NASA/TM—2019-219990

NASA Glenn Icing Research Tunnel: 2018 Change in Drop-Sizing Equations Due to Change in Cloud Droplet Probe Sample Area

Laura E. King-Steen
HX5 Sierra, LLC, Cleveland, Ohio

Emily N. Timko
Jacobs Technology, Cleveland, Ohio

Robert F. Ide
HX5 Sierra, LLC, Cleveland, Ohio

Judith F. Van Zante
Glenn Research Center, Cleveland, Ohio

September 2019

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., "quick-release" reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 757-864-6500

- Telephone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Program
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM—2019-219990

NASA Glenn Icing Research Tunnel: 2018 Change in Drop-Sizing Equations Due to Change in Cloud Droplet Probe Sample Area

Laura E. King-Steen
HX5 Sierra, LLC, Cleveland, Ohio

Emily N. Timko
Jacobs Technology, Cleveland, Ohio

Robert F. Ide
HX5 Sierra, LLC, Cleveland, Ohio

Judith F. Van Zante
Glenn Research Center, Cleveland, Ohio

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

September 2019

Acknowledgments

The authors would like to thank NASA's Aerosciences Evaluation and Test Capabilities (AETC) Project for funding this effort and all cloud calibration efforts. Thanks are also due to Droplet Measurement Technologies, Inc., for adding probe beam-mapping to their company's capabilities, and specifically to Matt Freer for his informative help through this process. Thanks are also due to the other Icing Research Tunnel (IRT) engineers for their continued support through cloud calibration efforts: Seth Sederholm, Sean Currie, Waldo Acosta, and Rob Armstrong; and the expert and very patient IRT technicians: Dave Bremenour, Jason Bryant, Josh Kertcher, Marty Greene, Bill Magas, Rob Maibauer, Terry Mathes, Shaun McNea, and Perry Vraja.

This work was sponsored by the Advanced Air Vehicle Program
at the NASA Glenn Research Center

Level of Review: This material has been technically reviewed by technical management.

Available from

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

This report is available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov/

NASA Glenn Icing Research Tunnel: 2018 Change in Drop-Sizing Equations Due to Change in Cloud Droplet Probe Sample Area

Laura E. King-Steen
HX5 Sierra, LLC
Cleveland, Ohio 44135

Emily N. Timko
Jacobs Technology
Cleveland, Ohio 44114

Robert F. Ide
HX5 Sierra, LLC
Cleveland, Ohio 44135

Judith F. Van Zante
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

Although there has been no physical change to the cloud drop diameters in the NASA Glenn Icing Research Tunnel (IRT), the IRT cloud calibration team now has an improved understanding of the facility's drop-sizing instrumentation, which has resulted in a recent change to the drop-sizing equations. Only the calculated values given in the previous calibration report have changed. In 2017, IRT staff found reason to believe that since at least 2014, the sample area for its Cloud Droplet Probe (CDP) (Droplet Measurement Technologies, Inc.) has been closer to 0.289 mm^2, rather than the user manual's suggested value of 0.24 mm^2. In September 2017, the probe's sample area was measured both before and after the probe was realigned, and the end sample area was measured to be 0.248 mm^2. Following the probe's realignment, drop size measurements were made in the IRT using the CDP as well as optical array probes OAP–230X and OAP–230Y (Particle Measurement Systems, Inc.). These measurements suggested that 0.289 mm^2 was the more accurate value for historical measurements. When the CDP sample area used for calculations was changed from 0.24 to 0.289 mm^2, distributions previously reported to have a median volumetric diameter (MVD) between 30 and 100 μm were instead calculated to have MVD values 10 to 18 percent higher. The analyses that led to these conclusions are reported in this paper, as well as the new drop-sizing equations that have been developed for the corrected measurement values. This report contains updates to drop-sizing data for the IRT's "normal" operating conditions (MVD < 50 μm) and discusses the effects on the IRT's "large-drop" conditions (Mod1 nozzles, P_{air} < 10 psig), but it does not include updates to the drop-sizing equations for those large-drop conditions.

Nomenclature

CDP	Cloud Droplet Probe, drop sizer, 2 to 50 µm
Dv0.##	drop diameter at which ## percent of the total volume of water is contained in smaller drops
FAA	Federal Aviation Administration
FZDZ	freezing drizzle
FZRA	freezing rain
IRT	Icing Research Tunnel
LWC	liquid water content (g/m^3)
MVD	median volumetric diameter (µm)
$MVD_{\#\#}$	MVD calculated with a CDP sample area of ##
OAP–230X	Optical Array Probe, drop sizer, 15 to 450 µm
OAP–230Y	Optical Array Probe, drop sizer, 50 to 1,500 µm
SA	sample area
SLD	supercooled large drops
P_{air}	spray nozzle atomizing air pressure (psig)
P_{water}	spray nozzle water pressure (psig)
V	calibrated true airspeed (velocity) in the test section (kn)
ΔP	spray nozzle $P_{water} - P_{air}$ (psid)

Introduction and Reason for Change

There has been no physical change to the drop sizes (or liquid water content (LWC) or uniformity) in the NASA Glenn Icing Research Tunnel (IRT); only the calculated values given in the previous calibration report (Ref. 1) have changed. However, the calculated median volumetric diameter (MVD) values have increased by 10 to 18 percent for distributions that were previously reported to have an MVD between 30 and 100 µm. Because of this, the IRT staff believed it was necessary to report the change in facility calibration equations. The full report of the IRT cloud calibration is given in Reference 1; this report should be used in conjunction with that one.

The recent changes in the drop-sizing equations for the IRT cloud are the result of an improved understanding of the facility's drop-sizing instrumentation. Before September 2017, the sample area that was used for the Cloud Droplet Probe (CDP) (Droplet Measurement Technologies, Inc.) was the value reported in the user's manual: 0.24 mm^2. In 2017, the IRT sent the probe to its manufacturer for alignment and recalibration. The sample area size was measured twice using a new capability to map the probe's beam and determine the sample area size. Prior to realignment, the sample area (as received) was measured to be 0.289 mm^2. After realignment, the sample area was measured to be 0.248 mm^2. Drop-sizing measurements were then made in the IRT with the newly aligned probe and with optical array probes OAP–230X and OAP–230Y (Particle Measurement Systems, Inc.). In comparing the newest measurements with the drop size distributions reported in the 2015 calibration paper, it appeared that the distributions measured between 2014 and 2017 (before realignment) would be more accurate if calculated using the as-received sample area of 0.289 mm^2 for the CDP. The analyses leading to this conclusion are reported in this paper, as well as the new drop-sizing equations that have been developed for the corrected measurement values.

The new calibration equations (transfer functions) are included in this report to relate the inputs of spray bar atomizing air pressure and water pressure to the outputs of MVD. These correlations were completed for Federal Aviation Administration (FAA) "typical" icing conditions described in U.S. Code of Federal Regulations (CFR) Title 14, Part 25, Appendix C, Atmospheric Icing Conditions (Ref. 2), and Part 29, Appendix C, Icing Certification (Ref. 3). Drop-sizing equations have not yet been completed for CFR Title 14, Part 25, Appendix O, Supercooled Large Drop Icing Conditions (Ref. 4), and are not included in this report.

Facility Description

The IRT is an atmospheric, closed-loop, refrigerated wind tunnel that simulates flight through an icing cloud. A plan view of the facility is shown in Figure 1. The test section is 6 ft high by 9 ft wide by 20 ft long. The facility's airspeed ranges between 50 and 325 knots. Tunnel temperature can be controlled between a total temperature of 10 °C and a static temperature of –35 °C. Upstream of the contraction section are 10 rows of spray bars with two different air-atomizing nozzle types: Mod1 (lower water flow rates) and Standard (higher water flow rates). There are a total of 88 Mod1 nozzles and 165 Standard nozzles in the spray bars. Each nozzle location is fed from two water manifolds through remotely controlled solenoid valves. It is possible to turn on only the Mod1 nozzles, only the Standard nozzles, or both (with the same air pressure). The drop sizes for the cloud are expressed in terms of MVD. They range from 15 to 50 μm for normal operating conditions and up to 275 μm for large-drop conditions (Mod1 nozzles, P_{air} < 10 psig). LWC is expressed in terms of grams of water per cubic meter of air (g/m^3).

