



AEROSPACE INFORMATION REPORT

AIR6977™

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Water Content Instrumentation
for Icing Cloud Characterization

RATIONALE

The need for a single, comprehensive document providing guidance on instrumentation that measures liquid, ice, and total water content in supercooled, mixed-phase, and glaciated clouds was identified. This document would eliminate duplication of effort as the information appears sporadically in several other SAE documents. This SAE Aerospace Information Report (AIR) is intended to be the definitive source for such information.

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1. SCOPE

This SAE Aerospace Information Report (AIR) provides a comprehensive overview of primary water content measurement instrumentation, for both facility-based icing research and in-flight icing research, over the range of commonly used aircraft certification icing envelopes. It includes information on the theory of operation of the instruments, system errors and limitations, and practical considerations when using them for cloud characterization. This document does not address other icing cloud measurements of interest, such as particle sizing, or measurement of phenomena such as snow, sleet, or hail.

1.1 Purpose

The purpose of this document is to provide a single, comprehensive document on instrumentation for water content measurements that can be referred to by other SAE documents in order to avoid duplication. It can also be used as a companion document to AIR4906 in order to provide a complete review of instrumentation and methods for the characterization of icing clouds.

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

ARP5624 Aircraft Inflight Icing Terminology

Chalmers, J., Davison, C., MacLeod, J., Neuteboom, M., and Fuleki, D. (2019). Icing test and measurement capabilities of the NRC's gas turbine laboratory. *SAE Technical Paper 2019-01-1943*, doi: 10.4271/2019-01-1943.

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Orchard, D., Clark, C., and Chevrette, G. (2019). Measurement of LWC for SLD conditions in the NRC's altitude icing wind tunnel. *SAE Technical Paper 2019-01-2007*, doi:10.4271/2019-01-2007.

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-2001-0679 Ludlam Limit Considerations on Cylinder Ice Accretion: Aerodynamics and Thermodynamics

AIAA-2002-0679 Accuracy of Measurements of Cloud Ice Water Content by the Nevzorov Probe

AIAA-2004-731 Ice Particle Impact on Cloud Water Content Instrumentation

AIAA-2005-859 A Multiwire Hot-Wire Device for Measurement of Icing Severity, Total Water Content, Liquid Water Content, and Droplet Diameter

AIAA-2005-860	Preliminary Comparison of Ice Water Content as Measured by Hot Wire Instruments of Varying Configuration
AIAA-2005-861	Determination of Median Volume Diameter (MVD) and Liquid Water Content (LWC) by Multiple Rotating Cylinders
AIAA-2008-435	Isokinetic TWC Probe in a Naturally Aspirating Configuration Initial Aerodynamic Design and Testing
AIAA-2009-3861	Naturally Aspirating Isokinetic Total Water Content Probe Evaporator Design and Testing
AIAA-2010-7530	Naturally Aspirating Isokinetic Total Water Content Probe Preliminary Test Results and Design Modifications
AIAA-2012-2933	NASA Glenn Icing Research Tunnel: 2012 Cloud Calibration Procedure and Results
AIAA-2012-3040	Naturally Aspirating Isokinetic Total Water Content Probe: Pre-flight Wind Tunnel Testing and Design Modifications
AIAA-2014-2331	A Thermal Analysis of a Hot-Wire Probe for Icing Applications
AIAA-2014-2752	Simulation of Fluid Flow and Collection Efficiency for an SEA Multi-Element Probe
AIAA-2016-4051	An Assessment of the Icing Blade and the SEA Multi-Element Sensor for Liquid Water Content Calibration of the NASA GRC Icing Research Tunnel
AIAA-2016-4052	Development and Validation of a Compact Isokinetic Total Water Content Probe for Wind Tunnel Characterization
AIAA-2016-4058	Description and Results for a Simple Ice Crystal Detection System for Airborne Applications
AIAA-2016-4059	Isokinetic TWC Evaporator Probe: Development of the IKP2 and Performance Testing for the HAIC-HIWC Darwin 2014 and Cayenne-2015 Field Campaigns
AIAA-2016-4060	Isokinetic TWC Evaporator Probe: Calculations and Systemic Uncertainty Analysis
AIAA-2017-4088	Validation of Compact IKP
AIAA-2020-2810	Development and Validation of a Compact Isokinetic Total Water Content Probe for Differentiating Mixed Phase Environments
AIAA-2020-2811	Simulation of Fluid Flow and Collection Efficiency at Low Stokes Number
AIAA-2021-2643	Simultaneous Ice Water Content Measurements at Multiple Locations on the NASA DC-8 Aircraft During the 2018 HIWC RADAR Flight Campaign
AIAA-2021-2649	Isokinetic Probe Total Water Content Measurements in the NASA Icing Research Tunnel with Supercooled Large Drop Conditions
AIAA-2021-2653	An Examination of Causes of Multi-Wire Bias During SLD Instrumentation Testing in the IRT
AIAA-2021-2654	Test Results for the SEA Ice Crystal Detector (ICD) under SLD Conditions at the NASA IRT
AIAA-2021-2656	Comparison of a Compact Isokinetic Total Water Content Probe to Standard and T-Shaped Multi-Element Probes for Characterizing Glaciated, Liquid and Mixed-Phase Environments

