouples are used, Type T is generally preferred over Type K for low-temperature applications such as expected from an icing tunnel. A flow-through temperature probe that allows airflow to pass over the sensing element is recommended. The probes should be calibrated for the operating range of the facility and they should be able to achieve the recommended temperature measurement uncertainty specified in Table 1.

The temperature measurements from test section centerline location are to be used for calibration relationships indicated by the last column of Table 1, as described in 7.1.1. The additional measurement locations are used to determine spatial distribution of parameters indicated in Tables 1 and 2.

AIAA R-093-2003 is a good resource for the aero-thermal calibration of subsonic wind tunnels, although it is targeted toward non-icing wind tunnels.

5.2.3 Turbulence Instrumentation

A standard hot wire anemometer rake using single element and/or cross wire probes may be used in the measurement of dry air turbulence of the test section. Figure 8 depicts the configuration of an example hot wire anemometer rake. The individual probes may be mounted on a common mount as shown or spanwise along a calibration rake that spans the test section. Other commonly accepted methods, such as fast-response pressure probes, may be used to measure turbulence.

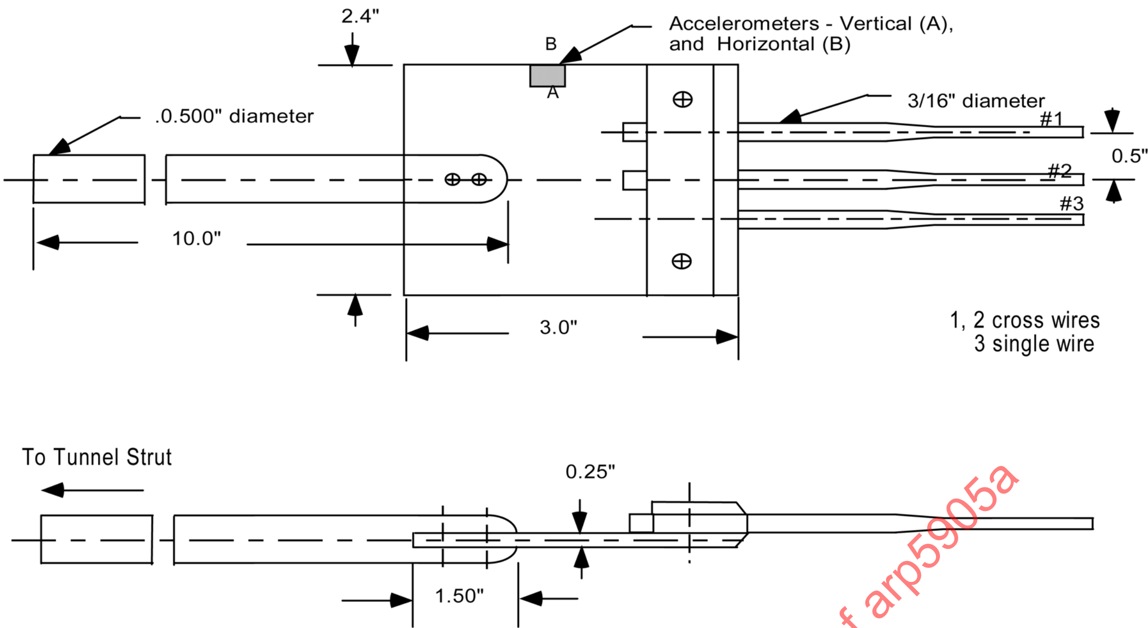

Figure 8 - Example of hot wire anemometer instrumentation probe

5.2.4 Droplet Size Measurement System

Water droplet size distributions and median volumetric droplet diameters (MVD) should be measured between Stations 3 and 4 of the test section (see Figure 1) using one or more of the commonly accepted instruments described in AIR4906. Drop-sizing probes work using various techniques, including light-scattering, diode shadowing, particle imaging, and phase-doppler interferometry. Any probe that is used must be calibrated before using it. It is highly recommended that the user take time to familiarize with the instrument's operation and understand how its strengths and weaknesses might play out in their facility's test environment. More information on particle size distributions (PSDs) is given in Appendix D.

5.2.5 Liquid Water Content (LWC)

LWC should be measured at the geometric center of the tunnel at Station 4 (see Figure 1). Measurement techniques include unheated ice accretion, heated element, or evaporation. Refer to AIR6977 for details on LWC instrumentation options, including the strengths and weaknesses of different techniques and instruments. Test models are not installed in the tunnel when using these measurement devices.

5.2.6 Bulk Liquid Water Content

An alternate method used in engine test facilities for determining LWC with a model installed in the test section is based upon bulk water flow rate corrected for evaporation. The bulk LWC required establishes the bulk water flow rate based upon:

$$\omega_{wB} = K\ LWC_B\ V_{TS}\ A \quad \text{(Eq. 5)}$$

where:

ω_{wB} = bulk water flow rate

V_{TS} = freestream test section velocity

A = flow area

K = unit conversion factor

= 1×10^{-3} with ω_{wB} in kg/s, LWC_B in g/m^3, V_{TS} in m/s, and A in m^2

= 4.488×10^{-4} with ω_{wB} in US gal/min, LWC_B in g/m^3, V_{TS} in ft/s, and A in square feet

The bulk water flow rate is corrected for evaporation. This is done by calculating the amount of water evaporated based upon absolute humidity, ambient temperature, initial temperature of the water injected, air and water velocities, cell configuration, and the droplet spectrum. The bulk water flow rate is measured with calibrated turbine flow meters in a closed-circuit control scheme.

5.2.7 Cloud Uniformity

Cloud uniformity should be measured at Station 4 (see Figure 1) using the icing calibration grid (see Figure 9) or through measurements of LWC at a matrix of points across the test section using one of the instruments mentioned in AIR6977. The spacing of the grid or matrix should be related to the size of the tunnel test section. Facilities may also choose to use a tomography ring or laser sheet to measure cloud uniformity. See 7.2.2 for further details on measuring icing cloud uniformity.

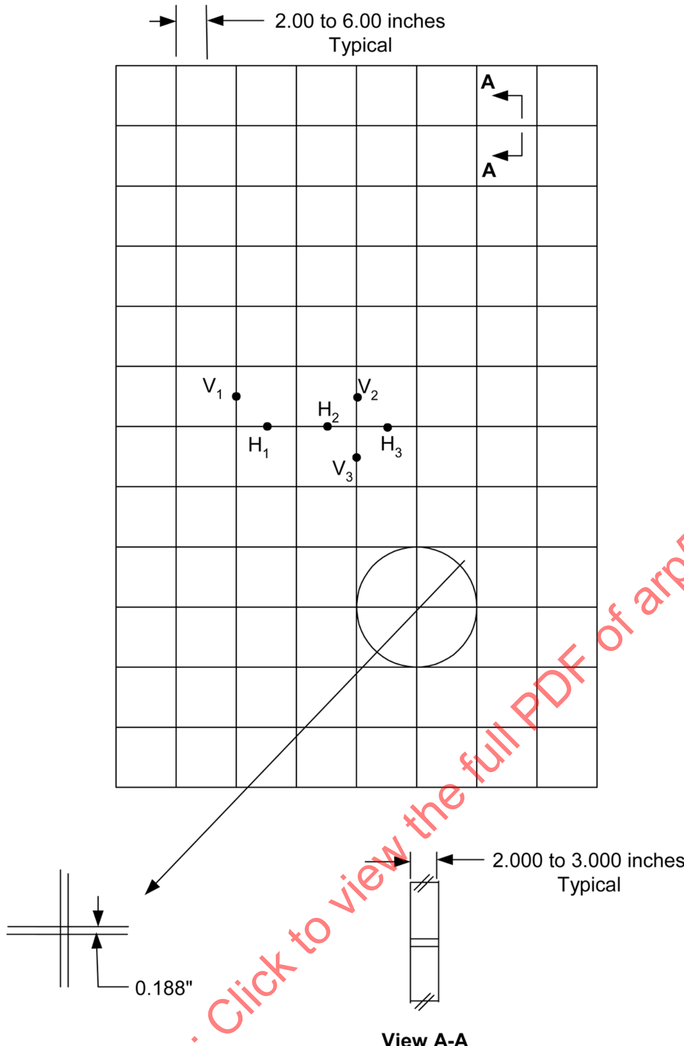

Figure 9 - Example of icing cloud calibration grid

6. FACILITY CALIBRATION

A facility should be in calibration when performing certification tests. The intent of the calibration is to establish a history on the repeatability of the facility with respect to relevant aero-thermal and icing-related parameters over long periods, beginning from the date of commissioning.