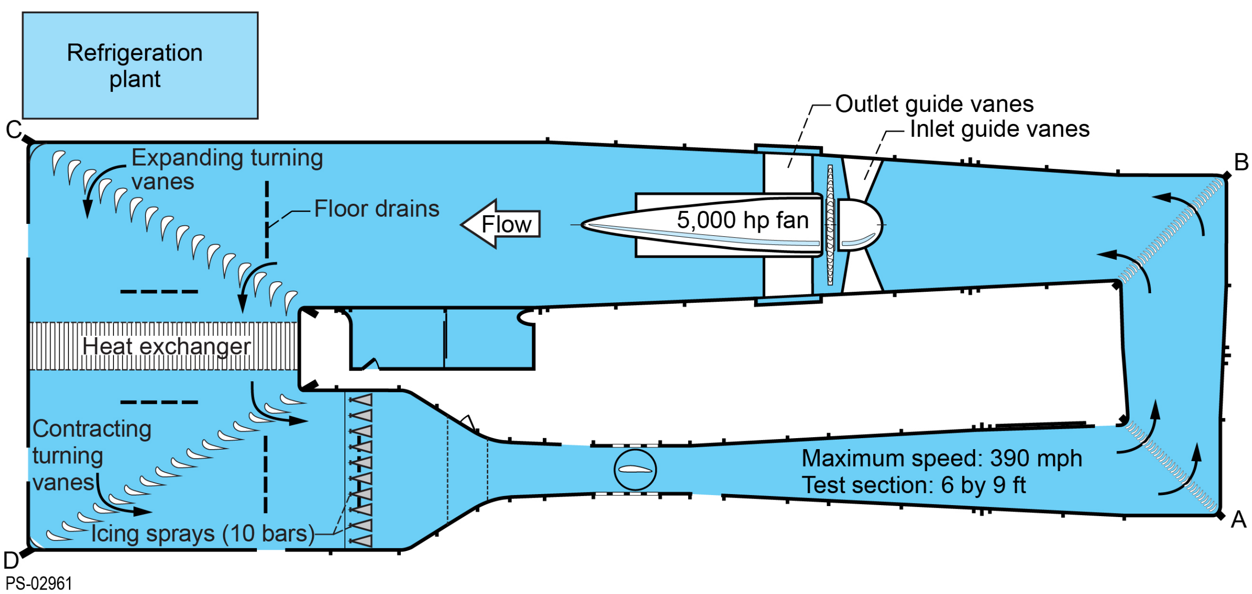

Figure 1.—Plan view schematic of Icing Research Tunnel.

Figure 2.—Drop-sizing probes used for calibration in Icing Research Tunnel.
(a) Cloud Droplet Probe (CDP) (Droplet Measurement Technologies, Inc.).
(b) Optical array probe OAP–230X (Particle Measurement Systems, Inc.).
(c) Optical array probe OAP–230Y (Particle Measurement Systems, Inc.).

Drop-Sizing Data Acquisition and Processing

Description of Drop-Sizing Probes

Data from three drop-sizing probes were used to build the 2014 and 2015 IRT drop size calibration curves. These were the Cloud Droplet Probe (CDP) (2 to 50 µm) and two optical array probes, OAP–230X (15 to 450 µm) and OAP–230Y (50 to 1,500 µm), which are shown in Figure 2. The CDP was manufactured by Droplet Measurement Technologies, Inc. The OAP–230X and OAP–230Y were manufactured by Particle Measurement Systems, Inc. These instruments are no longer being manufactured, but can still be serviced. The IRT's OAP–230Y was not functional during the January 2014 tests but was repaired before the January 2015 tests.

The CDP measures drop sizes from 2 to 50 µm in diameter using the Mie scattering theory for forward-scattered light intensity. Because the CDP measures the smallest drop sizes of the three probes, and because all spray conditions in the IRT contain small drops, data from the CDP are collected and used for all spray conditions. Spray conditions ranged over the following: air pressures, P_{air} = 10 to 60 psig for the Standard nozzles and 2 to 60 psig for the Mod1 nozzles; delta pressures (water pressure minus air pressure), ΔP = 5 to 150 psid for the Standard nozzles, and 5 to 250 psid for the Mod1 nozzles.

Both the OAP–230X and the OAP–230Y measure drop size using a shadowing technique. Data were taken with the OAP–230X for all spray conditions that produce a MVD greater than approximately 18 µm. The OAP–230Y was used only for spray conditions that have historically produced a MVD above 110 µm.

Data Processing of Drop Size Distributions

To calculate the drop size distribution and the MVD, the drop size data from multiple probes are combined. Small MVD values (up to about 18 µm) require only the CDP's measurements, but the largest MVD values (above 110 µm) require combined measurements from all three probes. The number of drops that are recorded in each bin are divided by the probe's sample volume for that drop size to obtain the number density. That value is then normalized by the bin width to determine normalized number density (per µm). A number density distribution example is shown in Figure 3. The squares show the size distribution as measured by the CDP, the triangles show the size distribution as measured by the OAP–230X, and the circles show the size distribution as measured by the OAP–230Y. Note that the first three bins of the OAP–230X (the smaller black triangles) overlap with the CDP, and the first eight bins of the OAP–230Y (the smaller black circles) overlap with the OAP–230X; these overlap bins are not used in the drop size calculation. The number density for each bin is used with its respective (midsize) drop diameter to calculate the LWC per bin. This is used to calculate the normalized cumulative volume distribution. Normalized cumulative volume distributions for the IRT are shown in Figure 4 (calculated with the updated CDP sample area). Bin volumes are plotted cumulatively, such that each data point represents the amount of water contained in all smaller diameters, normalized by the total volume contained in all bins. The MVD, which is used to characterize the drop size distribution, is the value at which half of the water volume is contained in smaller (or larger) drops; MVD is also referred to as "Dv0.50."

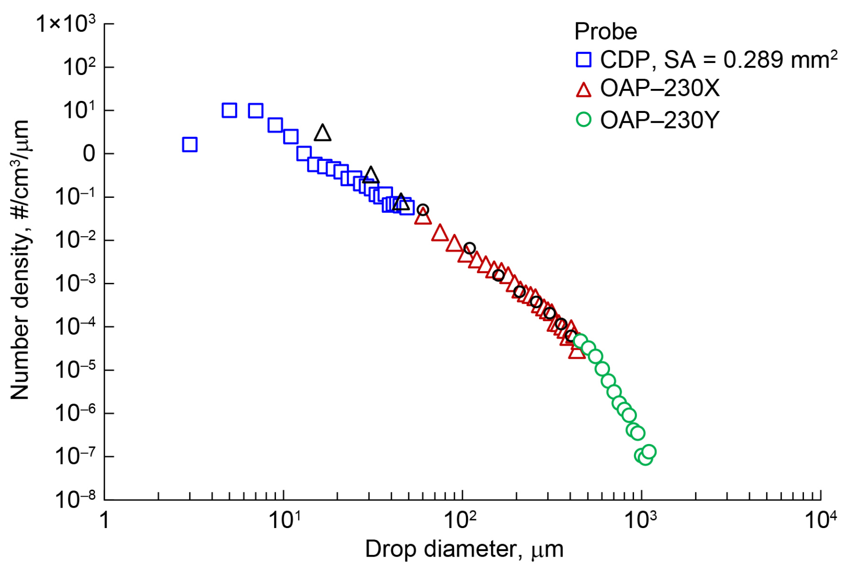

Figure 3.—Drop size distribution presented as number density versus drop diameter, measured by Cloud Droplet Probe (CDP) and optical array probes OAP–230X and OAP–230Y; median volumetric diameter (MVD) = 270 µm. Smaller black triangles and circles are overlap points and are not used in MVD calculations. CDP sample area, SA.