2.1.3 Droplet Measurement Technologies Publications

Available from Droplet Measurement Technologies, 2400 Trade Centre Ave, Longmont, CO 80503, <https://www.dropletmeasurement.com>.

DOC-0361C LWC-300/301: Liquid Water Content Sensor Operator's Manual

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2.2 Related Publications

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

2.2.1 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-2004-730 Development of a Total Liquid Water Content Probe

AIAA-2009-3862 Naturally Aspirating Isokinetic Total Water Content Probe: Intake Deicing and Heat Transfer

AIAA-2018-3970 Total Temperature Measurements Using a Rearward Facing Probe in Supercooled Liquid Droplet and Ice Crystal Clouds

2.2.2 Other Publications

Jeck, R. (2007). Calibration and use of Goodrich Model 0871FA ice detectors in wind tunnels. *Journal of Aircraft*, 44(1), 300-309, doi:10.2514/1.23543.

2.3 Definitions

Refer to ARP5624 for definitions of icing-related terms.

2.4 Symbols and Abbreviations

2.4.1 Symbols

A	Area
c_i	Specific heat capacity of ice
c_w	Specific heat capacity of water
d_c	Cylinder diameter
d_d	Droplet diameter
d_k	King probe wire diameter
d_{OP}	Diameter of orifice plate
d_{pipe}	Diameter of pipe
d_s	Diameter of sensing element
e_b	Icing blade collection efficiency
e_c	Rotating cylinder collection efficiency
$e_{i,LWC}$	Ice crystal collection efficiency of LWC collector element
$e_{i,TWC}$	Ice crystal collection efficiency of TWC collector element
e_k	King probe wire collection efficiency
$e_{l,LWC}$	Liquid droplet collection efficiency of LWC collector element
$e_{l,TWC}$	Liquid droplet collection efficiency of TWC collector element
H_E	Empirical Langmuir parameter
h_{heat}	Enthalpy to heat liquid water from wet bulb temperature to LE temperature
h_{vap}	Enthalpy to evaporate liquid water at LE temperature
IKF	Isokinetic factor
IWC	Ice water content
IWC_{CT}	Ice water content measured by capture tube

k_a	Thermal conductivity of dry air
K_{dry}	Dry term correction factor
K_s	Stokes parameter
K_0	Modified inertia parameter
l_c	Length of the cylinder over which ice is allowed to accrete
l_k	Length of King probe sensing element
l_s	Length of sensing element
L^*	Energy expended in heating and evaporating water
L^*_{ice}	Energy expended in heating and evaporating ice
LE	Leading edge
L_f	Latent heat of fusion
L_v	Latent heat of vaporization of water at T_e
LWC	Liquid water content
LWC_b	Liquid water content measured by icing blade
LWC_c	Liquid water content measured by rotating cylinder
m_{ice}	Mass of accreted or captured ice
$\dot{m}_h$	Mass flow through hygrometer
$\dot{m}_{IKP,air}$	Mass flow through isokinetic probe
$\dot{m}_{op}$	Mass flow through orifice plate
MR	Melt ratio
MVD	Median volumetric diameter
MW	Molar weight
Nu	Nusselt number
P_s	Static air pressure
P_{sensor}	Sensor element total power
P_{dry}	Dry power term
P_{wet}	Wet power term
P_{ref}	Reference sensor power
P_{OP}	Absolute pressure at orifice plate