Three types of calibration should be performed for each facility. They include: baseline calibration, interim calibration, and check calibration.

6.1 Baseline Calibration

The baseline calibration should be a full calibration of the facility and will include an aero-thermal calibration and icing cloud calibration as defined in 7.1 and 7.2. Full calibrations are required on initial commissioning or following any major facility modifications that change the aero-thermal characteristics or icing cloud, such as replacement of the heat exchanger, test section, spray bar systems, etc. As a minimum, baseline calibrations should be performed on a 5-year interval.

6.2 Interim Calibration

The interim calibration should be performed sometime between 1 and 2 years after the baseline calibration resulting from initial commissioning or a major change to the facility. The interim calibration should include, as a minimum, confirmation that the following parameters have not changed from the baseline calibration by repeating tests using a representative number of test conditions that span the operating conditions. These parameters include: (a) icing cloud uniformity, (b) tunnel axial centerline LWC measurements, (c) a model-relative spanwise measurement of the total and static pressure and total temperature at the model test station, and (d) tunnel axial centerline MVD.

If the interim calibration indicates a shift in tunnel performance from the established baseline calibration by values greater than the values in Table 1, the facility operator should correct the problem(s) and repeat the interim calibration. If the out-of-tolerance condition still exists, then the full calibration is required to reestablish a baseline after the operator has ensured system stability.

6.3 Check Calibration

The check calibration should be performed every 6 months, except when it is superseded by a baseline or interim calibration. The check calibration consists of measurements of icing cloud uniformity and centerline LWC measurements over a representative sampling of uniformity and LWC measurements from the baseline calibration. If the check calibration indicates a shift in tunnel performance from the established baseline calibration values greater than the values in Table 1, the problem should be corrected and the check calibration repeated. If the out-of-tolerance condition still exists, then the full calibration is required to reestablish a baseline after the operator has ensured system stability.

6.4 Ice Shape Continuity Check

A model may be tested during, or before and after, the above calibration tests to assess changes or stability of the tunnel's ice accretion characteristics. When commissioning a new facility, the ice shape test is used to establish reference ice shapes on an operator-owned model. The selection and design of the model is left to the discretion of the tunnel operator, as well as the set of icing conditions that may be used in this ice shape comparison test.

7. CALIBRATION PROCEDURES

The calibration procedures for the facility should be numbered, released, and maintained under company configuration (change) control procedures commonly accepted by the aerospace industry and the regulatory authorities.

The facility should perform an aero-thermal and icing cloud calibration per the time frames defined in Section 6 to demonstrate that the facility, instrumentation, and procedures continue to produce acceptable data. The calibration should cover the area of the test section where tests are performed in the facility. The calibration should cover the area of the test section where the LWC spatial uniformity defined in Table 1 is met.

7.1 Aero-Thermal Calibration

A dry air aero-thermal calibration should be conducted to determine the basic airflow qualities of the facility. The flow properties to be documented should be:

a. Centerline airspeed calibration

b. Centerline air temperature calibration

c. Airspeed distribution

d. Temperature distribution

e. Flow angularity distribution

f. Turbulence intensity distribution

g. Effects of testing at altitude (if applicable)

Each facility should develop a test matrix applicable for their intended operation range. The calibration matrix should, as a minimum, include:

a. An aerodynamic calibration consisting of: centerline static and total pressure calibration measurements and spatial distribution measurements of velocity, flow angularity, and turbulence at ambient temperature (or warmest controllable temperature) as in Table 2A. If the facility utilizes altitude testing capabilities, an aerodynamic calibration should be applicable to the range of total pressures or altitudes that the facility can achieve. Facilities with altitude capabilities should determine the centerline calibrations for airspeed and air temperature at the altitude range values given below. If the facility has completed measurements that show the spatial distribution of the airspeed, temperature, turbulence, and flow angularity do not vary with changing altitude by more than the performance targets in Table 1, then routine spatial distribution measurements are not necessary.

b. A thermodynamic calibration consisting of centerline temperature calibration measurements and temperature surveys at four temperatures spanning the range 0 to -30 °C (32 to -22 °F) or the minimum operating temperature to be used for tests as found in Table 2B.

Table 2A - Minimum test matrix for aerodynamic calibration

Vertical Position (Waterline) %(1)(3)	Horizontal Position (Buttock Line) %(2)(3)	Spray Bar Air Pressure(4)	Tunnel Total Air Temperature(5)	Test Section Velocity % of operating range	Tunnel Total Pressure or Test Section Altitude (if applicable) % of operating range(6)
0, ±25, ±50, ±75	0, ±25, ±50, ±75	Zero or Minimum, Maximum	Ambient	0, 33, 67, 100	0, 33, 67, 100

(1) The horizontal geometric centerline of the tunnel is waterline 0. Vertical position is the percentage of the distance from the horizontal geometric centerline to the tunnel floor or ceiling.

(2) The vertical geometric centerline of the tunnel is buttock line 0. Horizontal position is the percentage of the distance from the vertical geometric centerline to the tunnel wall.

(3) Note the ±25, ±50, ±75 should be of the distance across the test section, not the distance of the cloud uniformity. However, it may be recommended to increase measurement refinement, particularly if the facility's cloud is notably smaller than the test section area. As stated in Section 4, the aero-thermal performance requirements that were given in Table 1 only need to be met within the region of the uniform cloud (with ±20% LWC).

(4) Spray bar maximum air pressure is the maximum air pressure used for the facility's operating envelopes. Spray bar air temperature should be set at the nominal operating temperature. For guidance on determining the facility's nominal spray bar operating temperature, see Appendix A. Spray bar air pressure of zero designates the spray nozzle atomization air is not flowing. If the operations are such that the facility never collects test data with air pressure completely off, they may instead run this test at the minimum air pressure at which the facility collects data.

(5) These tables recommend total temperature targets rather than static temperature targets because, for most icing facilities, total temperature is the controlled parameter. Total temperature is measured directly, while static temperature is determined as a function of total temperature and Mach number (refer to AIAA R-093-2003). Thus, static temperature has greater potential for error. However, temperature may be tested either as a range of available total temperatures or a range of static temperatures. Since 14 CFR Parts 25 and 29, Appendix C requirements are specified in terms of static temperature, it may be preferred to set increments of static temperature to make the data easier to apply. The maximum total temperature is typically something close to the local facility ambient temperature. The minimum total temperature will likely be a function of cooling plant capacity and will potentially vary with airspeed. A facility's minimum total temperature may also be limited by particle freeze-out (i.e., approaching a static air temperature of -40 °C) or of water freezing inside the spray nozzles, inhibiting spray.

(6) Altitude can be tested either as a range of available total pressures or a range of available altitudes. For most icing facilities, the total pressure is the controlled parameter and altitude is determined as a function of total pressure and Mach number (i.e., similar to static temperature). Furthermore, the maximum total pressure is typically something close to the local facility ambient pressure. However, while tunnel dynamics tend to be defined by the total pressure, it may be preferred to set increments of altitude to make the data easier to apply.