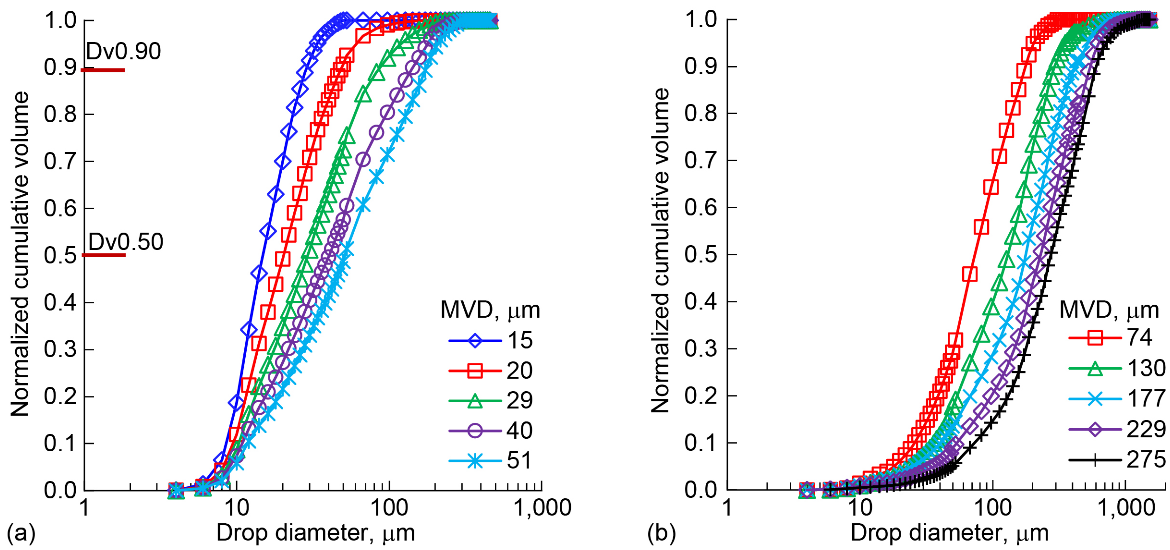

Figure 4.—Updated normalized cumulative volume distributions with Cloud Droplet Probe sample area = 0.289 mm^2. (a) Median volumetric diameter (MVD) ≤ 51 μm with Dv0.50 (= MVD) and Dv0.90 indicated (drop diameter at which 50 and 90 percent of total volume of water is contained in smaller drops). (b) MVD > 51 μm.

TABLE I.—CLOUD DROPLET PROBE SAMPLE AREA VALUES

Sample area, SA	Description
SA = 0.24 mm^2	Cloud Droplet Probe (CDP) SA specified in CDP user's manual; used before 2017
SA = 0.289 mm^2	CDP SA measured September 2017, before realignment
SA = 0.248 mm^2	CDP SA measured September 2017, after realignment

Description of CDP Sample Area Values

Before September 2017, the sample area that was used for the CDP was the value reported in the user's manual: 0.24 mm^2. In 2017, the probe manufacturer developed a new capability to map and measure the probe's sample area. The IRT sent its probe to Droplet Measurement Technologies, Inc., for realignment and requested the sample area be measured before ("as received") and after realigning. Droplet Measurement Technologies, Inc., measured the as-received sample area to be 0.289 mm^2. After the probe was realigned, the sample area of the CDP was measured to be 0.248 mm^2. The CDP sample area was reported to be larger than expected, meaning the calculated number density for drop sizes between 2 and 50 μm was lower than previously calculated. This meant the amount of liquid water contributed by the smallest drop sizes was also lower than previously calculated, and the MVD changed for those distributions that utilized combined data from the various probes. Subsequent analysis in this paper will refer to the three different MVDs calculated with the various CDP sample areas by using the values as subscripts (e.g., $MVD_{0.289}$). Figure 5 and Figure 6 show the impact that this sample area change has on the number density and cumulative volume plots, respectively, for a Standard-nozzle condition with a P_{air} of 25 psig and a ΔP of 50 psid. In 2014 this condition was labeled as $MVD_{0.24}$ = 47.4 μm, but based on the information learned in 2017, it could instead be labeled as $MVD_{0.289}$ = 55.6 μm. This is again because the calculated number density contributed by the CDP is lower, and so the contribution of the CDP to the total volume distribution is lower, which causes the new MVD value to be higher. A summarized description of the various CDP sample areas used in this paper is given in Table I.

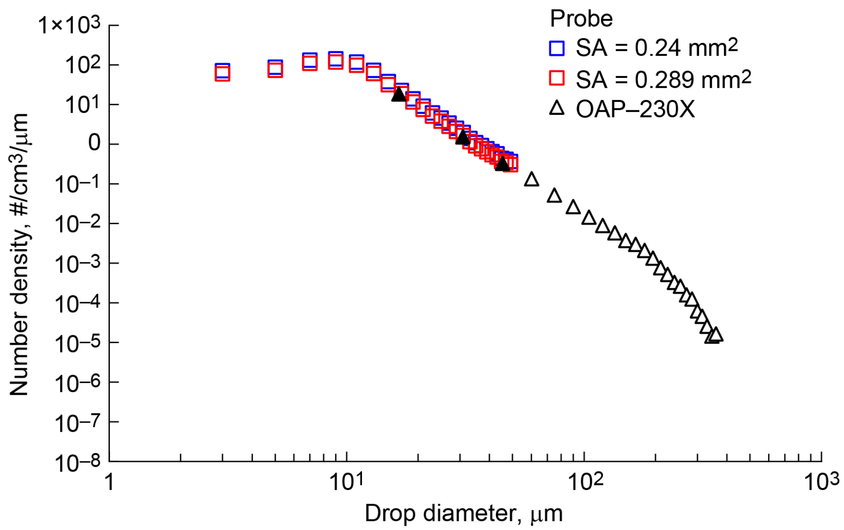

Figure 5.—Drop size distribution presented as number density (ND) versus drop diameter, measured by Cloud Droplet Probe (CDP) and optical array probe OAP–230X. Solid black triangles are overlap points and are not used in median volumetric diameter calculations. CDP sample area, SA.

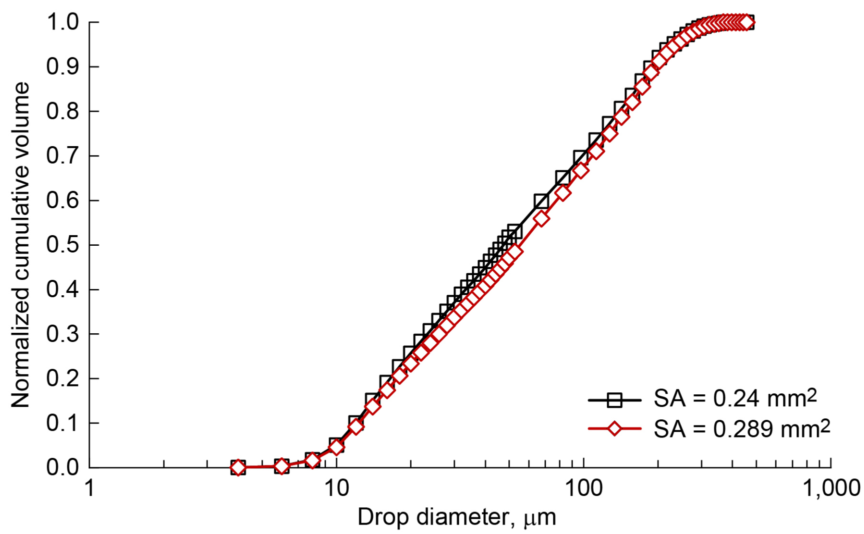

Figure 6.—Normalized cumulative volume distributions calculated using two different Cloud Droplet Probe (CDP) sample areas (SAs). A larger SA means a smaller calculated volume contribution from CDP.

September 2017 Tests With Realigned CDP

Following the realignment of the CDP, 2 days of testing were completed in the IRT to measure the drop size distributions using the CDP, the OAP–230X, and the OAP–230Y. Measurements were completed following standard IRT test practices for drop size calibration: test section airspeed was held constant at 130 knots, total temperature was held constant at –10 °C, and each probe was positioned at test section centerline. Drop-sizing measurements were completed across the IRT spray bar operating capabilities for Standard and Mod1 nozzles, including Mod1 with P_{air} < 10 psig. Drop-sizing data from the CDP for this test were processed using the newly measured sample area: 0.248 mm^2.