ΔP_{OP}	Pressure differential over orifice plate
Q_{LE}	Leading edge heat energy
$Q_{LE,corr}$	Leading edge heat energy, corrected
$Q_{LE,Dry-Dry}$	Leading edge heat transfer in dry conditions
$Q_{LE,Dry-Wet}$	Leading edge dry heat transfer in wet conditions
$Q_{LE,Wet}$	Leading edge heat transfer in wet conditions
r_{cf}	Final radius of the cylinder with accreted ice
r_{ci}	Initial radius of the cylinder
R_c	Collector sensor resistance
R_{dry}	Ideal gas constant for dry air
Re_d	Droplet Reynolds number
Re_{op}	Flow Reynolds number at orifice plate
t	Time
T_s	Static air temperature
T_{s-Dry}	Static air temperature in dry conditions
T_{s-Wet}	Static air temperature in wet conditions
T_c	Collector sensor temperature
T_e	Temperature of water evaporation at ambient pressure
T_K	King probe wire temperature
T_{LE-Dry}	Leading edge temperature in dry conditions
T_{LE-Set}	Leading edge temperature set point
T_{LE-Wet}	Leading edge temperature in wet conditions
T_0	0 °C/273.15 K
T_{OP}	Temperature of fluid at orifice plate
T_V	Virtual temperature
TWC	Total water content (LWC + IWC)
$\dot{V}_i$	Volume flow rate through probe inlet
V	Velocity
V_{ac}	AC voltage across collector sensor

V_{dc}	DC voltage across collector sensor
W	Calculated water content
W_{LWC}	Calculated water content from LWC sensor
W_{TWC}	Calculated water content from TWC sensor
α_c	Bulk convective heat transfer coefficient of collector sensor
γ	Ratio of specific heats
ϵ	Expansion coefficient
μ_a	Dynamic viscosity of air
μ_{OP}	Dynamic viscosity of fluid at orifice plate
ρ_a	Density of air
ρ_{ice}	Density of ice
ρ_w	Density of water
τ_{ice}	Thickness of ice
ϕ	Impingement parameter
ω	Mass mixing ratio
ω_{amb}	Specific humidity from background humidity sensor
ω_T	Specific humidity from IKP flow path humidity sensor
Ω	Mole mixing ratio
Ω_{wet}	Wet mole fraction from hygrometer

2.4.2 Abbreviations

ASME	American Society of Mechanical Engineers
CFD	Computational fluid dynamics
CIKP	Compact isokinetic probe
CSIRO	Commonwealth Scientific and Industrial Research Organization
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DMT	Droplet measurement technologies
FAA	Federal Aviation Administration
ICD	Ice crystal detector
IKP	Isokinetic probe

IRT	Icing research tunnel
NASA	National Aeronautics and Space Administration
NRC	National Research Council of Canada
SEA	Science Engineering Associates

3. WATER CONTENT MEASUREMENT TECHNOLOGIES

3.1 Background and Overview

Atmospheric clouds, including supercooled liquid water and ice crystals, may be studied in wind tunnels, cold chambers, engine test cells, and from instrumented research aircraft. The concentration of water particles in icing clouds is of particular interest in these studies and may be measured with a variety of instruments and technologies. This document includes reviews of what are considered primary measurement systems that provide a quantitative measurement of the liquid or frozen water concentration in an icing cloud; it does not discuss qualitative systems or those technologies not considered mature enough at this time to be a primary measurement.

Each instrument discussed in this document has unique features, advantages, measurement limitations, and uncertainties. Often, it is necessary to take measurements using several different techniques to ensure that the entire size distribution and full range of LWC/IWC has been measured. A summary of the instruments discussed in this document is given in [Table 1](#). It is important to note that the limitations of each instrument are provided in more detail in this document than can be summarized in this chart, and that these capabilities may change over time as the instruments are further developed and characterized.

