Creating a Bimodal Drop-Size Distribution in the NASA Glenn Icing Research Tunnel

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The Icing Research Tunnel at NASA Glenn has demonstrated that they can create a drop-size distribution that matches the FAA Part 25 Appendix O FZDZ, MVD<40 µm normalized cumulative volume within 10%. This is done by simultaneously spraying the Standard and Mod1 nozzles at the same nozzle air pressure and different nozzle water pressures. It was also found through these tests that the distributions that are measured when the two nozzle sets are sprayed simultaneously closely matched what was found by combining the two individual distributions analytically. Additionally, distributions were compared between spraying all spraybars and also by spraying only every-other spraybar, and were found to match within 4%. The cloud's water content uniformity for this condition has been found to be excellent: ±10%. It should be noted, however, that the liquid water content for this condition in the IRT is much higher than the requirement specified in Part 25 Appendix O. A separate conference paper has been written to examine the effect this distribution has on an airfoil.

Nomenclature

CDP	=	Cloud Droplet Probe
DelP	=	nozzle delta pressure: water pressure minus air pressure, in psid
Dv0.95	=	drop diameter at which 95% of the total volume of water is contained in smaller drops, in µm
expt	=	describes condition that was measured, experimentally
FZDZ	=	Freezing Drizzle
FZRA	=	Freezing Rain
IRT	=	Icing Research Tunnel
LWC	=	liquid water content, in g/m^3
MVD	=	median volumetric diameter, in µm
OAP-C	=	Optical Array Probe—Cloud
P_{air}	=	nozzle air pressure, in psig
SLD	=	Supercooled Large Drop

I. Introduction

IN November 2014, the FAA released new Supercooled Large Drop (SLD) icing criteria for aircraft certification, spelled out in Appendix O of Part 25 regulations[1] for transport category aircraft. The environmental conditions that are described in these regulations pose a substantial technical challenge for ground-test icing facilities for several reasons, one of which being that the defined drop-size distributions are bimodal and cannot be reproduced with a single set of spray nozzles, or at least not that are all using the same pressure settings. If a drop-size distribution contains a substantial number of larger drops, it could affect the cloud impingement limits on the model surface, which is critical information for protection systems. Other considerations in creating the Supercooled Large Drop conditions include the low liquid-water content values, the temperature of the drops, the drop trajectories, and drop breakup.

The Icing Research Tunnel (IRT) at NASA Glenn Research Center has been working to address some of these concerns—to know what Appendix O conditions can be replicated within the IRT, and to what fidelity. The ultimate goal is to know what impact an Appendix O condition has on an aircraft, so that aircraft ice protection systems can be properly designed and certified to fly in these icing conditions. Computer codes may be developed to aid in this, but they cannot be validated if there is no experimental data to confirm the results.

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This paper specifically addresses the creation of the bimodal distribution for Freezing Drizzle with a median volumetric diameter less than 40 µm (FZDZ, MVD<40 µm) using the IRT's two sets of spray nozzles. This drop-size distribution has been created in the IRT and measured to match the FAA Appendix O normalized liquid water content (LWC) cumulative distribution within 10% of the total volume for all drop sizes. Furthermore, these tests showed experimentally that for two different cases, the measured combined drop-size distributions from two nozzle spray conditions matched the mathematical sum of the two conditions sprayed individually. It should be noted from these tests, however, that combining spray conditions from two nozzles sets resulted in a liquid water content value much higher than specified by the FZDZ, MVD<40 µm distribution. Further work will be reported in Ref. 2 to test the differences that are affected on an ice shape with the new bimodal distribution.