Analysis and Results of Drop-Sizing Data

Determination of Correct Sample Area To Use for 2014 to 2015 Calibration Data

The sample area value of 0.24 mm^2 (used until 2017) was the value specified in the CDP user's manual, but when the probe was sent to the manufacturer, the as-received sample area was measured to be 0.289 mm^2. Unfortunately, there was no way of knowing what the actual sample area was during the 2014 and 2015 timeframes. But because the 2014 and 2015 data had been used to develop the IRT's drop-sizing equations, the first question to answer was which of these sample area values should actually be used to process the historical data. In order to determine the accuracy of the IRT drop-sizing calibration curves, it was necessary to determine which CDP sample area value (0.24 or 0.289 mm^2) was more accurate for the 2014 and 2015 drop size calibration data. To determine this, the 2014 and 2015 drop-sizing data were processed with each of the two sample area values ($MVD_{0.24}$ and $MVD_{0.289}$). In 2017, measurements were made in like conditions with a newly aligned probe that had an understood CDP sample area of 0.248 mm^2 ($MVD_{0.248}$). The 2014 and 2015 values were then compared with the new 2017 MVD values to determine the more accurate sample area for the 2014 and 2015 data. Figure 7 shows this comparison for both the Mod1 and Standard nozzles. For the Standard nozzles (Figure 7(a)), it is difficult to say which value is more accurate; at around 30 µm, $MVD_{0.24}$ looks more accurate, but at MVD = 50 µm, the comparison is about equal, and at 60 µm, $MVD_{0.289}$ looks more accurate. For the Mod1 nozzles (Figure 7(b)), however, it is fairly clear that $MVD_{0.289}$ is a closer match to the 2017 $MVD_{0.248}$. After examining the comparisons given by both figures, it was decided that the sample area of 0.289 mm^2 is
the more accurate value to use for past data.

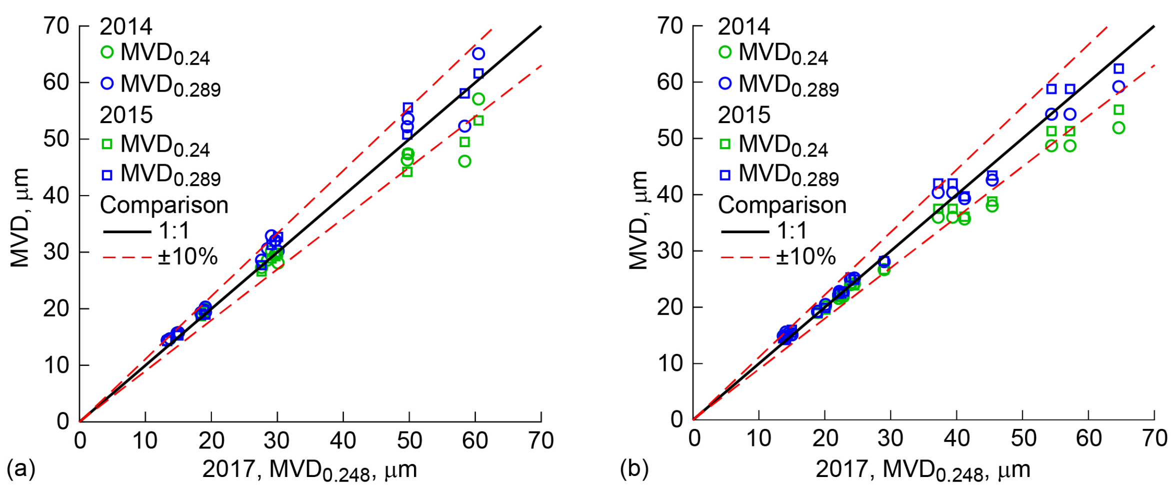

Figure 7.—Median volumetric diameter (MVD) values from 2014 and 2015 data calculated using Cloud Droplet Probe (CDP) sample area (SA) of 0.24 mm^2 from CDP user manual and SA of 0.289 mm^2 measured by manufacturer in 2017. These are compared against 2017 data from newly aligned CDP, with MVD calculated using its known measured sample area value of 0.248 mm^2. (a) Standard nozzles. (b) Mod1 nozzles.

Effect of Sample Area Change on 2014 to 2015 Data

After the sample area of 0.289 mm^2 was determined to be the better sample area value to use for CDP data taken in 2014 and 2015, the next step was to determine the effect this has on the data that were used to develop the IRT drop size calibration curves that have been utilized for the past 4 years. Figure 8(a) shows the difference, and Figure 8(b) shows the ratio comparison between the two calculated MVD values, plotted against the original MVD value used for the 2014 and 2015 calibration curves (Ref. 1). These plots include the effect seen for IRT conditions created with Mod1 nozzles and P_{air} < 10 psig, also known as large-drop conditions, to show how the amount of change varies across MVD values. It is greatest in the region where both the CDP and the OAP–230X give similar contribution to the total water content in the distribution. It can be seen that the difference is less than 18 percent for all conditions, but for MVD values between 30 and 100 μm, the difference is larger than 10 percent, which is greater than the professed accuracy of the drop-sizing equations for Appendix C conditions. These differences thus called for an update to the IRT drop-sizing calibration curves. As MVD increases beyond 80 μm, the fractional water content contributed by the CDP's drop-sizing range diminishes, lessening the increase in MVD.

Effect of Sample Area Change on Monomodal Distributions Close to Appendix O Conditions

Updated comparisons of the IRT distributions with Appendix O (Ref. 4) requirements are shown in Figure 9 for both freezing drizzle (FZDZ) and freezing rain (FZRA) conditions. These are primarily the same distributions shown in Figure 13 of Reference 1, but shown calculated with both possible CDP sample area values for 2014 and 2015 data (0.24 and 0.289 mm^2). The distributions are found to be very close to those reported previously. For FZDZ, MVD < 40 µm (Figure 9(a)) and FZDZ, MVD > 40 µm (Figure 9(b)), IRT distributions were selected that match the MVD (Dv0.50) or Dv0.98. Matching Dv0.98 (or similarly, Dv0.95 or 0.90) rather than the MVD would better assure that the effects of the larger drops in the distribution are captured. Also recognize that FZDZ, MVD < 40 µm conditions can be met with the more normal operation of P_{air} > 10 psig for the Mod1 nozzles. This is because IRT nozzles have long "tails"; that is, the largest drops produced for a spray condition are typically three to six times the MVD value.

Figure 9(c) plots the same data as Figure 3, but in the form of a normalized cumulative volume distribution. The IRT data plotted in Figure 3 and Figure 9(c) represent the maximum MVD in the IRT's calibrated operating range. For reference, Figure 9(c) compares this drop size distribution with the FAA's two FZRA distributions, MVD < 40 µm and MVD > 40 µm (Ref. 4).

Effect of Sample Area Change on Published Bimodal Conditions

In 2017, the IRT demonstrated that it was possible to simultaneously spray the Standard and Mod1 nozzle sets to create a bimodal distribution similar to the Appendix O requirements for FZDZ, MVD < 40 μm (Ref. 5). This specific drop size distribution has already been utilized for studies on supercooled large drop (SLD) conditions (Refs. 6 to 8). Figure 10 (adapted from Figure 11 in Ref. 5) shows the effect the change in CDP sample area had on this specific distribution. For all bin sizes containing drop-sizing counts, the difference in cumulative volume is, on average, 1.2 percent, and at most 2.9 percent. This does, however, tip the difference so that the normalized cumulative volume for all bin sizes is no longer within 10 percent, but it is still less than 13 percent. The difference between the two distributions is more than 10 percent only for bin sizes between 28 and 46 μm.