Table 1 - Water content instrumentation capability summary

Method	Instrument	Water Content Measurement
Unheated Ice Accretion	Icing blade	LWC limited by Ludlam limit
	Rotating cylinder	LWC limited by Ludlam limit
	Capture tube	IWC
Heated Element	King probe	LWC 0.05 to 3 g/m ³ @100 m/s
	Nevzorov probe	LWC-TWC 0.002 to 3 g/m ³ at 100 m/s
	Multi-element probe	LWC-TWC up to 10 g/m ³ <150 m/s
		LWC-TWC up to 6 g/m ³ <230 m/s
Evaporative	Robust probe/ice crystal detector	LWC-TWC up to 10 g/m ³ <150 m/s
		LWC-TWC up to 6 g/m ³ <230 m/s
	IKP-1	0 to 10 g/m ³ @ 200 m/s
	IKP-2	0 to 10 g/m ³ @ 200 m/s
	Compact IKP	0 to 12 g/m ³ @ Mach 0.5, sea level
		0 to 19 g/m ³ @ Mach 0.7, 15 km (50000 feet)

4. UNHEATED ICE ACCRETION METHODS

4.1 Technology Overview

4.1.1 Icing Blades

The standard icing blade method consists of exposing the narrow flat face of a metal blade of rectangular cross-section to water spray and accreting ice. Given the aerodynamic operating conditions of the facility, the size of the icing blade, the exposure time, and the droplet size, the LWC can be calculated from the measured ice thickness. Measurements, calculations, or assumptions for ice density and icing blade collection efficiency are required. An example of an icing blade is shown in [Figure 1](#), where a typical icing blade thickness is around 3.18 mm (0.125 inch) and depth is around 19 mm (0.75 inch) (AIAA-2012-2933).

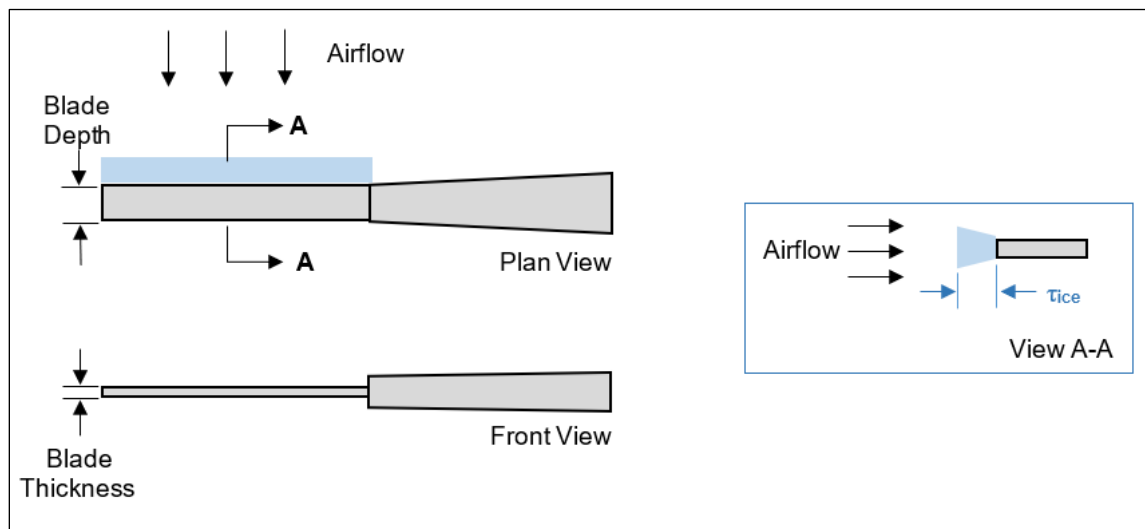


Figure 1 - Icing blade example
(From AIAA-2012-2933)

The icing blade should be pre-cooled to ambient conditions and then exposed to a stable icing cloud that will produce rime ice conditions. If necessary, this can be accomplished by placing the blade behind a shield to permit the icing cloud conditions to stabilize prior to exposing the blade. The ice thickness should be measured using chilled micrometers, to prevent ice melting during the measurements. The overall icing blade repeatability has been shown by NASA to be around $\pm 5\%$ over multiple decades (AIAA-2016-4051). A separate analysis by Stallabrass (1978) also observed the total of various sources of error to be around $\pm 5\%$ or less.