Table 2B - Minimum test matrix for thermodynamic calibration

Vertical Position (Waterline) %(1)(3)	Horizontal Position (Buttock Line) %(2)(3)	Spray Bar Air Pressure(4)	Tunnel Total Air Temperature °C (°F)(5)	Test Section Velocity % of operating range	Tunnel Total Pressure or Test Section Altitude (if applicable) % of operating range(6)
0, ±25, ±50, ±75	0, ±25, ±50, ±75	Zero or Minimum, Maximum	10, -6, -18, minimum (50, 22, 0, minimum)	0, 33, 67, 100	0, 33, 67, 100

(1) The horizontal geometric centerline of the tunnel is waterline 0. Vertical position is the percentage of the distance from the horizontal geometric centerline to the tunnel floor or ceiling.

(2) The vertical geometric centerline of the tunnel is buttock line 0. Horizontal position is the percentage of the distance from the vertical geometric centerline to the tunnel wall.

(3) Note the ±25, ±50, ±75 should be of the distance across the test section, not the distance of the cloud uniformity. However, it may be recommended to increase measurement refinement, particularly if the facility's cloud is notably smaller than the test section area. As stated in Section 4, the aero-thermal performance requirements that were given in Table 1 only need to be met within the region of the uniform cloud (with ±20% LWC).

(4) Spray bar maximum air pressure is the maximum air pressure used for the facility's operating envelopes. Spray bar air temperature should be set at the nominal operating temperature. For guidance on determining the facility's nominal spray bar operating temperature, see Appendix A. Spray bar air pressure of zero designates the spray nozzle atomization air is not flowing. If the operations are such that the facility never collects test data with air pressure completely off, they may instead run this test at the minimum air pressure at which the facility collects data.

(5) These tables recommend total temperature targets rather than static temperature targets because, for most icing facilities, total temperature is the controlled parameter. Total temperature is measured directly, while static temperature is determined as a function of total temperature and Mach number (refer to AIAA R-093-2003). Thus, static temperature has greater potential for error. However, temperature may be tested either as a range of available total temperatures or a range of static temperatures. Since 14 CFR Parts 25 and 29, Appendix C requirements are specified in terms of static temperature, it may be preferred to set increments of static temperature to make the data easier to apply. The maximum total temperature is typically something close to the local facility ambient temperature. The minimum total temperature will likely be a function of cooling plant capacity and will potentially vary with airspeed. A facility's minimum total temperature may also be limited by particle freeze-out (i.e., approaching a static air temperature of -40 °C) or of water freezing inside the spray nozzles, inhibiting spray.

(6) Altitude can be tested either as a range of available total pressures or a range of available altitudes. For most icing facilities, the total pressure is the controlled parameter and altitude is determined as a function of total pressure and Mach number (i.e., similar to static temperature). Furthermore, the maximum total pressure is typically something close to the local facility ambient pressure. However, while tunnel dynamics tend to be defined by the total pressure, it may be preferred to set increments of altitude to make the data easier to apply.

In both Tables 2A and 2B regarding velocity and total pressure test matrix conditions, tests should be repeated at a minimum of four equally spaced values over the intended operating range. An example is: minimum operating velocity = 50 kt and maximum operating velocity = 250 kt; then the calibration velocities would be 50 kt, 117 kt, 183 kt, and 250 kt and likewise for facility total pressure values. Additional data points for temperature, velocity, and total pressure may be taken at the discretion of the facility operator.

7.1.1 Centerline Total and Static Air Temperature Calibration

The tunnel centerline total temperature calibration measurements should be collected by positioning the instrumentation temperature sensor (thermocouple or RTD) at the geometric center of the test section and taking total temperature measurements at the velocities, temperatures, total pressures (or altitudes) and spray bar air pressures specified in Table 2B. Additional measurements may be taken at the discretion of the facility operator. These measurements along with the facility total temperature measurements can then be used to determine the tunnel centerline total temperature calibration. The calibrated static temperature in the test section should be calculated using the calibrated test section total temperature as well as the calibrated test section total and static pressures using Equations 1 and 2.

7.1.2 Centerline Total and Static Pressure Calibration

The tunnel centerline total and static pressure calibration measurements should be collected by positioning the instrumentation pitot-static probe at the geometric center of the test section and taking measurements at the velocities, nozzle air pressures, and tunnel total pressures (or altitudes) specified in Table 2A. Additional measurements may be taken at the discretion of the facility operator. These measurements along with the facility total and static pressure measurements (see 5.1.2) can then be used to calculate the tunnel centerline velocity calibration.

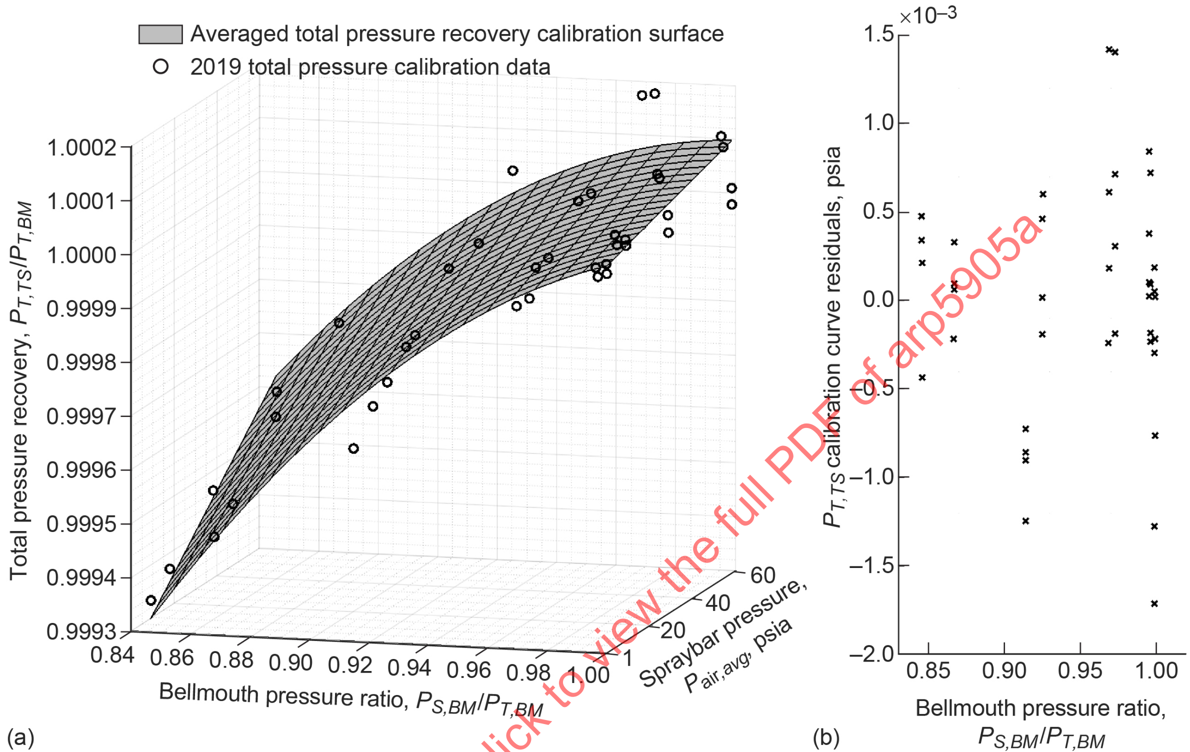

Figure 10 - Example of centerline total pressure calibration data

The ratio of the centerline total pressure to the facility total pressure is used to compute the calibrated total pressure; an example of this is shown in Figure 10 (for a single total pressure) (refer to Rinehart and Johnson, 2020). The ratio of the centerline static pressure to the facility static pressure is used to compute the calibrated static pressure; an example of this is shown in Figure 11 (for a single total pressure) (refer to Rinehart and Johnson, 2020). The calibrated total pressure and calibrated static pressure are then used to determine calibrated Mach number using Equation 1. Calibrated Mach number is then used along with calibrated static air temperature (see 7.1.1) to determine the calibrated freestream tunnel velocity using Equations 3 and 4.

NOTE: Using Bernoulli's principle to determine velocity directly from total and static pressure only applies to incompressible flow and is not recommended above Mach 0.3.