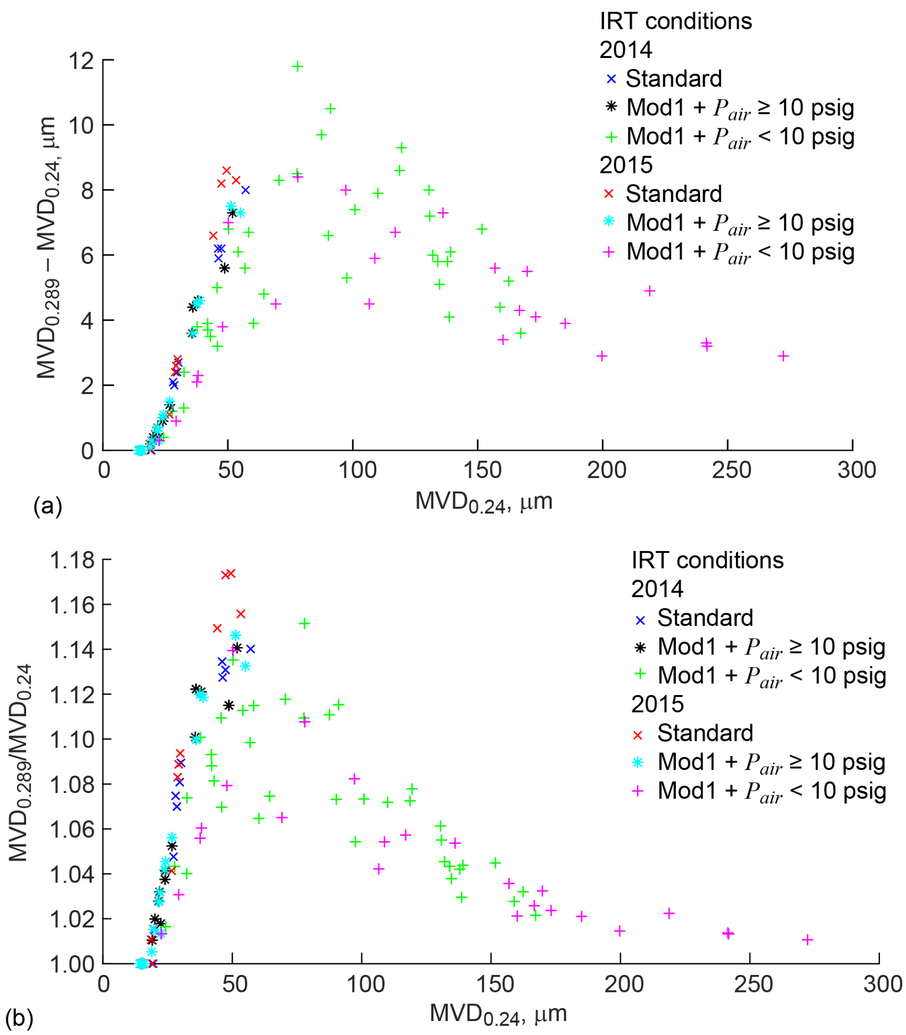

Figure 8.—2014 and 2015 drop-sizing data. Comparison of median volumetric diameter (MVD) values calculated with historical Cloud Droplet Probe sample area (SA) of 0.24 mm^2 provided by user manual and SA of 0.289 mm^2 measured by manufacturer in 2017, plotted against $MVD_{0.24}$ value used for 2014 and 2015 drop-sizing curves. (a) Difference between $MVD_{0.289}$ and $MVD_{0.24}$. (b) Ratio of values $MVD_{0.289}$ to $MVD_{0.24}$.

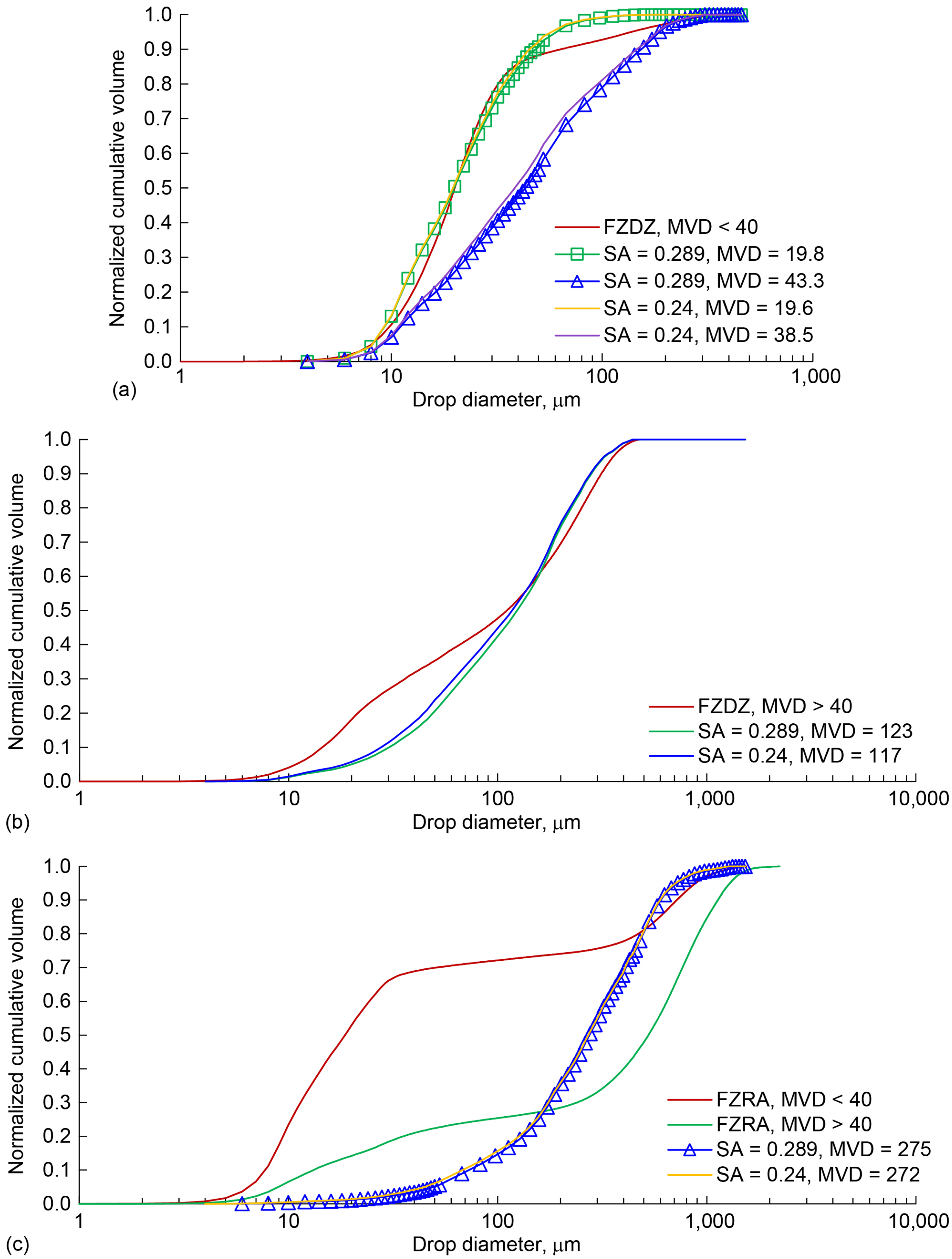

Figure 9.—Comparison of Appendix O conditions (Ref. 4) with Icing Research Tunnel (IRT) distributions calculated from Cloud Droplet Probe (CDP) sample area (SA) of 0.24 and 0.289 mm^2 (latter being more correct). (a) 2014 data. Freezing drizzle (FZDZ), median volumetric diameter (MVD) < 40 µm. (b) 2015 data. FZDZ, MVD > 40 µm. (c) 2015 data. Freezing rain (FZRA), MVD < 40 µm, and MVD > 40 µm, plotted alongside drop size distribution for largest MVD in IRT's calibrated range.

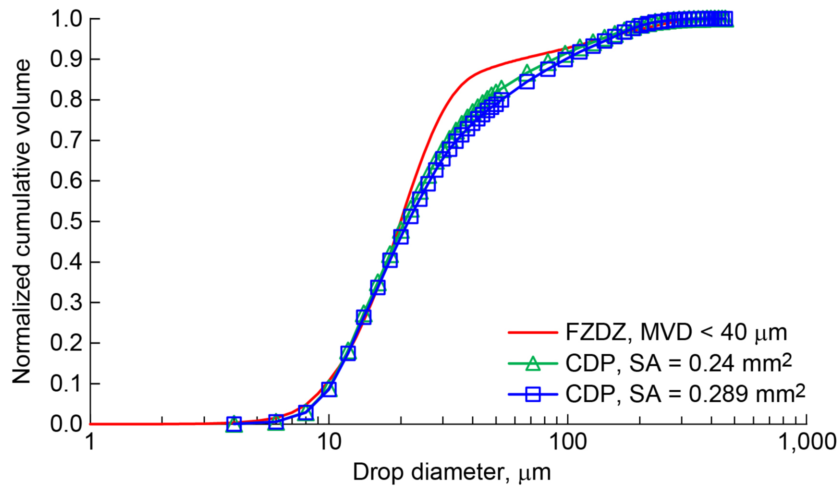

Figure 10.—Comparison of Icing Research Tunnel (IRT) combined Mod1 and Standard nozzle spray with Appendix O freezing drizzle (FZDZ), median volumetric diameter (MVD) < 40 μm distribution. CDP is Cloud Droplet Probe; SA is sample area. (Adapted from Ref. 5, Fig. 11.)