The shape of the ice accretion on the icing blade may be used to better understand the characteristics of the cloud conditions in a qualitative manner. For example, an “arrowhead” ice shape may indicate that ice crystals are present in the cloud and erosion of the accreted ice is occurring. The ice width may also be measured as a check of the collection efficiency assumption validity (see [4.3.2](#)).

An icing grid (essentially a series of icing blades oriented horizontally and vertically) is often used to measure the spatial distribution of the liquid icing cloud over a large area. Although this is a good method for evaluating spatial uniformity, blockage considerations must be taken into account or the grid-measured LWC may not match up exactly with measurements obtained using other methods recommended in this document. Therefore icing grids are generally not the best choice for primary measurements of LWC.

4.1.2 Rotating Cylinders

The rotating cylinder method involves placing a cylinder perpendicular to the air flow, exposing it to icing cloud while rotating it slowly, and measuring the mass of the ice accreted over a recorded duration. Rotating the cylinder gives a uniform ice buildup of circular cross-section that provides aerodynamic consistency, as well as consistency with the theoretical basis of calculations which assume a circular cross-section. Given the aerodynamic conditions, the geometry of the cylinder, the exposure time, and the droplet size, the LWC can be calculated from the measured ice mass on the cylinder. The material of the rotating cylinder is typically metal (stainless steel, aluminum, or copper alloy) with a smooth surface finish and no nicks, dents or burrs. It should be easily removable from the rotation drive mechanism through the use of a slip-over sleeve or threads. An example of a rotating cylinder system is shown in [Figure 2](#).

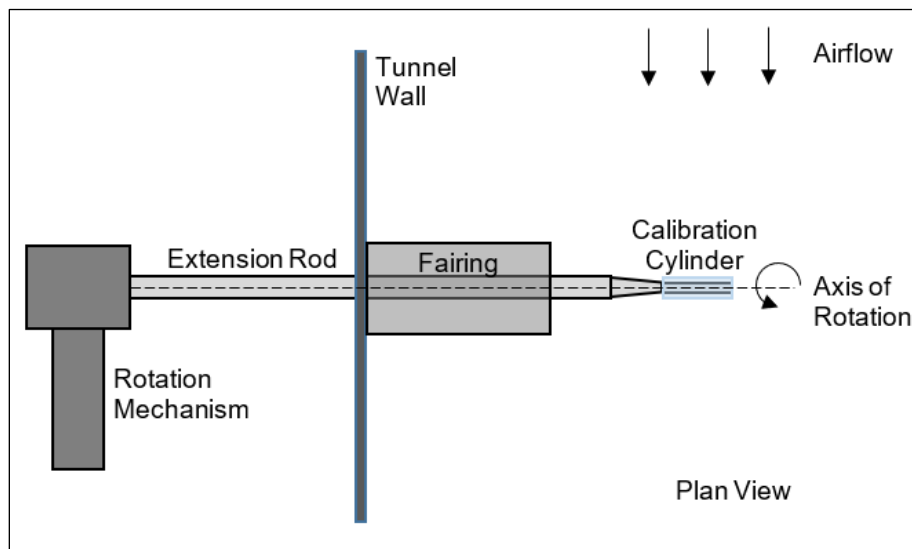


Figure 2 - Rotating cylinder example

The rotating cylinder should be pre-cooled to ambient conditions and then exposed to a stable icing cloud. This can be accomplished by placing the rotating cylinder behind a fairing to permit the icing cloud conditions to stabilize prior to exposure. A fairing over the extension rod can also help reduce aerodynamic loads to facilitate operation, provided the fairing does not interfere with the water spray approaching the exposed cylinder. If the cylinder is not sufficiently cooled, there may be a delay in the initial ice accretion and the subsequent accretion may be bumpy. If the cylinder is removed from the test section after cooling to permit the spray to stabilize, any frost that forms should be cleaned off prior to re-inserting the cylinder into the test section using a clean, dry cloth.