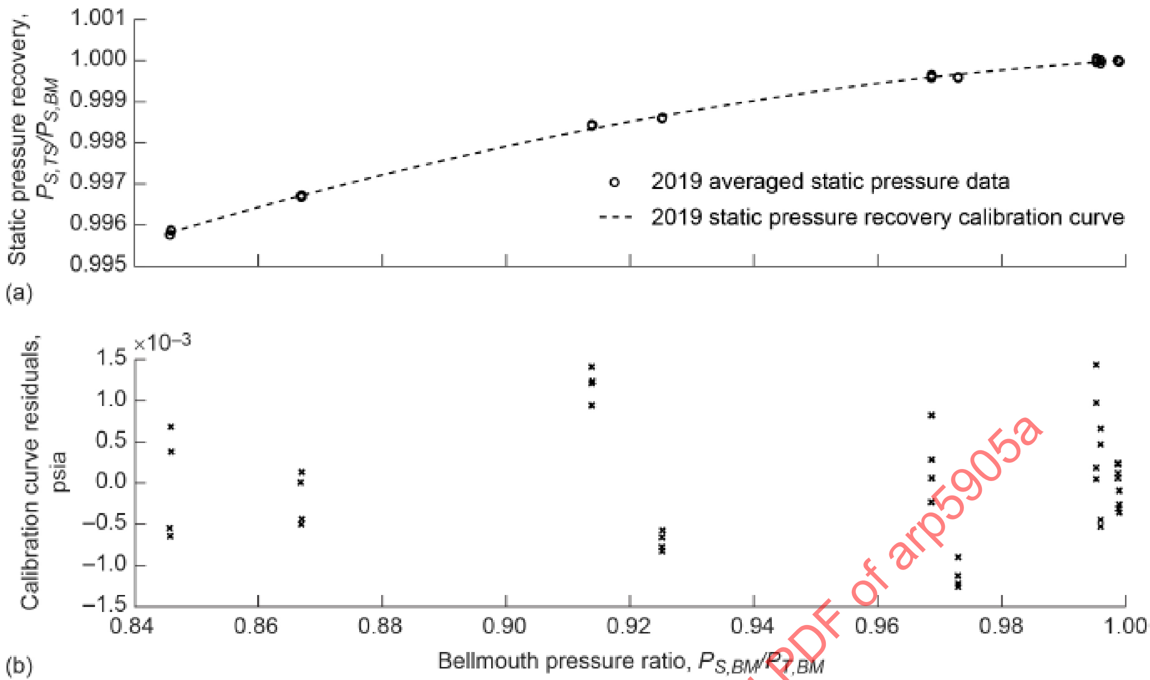

Figure 11 - Example of centerline static pressure calibration data

7.1.3 Airspeed and Clean Tunnel Flow Angularity Distribution

The test section velocity and flow angularity measurements should be collected at each intersection of the water line and buttock lines and for the velocities, spray bar air pressures, and total pressures (or altitudes) specified in Table 2A. The data should be obtained by positioning the instrumentation pressure/temperature survey device at each specified water line and buttock line position. The data sampling rate and duration should be such that it yields a statistically stationary value.

If the facility has altitude capability, velocity and flow angularity distribution measurements should be completed across the full range of facility altitudes at least once to determine if the spatial distribution of the velocity or flow angularity varies with changing altitude. If the variation is less than the performance targets in Table 1, then routine spatial distribution measurements at different altitudes are not necessary.

7.1.4 Turbulence Intensity Distribution

Turbulence measurements should be taken at the spatial locations where models are typically installed (for example, along a typical aircraft wing model spanwise direction over the length of the model). Measurement location spacing is left to the discretion of the tunnel operator. Subject to limitations of the measurement device, these measurements should be taken at the velocities, spray bar air pressures, and total pressures (or altitudes) specified in Table 2A. The data sampling rate and duration should be such that they yield a statistically stationary value. It is not required that turbulence intensity data be obtained at all of the spatial locations that pressure and temperature are obtained.

If the facility has altitude capability, turbulence distribution measurements should be completed across the full range of facility altitudes at least once to determine if the spatial distribution of the turbulence varies with changing altitude. If the variation is less than the performance targets in Table 1, then routine spatial distribution measurements at different altitudes are not necessary.

7.1.5 Temperature Distribution

The test section temperature measurements should be collected at the intersection of the water line and buttock lines and at the temperatures, velocities, spray bar air pressures, and total pressures specified in Table 2B. The data should be obtained by positioning the instrumentation temperature survey device at the specified water line and buttock line position. The data sampling rate and duration should be such that they yield a statistically stationary value.

If the facility has altitude capability, temperature distribution measurements should be completed across the full range of facility altitudes at least once to determine if the spatial distribution of the temperature varies with changing altitude. If the variation is less than the performance targets in Table 1, then routine spatial distribution measurements at different altitudes are not necessary.

7.2 Icing Cloud Calibration

An icing cloud calibration should be conducted to determine the basic icing cloud characteristics of the facility. Instrumentation required for measuring cloud characteristics are discussed in 5.2. Further description of liquid water content instruments is given in AIR6977, and further description of drop-sizing instruments is given in AIR4906.

Icing cloud calibration consists of measuring test section centerline droplet size MVD and LWC as well as LWC uniformity as a function of spray bar air and water settings and tunnel airspeed. The order in which the three measurements are made should be determined by considering the dependencies of each parameter on the others. Spray nozzles should be calibrated before establishing cloud uniformity, which should be completed before calibrating the MVD and cloud liquid water content.

7.2.1 Nozzle Calibration

The nozzle calibration should include air and water flow characteristics. For external mix spray nozzles, this should include dimensionless discharge coefficients $C_{d\,a}$ and $C_{d\,w}$, since the atomization gas flow and the liquid flow are uncoupled. However, for internal mix nozzles, it is generally necessary to characterize the nozzle flows based upon $C_{d\,a}$, $C_{d\,w}$, and $C_{d\,w/a}$, where $C_{d\,w/a}$ is the liquid flow characteristic in the presence of gaseous flow, or develop a combined liquid/gas flow coefficient. When a new spraying system is being installed, the original set of nozzles is calibrated and selected based on a maximum deviation of 3 to 5%. From the point that the cloud uniformity is established and the nozzle configuration is documented, if a nozzle goes bad, then the replacement nozzle should have a flow coefficient matching as closely as possible (generally 2% or less) to the one being replaced.

For facilities that control individual nozzles based on air pressure and water flow rate, it may not be necessary to ensure that flow coefficient is matched since flow rate is being directly monitored. However, care should be taken that replacement nozzles have the same droplet spray pattern as the nozzle being replaced. In this case, matching of nozzle flow coefficient would be sufficient. However, other testing such as bench testing of nozzle MVD versus air pressure and flow rate would also be sufficient.

For external mix spray nozzles, the dimensionless discharge coefficient is more appropriate than a flow coefficient and is defined as the ratio of actual flow versus ideal flow. For external mix nozzles, there exists only two discharge coefficients, $C_{d\,a}$ and $C_{d\,w}$, and both are required since the liquid and gas flows are independent within the nozzle. Therefore, the atomization gas flow and the liquid flow are uncoupled. If the nozzle is operated with an upstream to ambient air pressure ratio of:

$$\frac{P_a}{P_S} > 1.893 \qquad \text{(Eq. 6)}$$

then the flow through the orifice will be choked and the gas discharge coefficient will be given by:

$$C_{d\ a} = K \frac{\omega_a}{\frac{\pi}{4} d_o^2 \frac{P_a}{\sqrt{T_{Ta}}}} \qquad \text{(Eq. 7)}$$

where:

ω_a = air mass flow rate

d_o = orifice diameter

P_a = nozzle absolute total air pressure

T_{Ta} = nozzle absolute total air temperature

K = unit conversion constant

= 1.8804 for air with ω_a in lbm/s, d_o in inches, P_a in psia, T_{Ta} in °R

= 2.474 x 10^{-2} for air with ω_a in kg/s, d_o in m, P_a in kPa, T_{Ta} in K

The discharge coefficient for the liquid is based upon incompressible flow and the assumption that the approach diameter is much greater than the orifice diameter (i.e., D>>d_o such that $\left(\frac{d_o}{D}\right)^4 \approx 0.0$), and is defined as:

$$C_{dw} = K \frac{\omega_w}{\frac{\pi}{4} d_o^2 \sqrt{\frac{2\left(P_{S\ up} - P_{S\ dwn}\right)}{\rho_w}}} \qquad \text{(Eq. 8)}$$

where:

ω_w = water flow rate

d_o = orifice diameter

$P_{S\ up}$ = static pressure upstream of the orifice

$P_{S\ dwn}$ = static pressure downstream of the orifice

ρ_w = density of water

K = unit conversion factor

= 3.2733 x 10^{-5} for ω_w in gal/min, d_o in feet, $P_{S\ up}$ and $P_{S\ dwn}$ in psi, ρ_w in lbm/ft^3

For internal mix nozzles, the gas discharge coefficient $C_{d\ a}$ must be obtained in the presence of liquid flow, while the liquid discharge coefficient $C_{d\ w}$ must be obtained in the presence of airflow, since the liquid and airflow characteristics are coupled. Consequently, it may be easier to use the NASA approach and define a liquid flow coefficient, $C_{d\ w/a}$, based upon the difference in water and air pressures:

$$C_{d\ w/a} = K \frac{\omega_w}{\sqrt{P_w - P_a}} \qquad \text{(Eq. 9)}$$

where:

ω_w = water flow rate

P_w = water static pressure

P_a = air static pressure

K = unit conversion factor

An example of a typical nozzle water flow rate calibration is provided in Appendix C.

7.2.2 Icing Cloud Size and Uniformity

The matrix of measured points should be taken at a reference plane positioned at the center of rotation of the model support system, defined as Station 4 (see Figure 1). The spacing between points in the matrix should be no greater than 12.5%, not to exceed 15 cm (6 inches) of the span in either direction. For facilities with small test sections (<16 inches across the longest test section dimension), the spacing between points in the matrix does not need to be less than 2 inches, but the facility should consider the resolution that would be appropriate for their type of facility. All facilities should ensure their uniformity measurements cover the full cross-sectional area where test data will be collected.

7.2.2.1 Ice Accretion Techniques

For facilities using the ice accretion thickness measurements, it is recommended to establish a “baseline” cloud uniformity with a given target MVD, tunnel test section velocity, liquid water content, and total pressure (or altitude) (if the facility can control altitude). Once this is complete, it is recommended to make subsequent measurements that show how varying each of these parameters from the baseline affects the cloud uniformity. To establish a rime ice condition, a tunnel test section total temperature of no greater than -18 °C (0 °F) is recommended for all conditions, but facility temperature should not be so cold that the water drops risk freezing into ice crystals. The recommended test points for documenting icing cloud uniformity are described in Table 3:

Table 3 - Minimum test matrix for cloud uniformity calibration documentation

	Baseline	Recommended Variations
Target Water Droplet Size MVD (μm)	20	15, 40
Tunnel Test Section Velocity (% of Operating Range)	67	minimum, 33, 100
Liquid Water Content (g/m^3)	1.0	0.03 (or min), 2.0, 3.0 (or max)
Tunnel Total Pressure or Altitude, if Applicable (% of Operating Range)	67	0, 33, 100

The spray time for these conditions should be adjusted such that 6.4 mm (0.25 inch) of ice accretion occurs for the given LWC and airspeed. This can be done by using Equation 10 (refer to AIR6977, Equation 1) and treating the exposure time, t, as the unknown value.

$$LWC_b = K\,(\rho_{ice}\ \tau_{ice}) / (e_b\ V_{TS}\ t) \qquad \text{(Eq. 10)}$$

where:

ρ_{ice} = density of ice

τ_{ice} = thickness of ice

e_b = icing blade collection efficiency

LWC_b = icing blade liquid water content

t = time

K = unit conversion factor

= 10^3 with LWC_b in g/m^3, ρ_{ice} in kg/m^3, τ_{ice} in m, V_{TS} in m/s, and t in s; e_b is dimensionless

The accreted ice thickness must be low enough so as not to adversely affect collection efficiency. The target maximum ice thickness is 6.4 mm (0.25 inch), but in some cases the spray time may be shortened to ensure the ice is in rime conditions and that it has good adhesion. Such adjustments are expected more at larger MVDs and higher LWC values.

In Table 3, tests should be repeated at a minimum of four equally spaced velocities over the intended operating range. An example is: minimum operating velocity = 50 kt and maximum operating velocity = 250 kt; then the calibration velocities would be 50 kt, 117 kt, 183 kt, and 250 kt. Additional data points for MVD, water content, total pressure, and velocity may be taken at the discretion of the facility operator. It is also suggested to be aware of conditions that may give “worst-case” cloud uniformities (e.g., checking low nozzle air pressures), which provide less flow mixing and can thus create poorer cloud uniformity. If facility humidity is expected to vary substantially (i.e., open-circuit facilities in particular), the facility should also be aware of any possible humidity effects on cloud uniformity.

Thickness measurements should be taken at the midpoints of the vertical and/or horizontal components of the grid at the locations indicated in Figure 9 by the symbols V_1, V_2, V_3, H_1, H_2, and H_3. The measurements should be converted to relative ice thickness, $\tau_{ice\ R}$, normalized to the ice thickness measurement at the center of the tunnel:

$$\tau_{ice\ R} = \frac{\tau_{(x,y)} - \tau_{grid}}{\tau_C - \tau_{grid}} \propto \frac{LWC_{(x,y)}}{LWC_C} \qquad \text{(Eq. 11)}$$

where:

$\tau_{(x,y)}$ = thickness measurement at each x and y location

τ_{grid} = thickness of grid in the un-iced condition

and the tunnel centerline thickness measurement in the iced condition is given by:

$$\tau_C = \frac{\sum(V_2 + V_3 + H_2 + H_3)}{4} \ or \qquad \text{(Eq. 12)}$$
$$\tau_C = \frac{\sum(V_2 + V_3)}{2} \ or \ \tau_C = \frac{\sum(H_2 + H_3)}{2}$$

The icing cloud uniformity should be presented as contour plots, such as shown in Figure 12 (refer to Timko et al., 2021). In this example from NASA’s Icing Research Tunnel, the measured ice accretion values are plotted as a ratio of the average of the central 12 values.

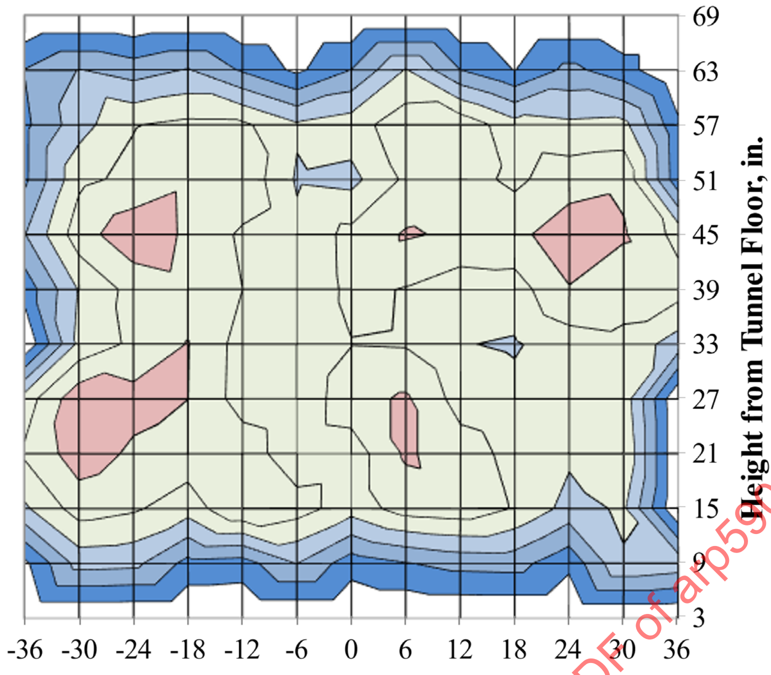

Figure 12 - Example of icing cloud uniformity and size data

7.2.2.2 Hot Wire Technique

Hot wire or other real-time LWC instruments may be used to determine the extent and uniformity of the LWC cloud. Measurements of LWC should be taken at a matrix of points as defined at the start of 7.2.2. The LWC value at any given point should be an average of the measurements over an interval sufficient to provide a statistically stable value of LWC at that point.