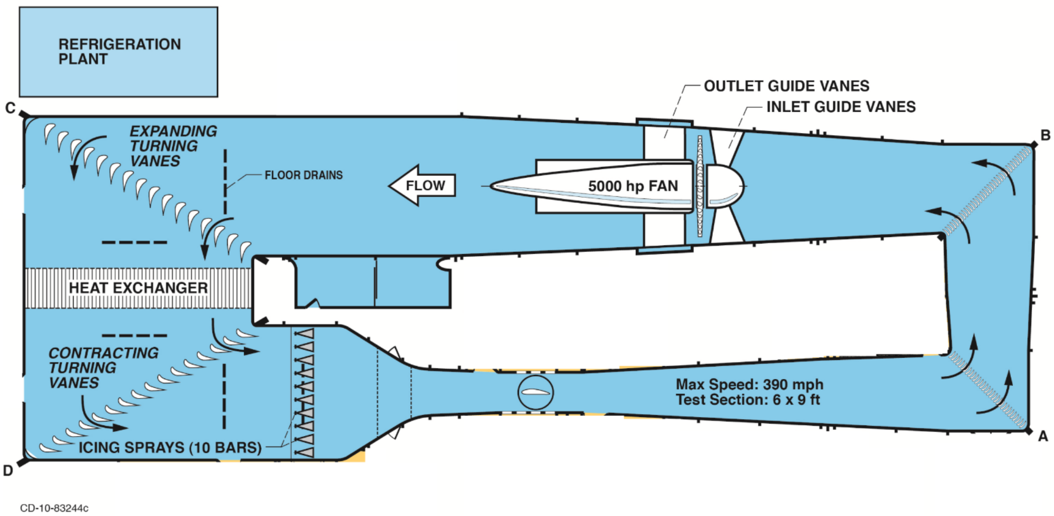

Figure 1. Schematic of the Icing Research Tunnel at NASA Glenn Research Center

II. The Icing Research Tunnel Spraybars

The Icing Research Tunnel is a closed-loop, atmospheric tunnel, with a 1.83 m by 2.74 m by 6.10 m (6 ft by 9 ft by 20 ft) test section. A tunnel schematic is shown in Fig. 1. The IRT's calibrated test section airspeed ranges between 50 and 350 knots. The test section temperature can be controlled between +10 °C total temperature to -35 °C static temperature.

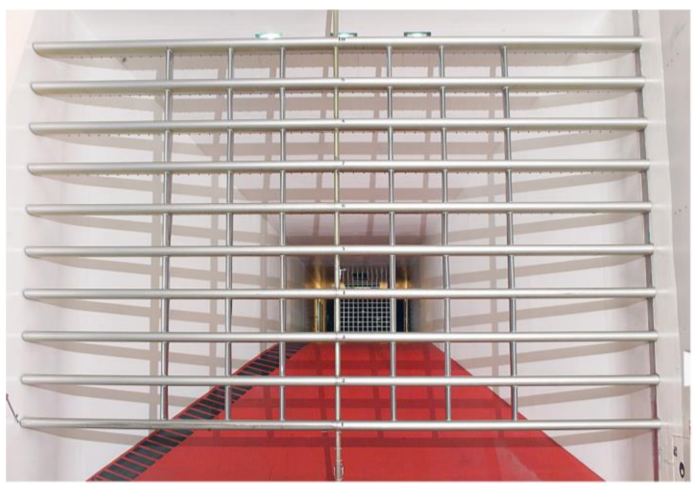

Figure 2. The IRT spraybars, viewed from upstream, looking down the contraction into the test section (uniformity grid is mounted in test section).

The spraybars that create the cloud are located just upstream of the contraction and consist of 10 bars (Fig. 2), each of which has one air manifold and two water manifolds, which allows two nozzle sets to be run, The two types of spray nozzles utilized in the IRT spray bars are the Standard nozzles that have a higher water flow rate, and the Mod1 nozzles that have a lower water flow rate. Both nozzle types use internal mixing of air and water to create the cloud. The primary difference is in the diameter of the water hypodermic tubing used in the nozzles. There are currently 165 Standard nozzles and 88 Mod1 nozzles in the spray bars. The two nozzle sets may be sprayed individually, or if they are set at the same air pressure, they may be sprayed simultaneously, with different water pressures. Nozzle air pressure (P_{air}) and delta (water) pressure (expressed as water pressure minus P_{air}, or DelP) and nozzle type are varied

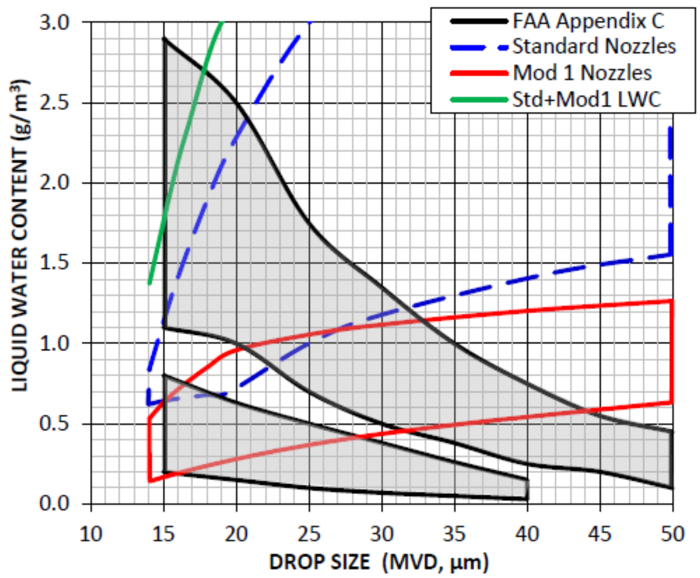

Figure 3. Comparison of the IRT operating envelopes, LWC versus MVD, to the FAA Icing Certification Criteria for an airspeed of 225 kts. The FAA Appendix C envelopes are shaded and indicated in black. The Mod1 nozzles are in red and the Standard nozzles are in dashed blue. The Mod1 and Standard nozzles can be combined under limited circumstances to produce higher LWC, shown in green. Figure taken from Ref. 3.

to create the desired drop size and water content. All water supplied to the IRT spray bars has been filtered and de-ionized.