Icing Research Tunnel Drop-Sizing Equations

Updated Appendix C Drop-Sizing Equations

The MVD curve fit equations were determined by using the measured P_{air}, ΔP, and MVD from all three drop-sizing data collection tests, including January 2014 (CDP sample area (SA) = 0.289 mm^2), January 2015 (CDP SA = 0.289 mm^2), and September 2017 (CDP SA = 0.248 mm^2). Data were inputted into the curve fit generator TableCurve (Systat Software, Inc.). The equations that were generated, while quite complex, fit the majority of the data within 10 percent for Appendix C conditions (Mod1 and Standard nozzles, $P_{air} \geq 10$ psig), which is the typical target for the IRT. Different curve fits were generated for the Standard and Mod1 nozzles. It was coincidentally discovered that the equations that fit to the data best were of the same form as the equations used in 2015, but with new coefficients. The equation for large-drop conditions (Mod1 nozzles, $P_{air} < 10$ psig) has not yet been updated and is not included in this report.

The 2018 Standard MVD curve fit equation is

$$MVD_{Standard} = \frac{a + b * P_{air} + c * P_{air}^2 + d * \ln(\Delta P)}{1 + e * P_{air} + f * P_{air}^2 + g * P_{air}^3 + h * \ln(\Delta P)} \qquad (1)$$

where $a = 18.0$, $b = 0.14$, $c = 0.001211$, $d = -4.1212$, $e = 0.04706$, $f = -0.000591$, $g = 0.00000412$, and $h = -0.457$.

The 2018 Mod1 MVD curve fit equation is

$$MVD_{Mod1} = a + b * P_{air}^c + d * (\Delta P)^e + f * P_{air}^c * (\Delta P)^e \qquad (2)$$

where $a = 11.2384$, $b = 198.215$, $c = -2.2067$, $d = 0.001323$, $e = 1.3602$, and $f = 29.5724$.

Figure 11 and Figure 12 summarize these MVD curve fits for Standard and Mod1 nozzles, respectively, and include data from January 2014, January 2015, and September 2017. In Figure 11(a) and Figure 12(a), the curve fit lines are plotted as a function of ΔP for each calibrated P_{air} line. Measured MVDs are plotted against the respective curve fits for two P_{air} lines in each plot. Figure 11(b) and Figure 12(b) show how the curve fit values from Equations (1) and (2) compare with the measured values for all Standard and Mod1 conditions. The 1:1 line and the ±10 percent lines are shown for reference. These plots show that the curve fits for the vast majority of the data points are within the IRT's typical targeted accuracy of ±10 percent.

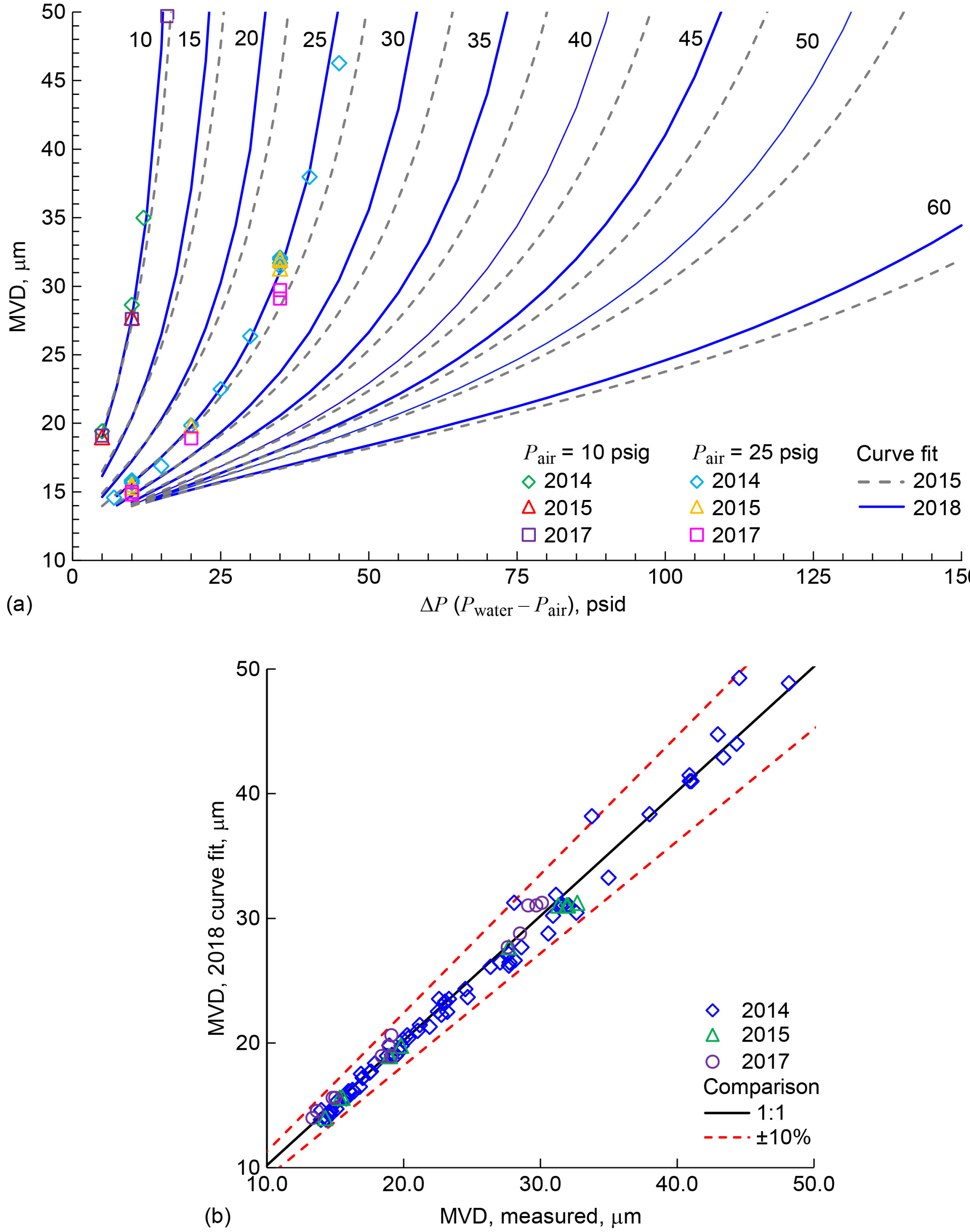

Figure 11.—Drop size calibration curves for Standard nozzles. (a) Median volumetric diameter (MVD) versus ΔP (spray nozzle $P_{water} - P_{air}$, psid) for each (labeled) atomizing air pressure (P_{air}) line. January 2014 and 2015 used Cloud Droplet Probe (CDP) sample area (SA) = 0.289 mm^2; September 2017 used CDP SA = 0.248 mm^2. Each line plots a constant nozzle air pressure. (b) Curve fit versus measured MVD for all Standard nozzle calibration points.