If a traversing system is used to enable a matrix of test points in a plane across the test section, then attention should be paid to ensuring that the instrument being traversed is located sufficiently far upstream from the traverse support arm that the aerodynamic effect of the support arm is minimized. At the same time, the support arm should be sufficiently stiff so that vibration of the instrument is minimized as well.

Water content uniformity can also be determined using laser tomography. Tomography utilizes light emitters and detectors situated as an inward-pointing ring, generally just upstream of the test section. The laser light emitters fire in a programmed sequence, and the detectors measure the amount of light extinction from each emitter. By coordinating the extinction levels measured by each detector for each emitter, the user can create a full picture of the cloud uniformity (refer to Bencic et al., 2013). If tomography is used to determine a facility's cloud uniformity, it is recommended that the system first be calibrated by comparing its measurements with data gathered using an ice accretion technique like that described above (refer to Van Zante and Rouse, 2014 and Van Zante et al., 2016).

7.2.3 Water Droplet MVD Calibration

Water droplet size MVD is a function of the nozzle air and water flow rates (for air-assisted atomization nozzles). A functional relationship should be determined between the MVD and these air and water flow rates, which is recommended to match the measured values within the limits specified in Table 1. Alternatively, the facility operator may choose to determine the relationship between other parameters related to flow rates, such as air and water pressure and the MVD. For facilities that have altitude capability, the nozzle air pressure should be referenced to the tunnel total pressure in order to simplify the calibration and gauge range selection. Even utilizing this approach, it is expected that the MVD calibration will be a function of total pressure (or altitude). MVD may also be dependent on humidity, since lower humidity results in greater evaporation effects and smaller drops are affected by evaporation more than larger drops due to having higher surface area to volume ratios. Facilities should either ensure that their humidity levels are consistent enough to not greatly impact the MVD values or should be able to account for differences in their calibration that may be caused by the changes in humidity. Droplet size distributions should be measured using one or more of the instruments described in AIR4906, as required. These instruments should be in current calibration. Further information on particle size distributions (PSDs) is given in Appendix D, which also includes an example of typical drop size distribution plotting.

In order to adequately determine the relationship between MVD and the independent variables, the facility should make measurements of MVD at an array of points defined by the two independent variables. The values chosen to define the array should not exceed 15% of the range of each independent variable necessary to cover the desired MVD range for the facility. As an example, a facility may choose to relate MVD to nozzle air pressure and water flow rate. In such a case, the facility should generate a plot of the relationship between MVD, air pressure, and water flow rate similar to that shown in Figure 13. The array of test points are indicated by the open square symbols. The test points are equally spaced over a region of minimum to maximum air pressure and minimum to maximum water flow rates. Alternatively, this may be shown as the relationship of nozzle air pressure and water flow rate to the MVD, as shown in Figure 14 (refer to Timko et al., 2021). In either case, lines may be plotted as constant MVD values or as constant air pressure values. For facilities that can control altitude, the nozzle air pressures should be specified to account for changing tunnel total pressure.