Drop sizes in the IRT are typically described in terms of median volumetric diameter (MVD), which is the drop diameter at which half the liquid water content volume is contained in smaller drops (and half in larger drops). Under "normal" operating conditions, when P_{air} is 10 psig or higher, the calibrated MVD range of the spray nozzles is between 14 and 50 μm for both nozzle sets. When P_{air} is set below 10 psig, larger drops can be created, resulting in a calibrated MVD as high as 270 μm and maximum drop sizes as high as 1200 μm. This is typically only done with the Mod1 nozzles, since they have a lower flow rate, better matching to the requirements of large-drop certification criteria. The calibrated cloud liquid water content (LWC) range of the IRT is between 0.2 and 4.5 g/m3 and is a function of airspeed. A full report on the cloud calibration of the IRT can be found in Ref. 3. Figures 3 and 4 are taken from Ref. 3 and show the operating range of LWC vs. MVD for the two nozzle sets. Figure 3 shows both nozzle sets in "normal" operation conditions at a tunnel airspeed of 225 knots, compared to FAA Appendix C conditions[4]. Figure 4 shows the operating envelopes for Mod1 nozzles under large-drop operating conditions.

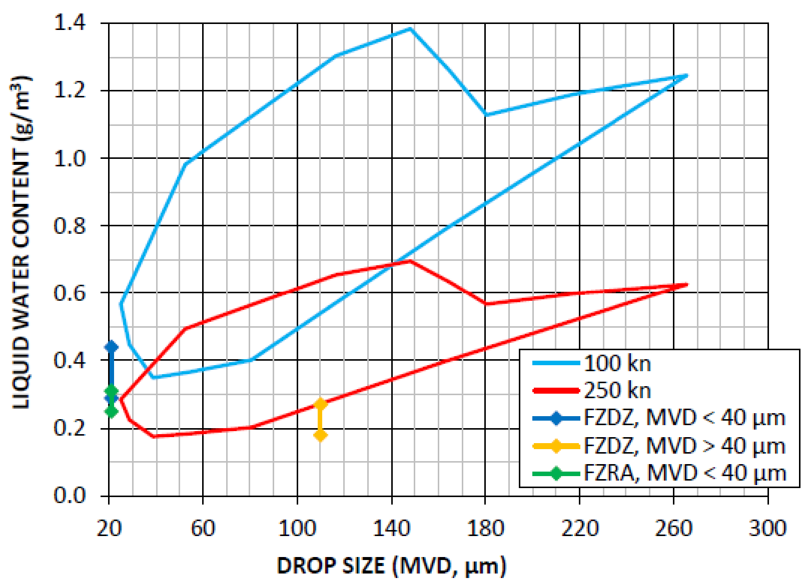

Figure 4. The IRT large-drop operating envelopes at an airspeed of 100 and 250 knots using Mod1 nozzles. For reference, the Appendix O max LWC ranges are also shown for each FZDZ and FZRA condition[1]. FZRA, MVD>40 μm has an MVD of 526 μm and an LWC between 0.21 and 0.26 g/m³ and it is not included on this plot. Figure taken from Ref. 3.

III. IRT General Procedures for Measuring Drop Diameter

Two drop-sizing probes were used for the data in this report. The Cloud Droplet Probe (CDP), from Droplet Measurement Technologies, and an Optical Array Probe—Cloud (OAP-C) produced by Particle Measurement Systems.

The CDP is a forward-scattering probe. When a particle passes through the sample area of the beam, light is scattered in all directions and the probe records the forward scattered light intensity. This intensity is roughly proportional to the square of the diameter of the particle, as described by Mie Scattering Theory. The