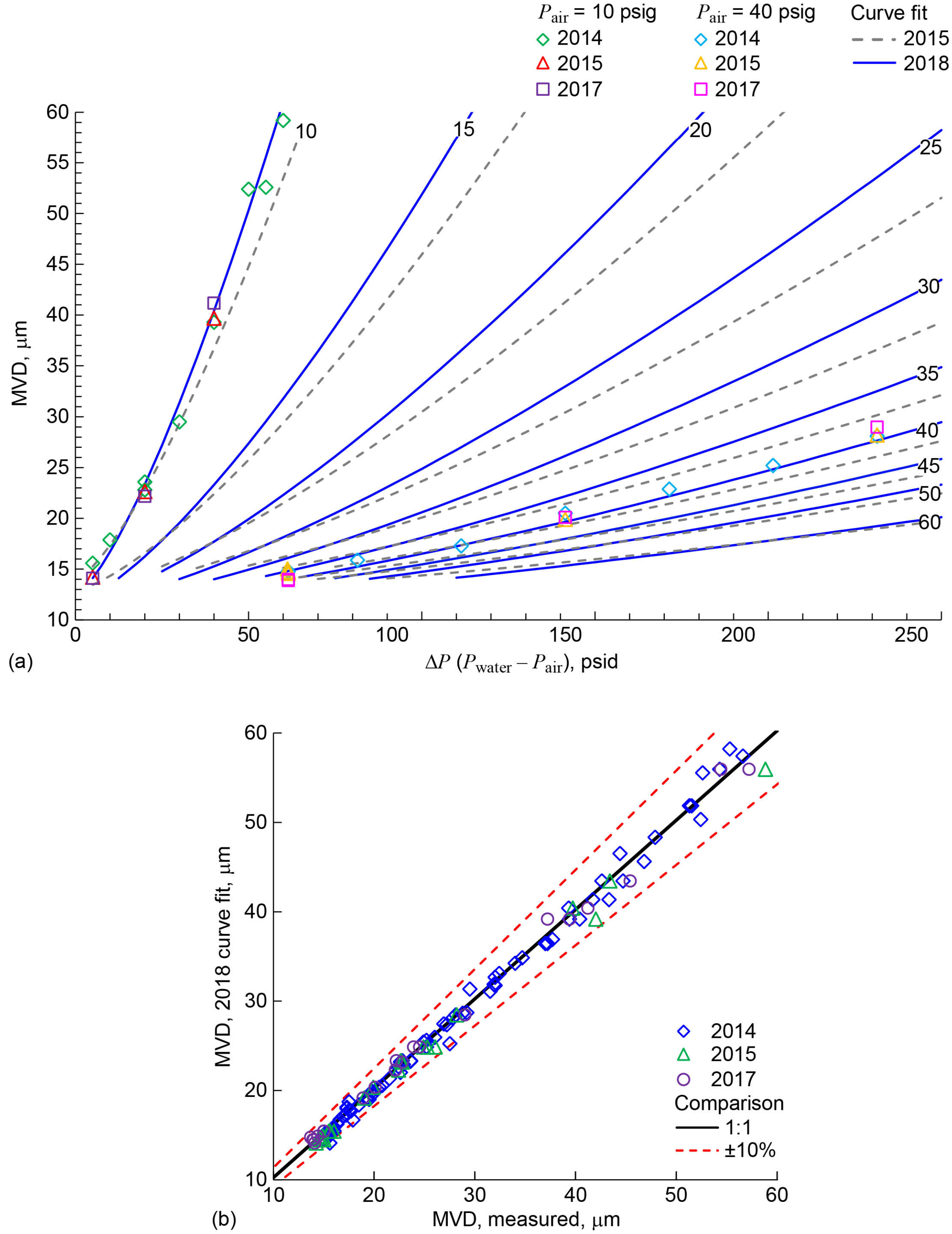

Figure 12.—Drop size calibration curves for Mod1 nozzles. (a) MVD versus ΔP for each (labeled) P_{air} line. January 2014 and 2015 used CDP sample area (SA) = 0.289 mm^2, and September 2017 used CDP SA = 0.248 mm^2. Each line plots a constant nozzle air pressure. (b) Curve fit versus measured MVD for all Mod1 nozzle calibration points.

Impact on Liquid Water Content Equations

The following two equations describe the calibrated values for LWC of the IRT:

$$LWC_{\text{Standard}} = \left(a * V + b * P_{\text{air}} + c\right) * \left(\frac{MVD - 3}{d}\right)^{e} * \frac{\sqrt{\Delta P - 1}}{V} \quad (3)$$

$$LWC_{\text{Mod1}} = \left(a * V + b * P_{\text{air}} + c\right) * \left(\frac{MVD - 2}{d}\right)^{e} * \frac{\sqrt{\Delta P}}{V} \quad (4)$$

Because these equations contain a MVD component, it was necessary to ensure that the change to the defined MVD values did not cause the calculated LWC values to deviate too far from their measured values, as the IRT's LWC values have not changed. To address this, all measured LWC values taken in 2014 were checked against their respective calculated values using the newly defined MVD values. The results of this analysis are shown in Figure 13. For the Standard nozzles (Figure 13(a)), the average change in calculated LWC was less than 1 percent, and nearly all test points still match the calibrated values within ±10 percent. The calculated LWC for Standard nozzles shifted by more than 4 percent for only a few data points. For the Mod1 nozzles (Figure 13(b)), the average change in calculated LWC was less than 1 percent, and there was actually one fewer point outside the ±10 percent limits than in 2015. The calculated LWC for Mod1 nozzles shifted by more than 2 percent for only a few data points. It was therefore determined that it was unnecessary to update the IRT LWC equations following this change to the defined MVD values.

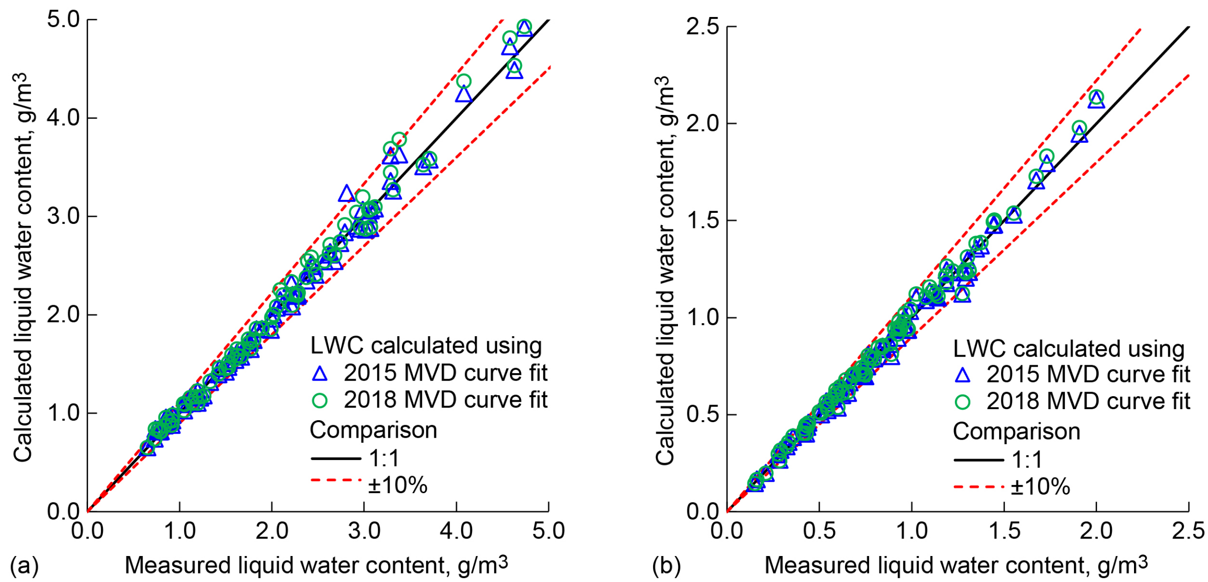

Figure 13.—Comparison of liquid water content (LWC) curve fits versus measured LWC showing effect of new median volumetric diameter (MVD) calibration curves on LWC curve fits. LWC values have been corrected for collection efficiency. (a) Standard nozzles. (b) Mod1 nozzles.

Updated Operating Envelopes

The IRT's updated 2018 icing envelopes for both the Mod1 and Standard nozzles are compared with the Appendix C icing criteria in Figure 14. The airspeed of 225 knots has been selected. The change to the operating envelopes appears to be less substantial than the change to the drop-sizing equations (Figure 11 and Figure 12) because the change in calculated MVD values is less than a few microns until MVD > 30 µm, and there is no shift in LWC values.

Figure 14 shows the operating envelopes for 225 knots. At lower airspeeds, the curves shift to higher LWC values, and at higher airspeeds they shift down. While the commonly requested data points MVD = 20 µm, LWC = 0.5, and 1 g/m^3 are easily achieved, another requested point, MVD = 40 µm, LWC = 0.07 g/m^3, will likely never be achieved with the current nozzle design. A comparison of this plot with the operating envelope published in 2015 (Ref. 1) will show a few minor adjustments to some of the corners of the 2015 curves; these changes were made to more accurately represent the specific conditions for which the IRT has cloud calibration data.