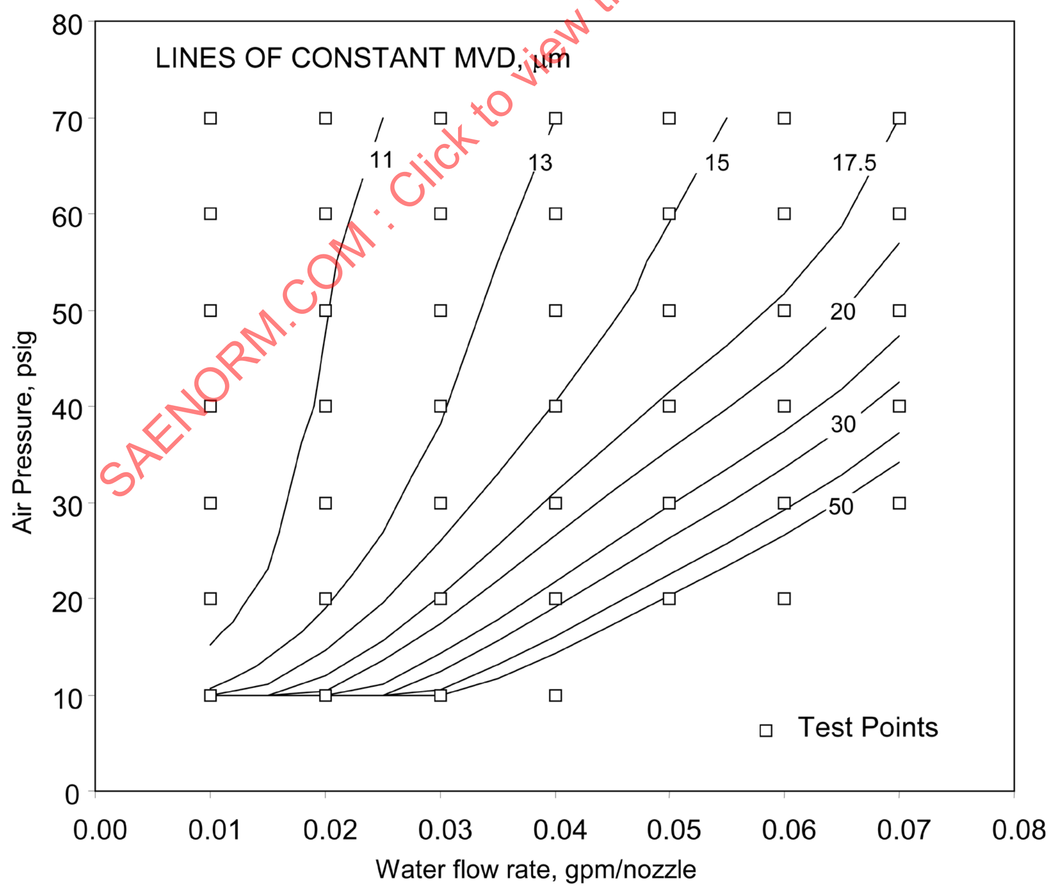

Figure 13 - Facility droplet size MVD calibration

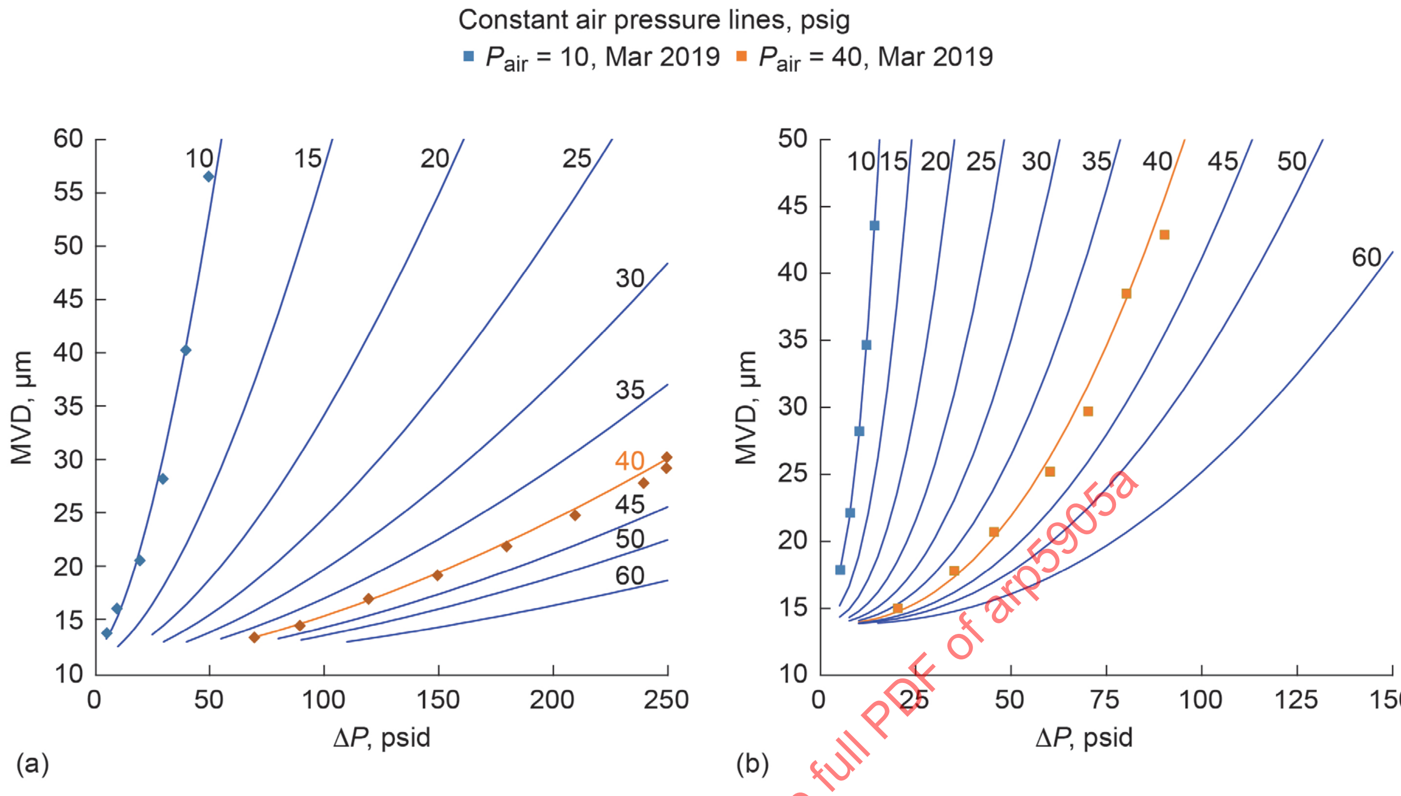

Figure 14 - Facility droplet size MVD calibration for two nozzle sets

The MVD value taken at any given intersection of the independent variables should be over a sufficient time interval to provide a statistically stable value of MVD for those conditions. In order to evaluate the validity of the MVD relationship generated by this procedure, a sufficient number of widely spaced additional values should be taken to determine the repeatability of the MVD measurements.

For the MVD calibration, the tunnel conditions should be set for an airspeed of between 50 and 100% of the maximum tunnel airspeed at 0%, 33%, 67%, and 100% of the total pressure (or altitude) range and a test section static air temperature cold enough to minimize cloud recirculation. MVD measurements should be taken on the tunnel centerline within the constant area of the test section. It is recommended that each facility run a test to look for possible velocity effects on MVD values. If no velocity effect is seen, it does not need to be included in regular calibrations.

7.2.4 Liquid Water Content Calibration

The LWC in the tunnel test section is primarily dependent upon the spray bar water flow rate, test section airspeed, and cloud cross-sectional area. It may also be dependent to a lesser degree upon droplet MVD, nozzle air pressure, relative humidity, test section temperature, tunnel total pressure, or other factors.

Each facility should first determine the functional relationship between the LWC, water flow rate, and test section airspeed. This may be performed experimentally, provided that the curve defining the functional relationship has been determined with a sufficient number of points to be statistically valid. Alternatively, a relationship may be postulated through computational analysis, in which case it will be necessary to verify this relationship experimentally. In either case, it is necessary to perform a set of experiments to determine or substantiate the relationships using one or more of the instruments described in 5.2.5 to measure LWC. It is recommended that the functional relationship that is selected match the measured values within the limits specified in Table 1. An example of a typical LWC calibration, including the investigation of nozzle air pressure and airspeed effects, is contained in Appendix B. Because of LWC instrument limitations (refer to AIR6977), it is possible that facilities may choose to use multiple LWC instruments (e.g., an ice accretion device and a heated element device) to span their full operating range.

When commissioning a new test facility, it is recommended to check centerline LWC values with at least two different means. This check may be a second LWC instrument that utilizes a different measurement technique or comparison to computational analysis, as described above. This is recommended because there are several factors that can lead to inaccuracy in LWC values (refer to AIR6977). Not all calibration test points need to be checked, but tests should cover a range of test conditions where both means of LWC measurement are expected to have a reasonable amount of accuracy.

Since evaporation will affect the amount of liquid water present, facilities should either ensure that their humidity levels are consistent enough to not greatly impact the calibrated LWC values or should be able to account for differences in their calibration that may be caused by the changes in humidity.

8. ACCEPTANCE CRITERIA

The acceptance criteria are consistent with the variables and quantities defined in Section 4 and Table 1.

8.1 Aerothermodynamic

The aero-thermal performance characteristics should be applied only within the selected test volume. If the tunnel calibration shows that the aero-thermal performance meets the spatial uniformity requirements shown for the aerodynamic parameters in Table 1, then the tunnel aerothermodynamics should be deemed acceptable for icing tests.

8.2 Icing Cloud

The calibration should cover the area of the test section where the LWC spatial uniformity defined in Table 1 is met. This area may vary from condition to condition. Temporal stability of the LWC and droplet MVD values may be inferred from the controlled spray bar parameters or measured in situ during testing. The acceptable area for icing testing should be restricted to the area of the icing uniform cloud as defined in Section 5. If the icing calibration demonstrates that the conditions of spatial uniformity and temporal stability in the icing cloud parameters from Table 1 are met, then the tunnel should be deemed acceptable for icing tests.

It is recommended that the functional relationship that is determined for MVD (see 7.2.3) match the values measured during the facility full calibration within the limits specified in Table 1. It is also recommended that subsequent data acquired during the interim calibration show continued adherence to the chosen functional relationships within the limits specified in Table 1. If there are subsequent data acquired that do not adhere to the functional relationship within the limits specified in Table 1, then it is recommended the measurements be compared to data taken during the full calibration under the same test conditions. If the change is larger than the instrument measurement uncertainty described in Table 1, a new full calibration of the facility may be needed.

It is recommended that the functional relationship that is determined for LWC (see 7.2.4) match the values measured during the full calibration within the limits specified in Table 1. It is also recommended that subsequent data acquired during interim and check calibrations show continued adherence to the chosen functional relationships within the limits specified in Table 1. If there are subsequent data acquired that do not adhere to the functional relationship within the limits specified in Table 1, then it is recommended the measurements be compared to data taken during the full calibration under the same test conditions. If the change is larger than the instrument measurement uncertainty described in Table 1, a new full calibration of the facility may be needed.

9. CALIBRATION AND ACCEPTANCE REPORT

A final report should be prepared and be available after each calibration (full, interim, and check) consistent with the requirements of Section 7 that defines the techniques used and should contain, as a minimum, the data required in this section. The report should contain photographs of the test setup, a list of instrumentation, and test results. The intent of the final test report is to provide guidance to the user with regard to the calibration process and results.

Test results should consist of the following:

a. Aerothermodynamic calibration, which should include graphical presentation of the measurements taken for:

1. Static and total pressure calibration defined in 7.1.2
2. Total and static air temperature calibration defined in 7.1.1
3. Velocity distributions and flow angularity defined in 7.1.3
4. Turbulence intensity defined in 7.1.4
5. Temperature distribution defined in 7.1.5

b. Icing cloud calibration, which should include graphical presentations of the measurements taken for:

1. Icing cloud size and uniformity defined in 7.2.2
2. Water droplet size MVD calibration for each nozzle configuration defined in 7.2.3
3. LWC calibration defined in 7.2.4

NOTE: The facility operator should maintain a record that indicates the quality of the engineering data used to generate plots in (2) and (3).

c. Test Facility Qualification Statement: If results from testing are to be used for acceptance of the facility, such that data generated in the facility will be submitted to a regulatory/certifying agency for certification credit, the facility operator should include a statement that all testing and calibration have been performed in accordance with these recommended practices and found to be in accordance with the acceptance criteria defined in Section 8.