The rotating cylinder method is particularly suited to smaller wind tunnel test sections because the rotation drive mechanism can be kept outside of the tunnel and the length of the extension rod to the calibration cylinder can be kept short. It is helpful to fit the extension rod with a bushing such that when the bushing is in contact with the outside of the tunnel, the lateral position of the cylinder lines up with the center of the test section. A large bushing or flat plate that is flush with the outside of the tunnel wall can also help the operator keep the rotating cylinder steady and perpendicular to the flow under heavy aerodynamic loads, and seal the hole in the window where the rotating cylinder is inserted into the test section.

4.1.3 Capture Tubes

The capture tube method requires exposing a container, typically a tube or cylinder as shown in [Figure 3](#) with one open end and one capped end, into an icing cloud and accreting ice inside of it. Given the aerodynamic operating conditions of the facility, the opening area of the cylinder facing perpendicular to the flow, and the exposure time, the TWC can be calculated from the measured ice mass. Measurements, calculations, or assumptions for ice density and cylinder collection efficiency are required. Typical capture tubes have a circular opening with a sharp leading edge, approximately 10 mm diameter and a length of 10 to 20 cm (Strapp, Schwarzenboeck, Bedka, et al., 2020).

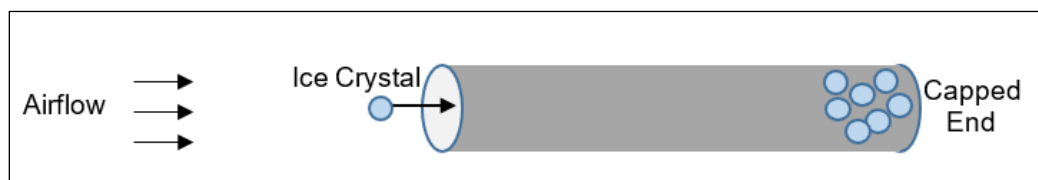


Figure 3 - Capture tube example

Capture tubes must be cold and dry when exposed to a stable ice crystal cloud. Note they are only suitable for a glaciated cloud, as a liquid water spray will freeze on contact and plug the open end of the tube. Care must be taken to ensure that the capture tube does not fill up with ice such that the particles bounce out of the open area.

4.2 Theory of Operation

4.2.1 Icing Blades

The icing blade is a simple method to measure LWC using ice thickness and exposure time. For the most accurate results, the measurements should be taken at multiple locations along the length of the icing blade (centerline and ± 3 cm for example) and the median value of the measurements used in order to minimize the influence of a potential outlier (AIAA-2012-2933).

The LWC measured by the icing blade method can be calculated using Equation 1 (Stallabrass, J.R., 1978):

$$LWC_b = 1000 \frac{\rho_{ice} \tau_{ice}}{e_b V t} \quad (\text{Eq. 1})$$

where:

LWC_b = LWC measured by icing blade (g/m^3)

ρ_{ice} = density of ice (kg/m^3)

τ_{ice} = average of the ice thickness accumulated on the ice blade (m)

e_b = blade collection efficiency (dimensionless)

V = freestream velocity (m/s)

t = time of exposure to the LWC laden airstream (seconds)

The blade collection efficiency can be calculated using a droplet trajectory code and is defined as the ratio of water droplet mass flux at a specific location on the surface of a body to the droplet mass flux in the freestream (ARP5624).

4.2.2 Rotating Cylinders

The rotating cylinder method has been used for many years. A number of technical papers have been written addressing considerations and practices for using this method; one of the most comprehensive is that by Stallabrass (1978), which forms the basis of this section. Derivation and background for equations presented in this section can be found in that paper.

The LWC measured by the rotating cylinder method can be calculated using Equation 2:

$$LWC_c = 1000 \frac{\pi \rho_{ice} (r_{cf} - r_{ci})}{e_c V t} \quad (\text{Eq. 2})$$

where:

LWC_c = LWC measured by rotating cylinder (g/m^3)

ρ_{ice} = density of ice (kg/m^3)

r_{cf} = final radius of the cylinder with accreted ice (m)

r_{ci} = initial radius of the cylinder (m)

e_c = cylinder collection efficiency (dimensionless)

V = freestream velocity (m/s)

t = time of exposure to the LWC laden airstream (seconds)