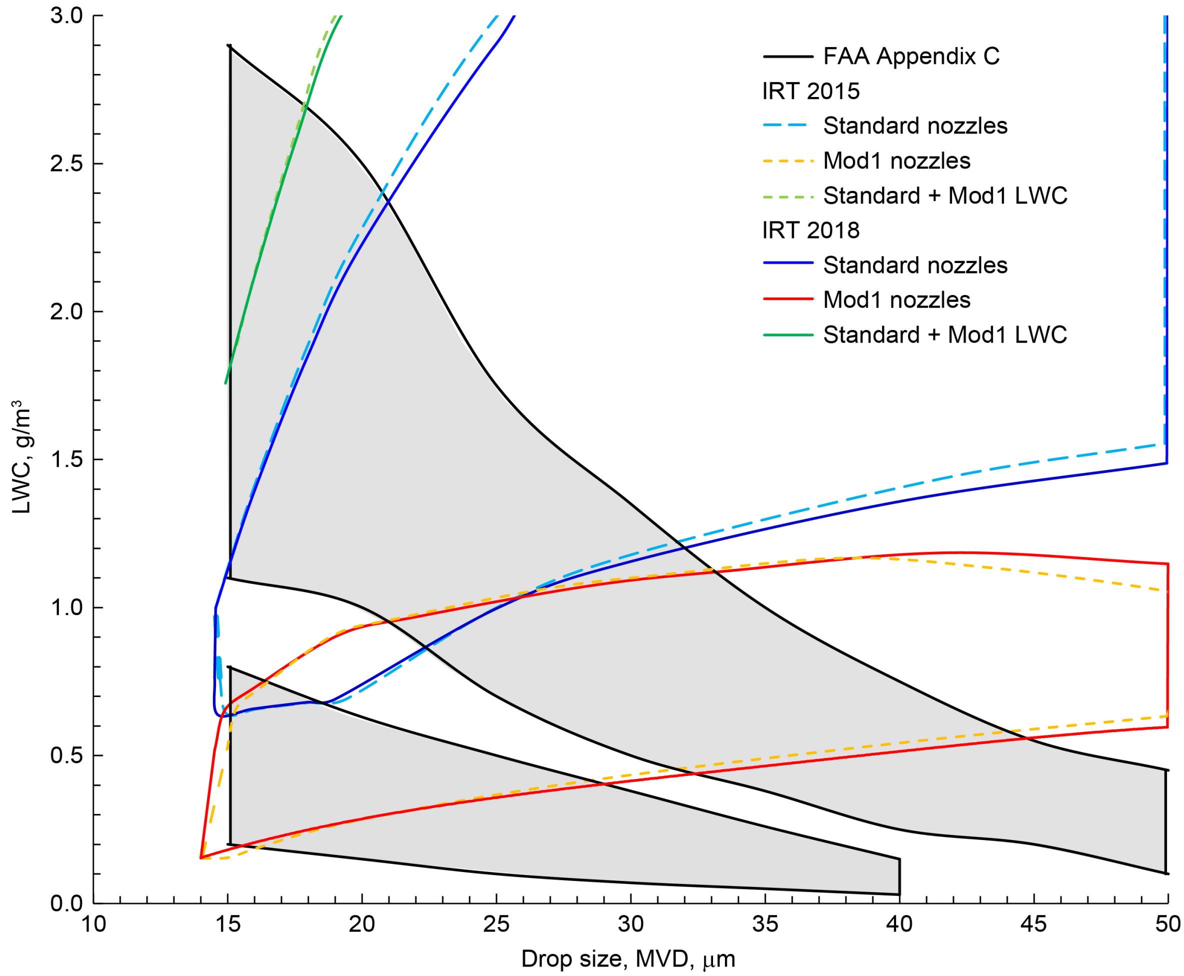

Figure 14.—Comparison of Icing Research Tunnel (IRT) operating envelopes, liquid water content (LWC) versus median volumetric diameter (MVD), with Federal Aviation Administration (FAA) Appendix C icing certification criteria for airspeed of 225 knots.

Conclusions

In 2017, after sending the Cloud Droplet Probe (CDP) to the manufacturer for realignment, the Icing Research Tunnel (IRT) staff received information that improved their understanding of the probe's sample area. The beam area was mapped before aligning and was discovered to be 0.289 mm^2 instead of 0.24 mm^2, the value reported in the CDP user manual. Unfortunately, there was no way of knowing what the actual sample area was during the 2014 and 2015 time frames. IRT staff used the as-received sample area to recalculate median volumetric diameter (MVD) values (i.e., $MVD_{0.289}$) for IRT drop-sizing data taken in 2014 and 2015. After the probe was realigned, the sample area was measured to be 0.248 mm^2. The new values ($MVD_{0.289}$) and the old values ($MVD_{0.24}$) were each compared with measurements taken in September 2017 using the realigned probe ($MVD_{0.248}$), and it was determined that the sample area value of 0.289 mm^2 was the more accurate value to use for historical data.

Applying this change to the historical data caused the calculated number density values of the CDP to decrease, which also decreased the liquid water content (LWC) contributed to drop size distribution by the CDP. This caused spray conditions that required multiple drop-sizing probes (i.e., conditions for which MVD > 18 μm) to have a higher calculated MVD value.

The conditions most affected by the change were those with MVD values between 30 and 100 μm, that is, where the LWC contributed by the CDP and the optical array probe OAP–230X was similar. These MVD values increased by 10 to 18 percent with the new CDP sample area of 0.289 mm^2. A few other drop size distributions were examined, including the IRT's previously published attempts to match Federal Aviation Administration (FAA) Appendix O conditions and the bimodal match to freezing drizzle (FZDZ), MVD < 40 μm. These distributions did not change by more than a few percent. However, the normalized cumulative volume for the bimodal distribution now differs by more than 10 percent from the Appendix O distribution for drop sizes between 28 and 46 μm. That difference is as high as 12 percent.

The 2014 and 2015 measured MVD values were recalculated with the new CDP sample area value of 0.289 mm^2, and new drop-sizing equations were built for Appendix C conditions (Mod1 and Standard nozzles, $P_{air} \geq 10$ psig and MVD < 50 μm) that match within ±10 percent of the measured values. The IRT's Appendix C LWC equations were also checked, and the new MVD values did not cause the calculated LWC values to differ from the measured LWC values by more than 10 percent; hence, there is no need to develop new LWC calibration equations. The new operating envelopes were also plotted and compared against the old operating envelopes, and there was found to be little difference between the two.

The new drop-sizing equations were implemented in the IRT in May 2018. Drop size distributions for tests run in the IRT between January 2014 and April 2018 may be clarified with IRT cloud calibration staff. This change makes the previous values conservative—in other words, if previous IRT testing showed that an ice protection system could handle a cloud with a certain MVD value, the analysis in this paper suggests that the system could actually handle a cloud with a larger MVD value.

References

1. Steen, Laura E., et al.: NASA Glenn Icing Research Tunnel: 2014 and 2015 Cloud Calibration Procedure and Results. NASA/TM—2015-218758, 2015. http://ntrs.nasa.gov
2. Federal Aviation Administration: Atmospheric Icing Conditions. U.S. Code of Federal Regulations, Title 14, Part 25, Appendix C, 2015.
3. Federal Aviation Administration: Icing Certification. U.S. Code of Federal Regulations, Title 14, Part 29, Appendix C, 1983.
4. Federal Aviation Administration: Supercooled Large Drop Icing Conditions. U.S. Code of Federal Regulations, Title 14, Part 25, Appendix O, 2015.

5. King-Steen, Laura E.; and Ide, Robert F.: Creating a Bimodal Drop-Size Distribution in the NASA Glenn Icing Research Tunnel. AIAA 2017–4477, 2017.
6. Potapczuk, Mark G.; Tsao, Jen-Ching; and King-Steen, Laura E.: Bimodal Ice Accretion on a NACA 0012 Airfoil Model. AIAA 2017–4478, 2017.
7. Potapczuk, Mark G.; and Tsao, Jen-ching: Further Examinations of Bimodal SLD Ice Accretion in the NASA Icing Research Tunnel. AIAA 2018–3182, 2018.
8. Potapczuk, Mark G.; and Tsao, Jen-ching: The Influence of SLD Drop Size Distributions on Ice Accretion in the NASA Icing Research Tunnel. SAE Technical Paper 2019–01–2022, 2019.