10. NOTES

10.1 This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user.

10.2 Revision Indicator

A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

PREPARED BY SAE AC-9C AIRCRAFT ICING TECHNOLOGY COMMITTEE

APPENDIX A - WATER QUALITY, DROPLET FREEZE-OUT, AND DROPLET SUPERCOOLING

Water quality, supercooling, and droplet freeze-out can each potentially have a substantial impact on an LWC calibration. Appendix A provides the reader with information on mitigating these effects.

The water used for the spray system is normally filtered and purified to help prevent nozzle clogging and also to minimize droplet freeze-out. Several different methods have been used to remove dissolved solids, including reverse osmosis, de-mineralizing, and distilling systems. The effects of water impurity on ice shapes, due to changes in water surface tension and other characteristics, are not fully understood but are estimated to be small.

The air and water used to generate the icing clouds is normally heated to minimize droplet freeze-out. However, caution needs to be taken to ensure that the air and water temperatures are not too warm to prevent droplet supercooling at the test object. The appropriate air and water temperatures are a function of the air and water pressures over which the nozzles are operated, the nozzle type, the residence time of the droplets between the spray bars and the test object, and test section altitude (if applicable). A test method for determining the correct air and water temperatures is described below. This test only needs to be performed once provided the air and water temperatures and the water quality are measured and maintained.

1. Set the spray bar air pressure to the maximum pressure. Install an object on which to accrete ice in the test section and cool the tunnel to a total temperature of -7 °C (20 °F). Heat the spray bar air and water temperatures to some initial value and spray for a time sufficient to build measurable ice on the test object. Measure the ice thickness.

2. Repeat the above test using warmer and colder spray bar air and water temperature values until the range of spray bar air and water temperatures that generate the same amount (maximum amount) of ice is found. This is the acceptable spray bar air and water temperature range for this spray bar air pressure.

3. Repeat steps 1 and 2 for the minimum spray bar air pressure. If the results of these tests show that there is an overlap in the acceptable spray bar air and water temperature ranges between these two air pressures, then this overlap range is the acceptable spray bar temperatures for all spray bar air pressures. If there is no overlap, then the test should be repeated for an intermediate air pressure, and the temperature versus air pressure data can be curve-fit to determine the correct air and water temperatures for any air pressure.

4. Repeat steps 1 through 3 at a colder tunnel total temperature, e.g., -20 °C. At cold temperatures, one of the unheated ice accretion instruments as described in AIR6977 may be used as the test object, as these are generally well understood in rime ice conditions. If the results of step 4 show that there is overlap in the acceptable spray bar air and water temperature ranges between these two air pressures, then this overlap range is the acceptable temperatures for all spray bar air pressures and all tunnel air temperatures. If there is no overlap, then the test should be repeated for an intermediate tunnel air temperature, and the temperature versus tunnel temperature data can be curve-fit to determine the correct air and water temperatures for any tunnel air temperature.

5. If the facility has altitude capabilities, repeat steps 1 through 3 for the minimum tunnel total pressure or maximum altitude.

NOTE: It is possible that, through this process, a facility may better determine operating limits for their spray bar air and water pressure values (alone or in combination) as well as corresponding spray bar air and water temperatures. The goal should be to create a cloud comprised of supercooled liquid water where the LWC at test section center may be predicted correctly and repeatably.

Key considerations:

1. The key idea behind this test is that if there is particle freeze-out, it will be evidenced by less ice accretion on the test object. Likewise, if the water is too warm and not properly supercooled, this will also be evidenced by less accretion on the object, as the water is less likely to freeze to the surface. This is why the test specifies to look for the maximum amount of ice thickness. Using something like a heated element water content instrument will not allow the user to distinguish these characteristics. However, different test objects may suffice for accreting ice onto as long as the test and ice measurement methods are executed methodically and consistently.

2. If an icing facility suspects that they are getting early freeze-out of water particles, it is most important to make sure that impurities have been removed from the water supply.

3. Particle freeze-out is most likely to be seen at high nozzle air pressures, where the water is substantially cooled by atomizing air and expansion of that air. This is especially the case if the particles generated are small, such as with an MVD around 15 μm or smaller.

4. The target air and water temperature settings may also be affected by nozzle water pressure (or water flow rate). As noted, freeze-out is most likely for small particle sizes (typically, high P_a and low $\Delta P_{w\text{-}a}$), and insufficient supercooling is most likely for large particles (typically, low P_a and high $\Delta P_{w\text{-}a}$). These are the two conditions most likely to render a cloud unacceptable for testing, and facilities should ensure that their spray bar operations do not result in either of these situations. For this reason, facilities may want to perform steps 1 and 2 of the test at the minimum operating water pressure, and perform step 3 of the test at the maximum operating water pressure. If doing this results in no acceptable temperature overlap between step 3 and steps 1 and 2, then an additional step at an intermediate air pressure is warranted, as is noted in the latter part of step 3. Facilities should then also use a corresponding intermediate water pressure(s) that creates an intermediate MVD in order to develop a sufficient curve-fit. Meanwhile, other parameters can affect the overall LWC; e.g., the evaporation of water drops through the contraction section will likely be highest when LWC values are low (typically, low P_a and low $\Delta P_{w\text{-}a}$) and when altitude is high (if altitude is controllable) since high LWCs result in faster saturation of the air. By keeping air and water temperature operations consistent and monitoring humidity as noted in 5.1.3 and 7.2.4, such effects should ideally be accounted for in the final LWC calibration values.

5. The above test specifies starting at a warmer temperature because this is where a lot of critical testing occurs, and it is critical that the water be supercooled in these conditions in order to re-create the hazard that exists for articles in flight. In these conditions, it may be preferable to use a larger test article (e.g., an NACA 0012 airfoil) to look for ice buildup. It is important to define what you are measuring on the test article; ice mass measurements may be more useful than ice thickness. Ice accretion instruments like those defined in AIR6977 may also be used, but it should be noted that the calculations to determine LWC from these instruments require a rime ice and a known ice density for accurate measurements, so accurate LWC measurements should not be expected from these instruments at the warmer temperatures.

6. Regarding Steps 4 and 5: Particle freeze-out is of course more likely at cold temperatures. This test is not suggested at the facilities' coldest temperature(s) because of the higher likelihood that the spray nozzles may freeze over and contaminate the test results, although facilities should be aware of this affect too. Particle freeze-out is also more likely at higher altitudes, presumably due to a lower evaporative temperature of water and thus higher evaporative cooling.

7. The shape and texture of the ice buildup can also inform the user if there is particle freeze-out or if water is not sufficiently supercooled. For rime ice, if the upstream face of the ice develops a pointed shape (like an arrowhead) and/or if the sides of the ice are particularly smooth, that can be an effect of erosion due to ice crystals in the cloud. Meanwhile, at warm temperatures, if the horn structures on the ice move further aft or there is much more runback, it can be an indication the water is not sufficiently supercooled.

8. Supercooling and freeze-out may also change with tunnel airspeed, as this changes the temperature delta experienced by the particles (total versus static temperature) and also changes the particle residence time between the spray bars and the test section. If facilities have a wide airspeed range, they may need to take this into consideration as well.

9. Lastly, if the determined recommended air and water temperatures vary widely across the facility operation envelope, additional MVD characterization work may be needed at the conditions that require the maximum and minimum air and water temperatures. This is because water surface tension can change with temperature, leading to potential differences in particle breakup at the nozzle exit. If the differences observed are less than the uncertainties stated in Table 1, no further characterization work is needed.