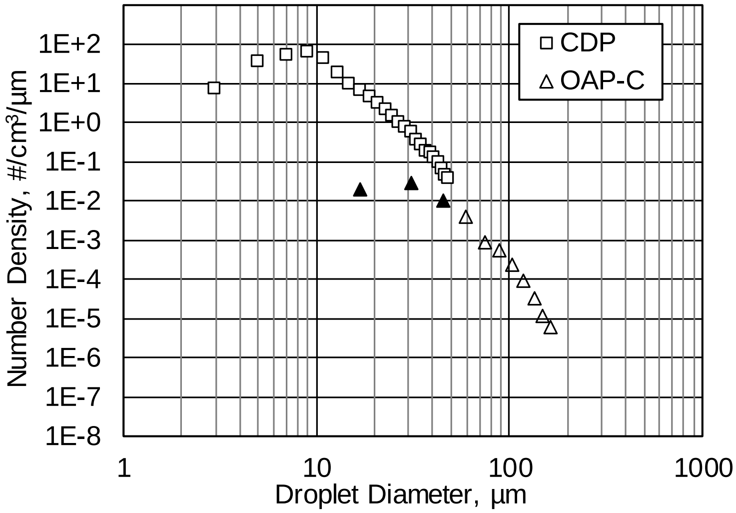

Figure 5. Number Density (in counts per cm³), normalized by the width of each bin and plotted against the middle diameter for each bin. The three triangles for the OAP-C plotted between 15 – 50 µm are shaded black because they are not used in the calculation of MVD. For this spray, P_{air}=15 psig, DelP=30 psid.

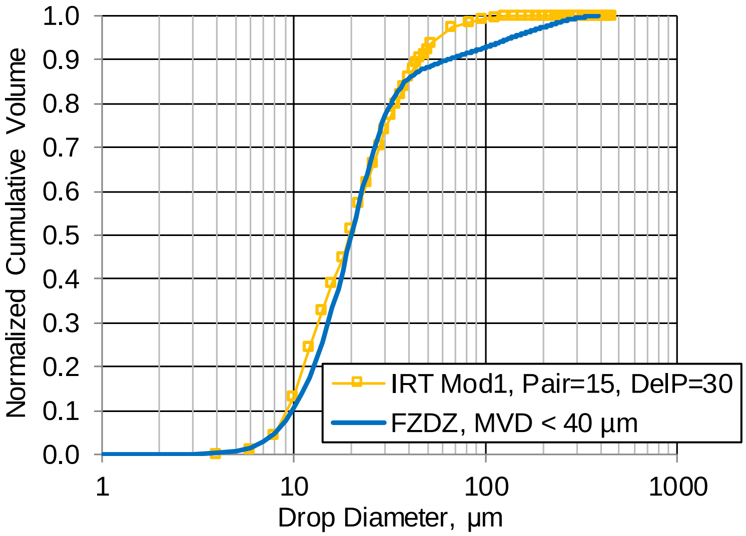

Figure 6. Normalized cumulative volume plot for data corresponding to Fig. 4 and also including the same data as Fig. 13a of Ref. 3, plotted alongside the Appendix O, FZDZ, MVD<40 µm distribution. This is an example of a typical mono-modal drop size in the IRT. The MVD for this condition is 19.6 µm.

measured particle diameters are sorted into bins, based on intensity threshold values within the data acquisition software. By this method, the CDP can measure drop diameters from 2 – 50 µm.

The OAP-C is an optical array probe that works using diode shadowing. As a particle passes across the beam, it creates a shadow across the array of receiving diodes. For a particle to be recognized by the probe, at least one diode must be shadowed by 60%. That is, its voltage has dropped to 40% (or less) of its unshadowed voltage. For each recognized particle, the value sent to the acquisition system is the total number of diodes that are shadowed by at least 50%. A particle is not recorded if an end-diode is shadowed, because the size outside the sample area is unknown. Particle sizes are sorted into bins, based on the magnification level of the probe, which determines the bin resolution. The IRT's OAP-C, model OAP-230X, is a 1-dimensional probe with a resolution of 15 µm per bin and 30 sizing diodes, which gives it an overall drop-size range of 15 - 450 µm. The smallest bins have a greater uncertainty, largely because the sizing resolution is on the same order of magnitude as the particle diameters. Particles between 15-30 µm diameter could also pass between diodes and not be counted at all.

To properly calculate the MVD, the full range of drop sizes present in the cloud must be measured (smaller drops and larger drops), so often both probes are required. To combine the drop-size distributions from each probe, the number of counts in each bin for each probe is divided by the probe sample volume (sample area multiplied by airspeed and time) to get the number density for each bin, which is reported per cubic centimeter. A plot of the number density normalized by the width of each bin is shown in Fig. 5. The number density is then multiplied by volume of water per drop, using the middle diameter for the bin ((max size – min size) / 2). This gives the liquid water content for the bin, reported in g/m³. These liquid water content values from each bin of the CDP and the OAP-C are then used together to calculate the MVD. Measurements from the OAP-C smaller than 50 µm are not used because the OAP-C has less fidelity than the CDP in this region, as already described. The cumulative LWC is the total LWC contained in drop sizes smaller than each bin's maximum drop diameter. This cumulative LWC is then normalized by the total LWC measured for that condition (sum of all included bins) to get

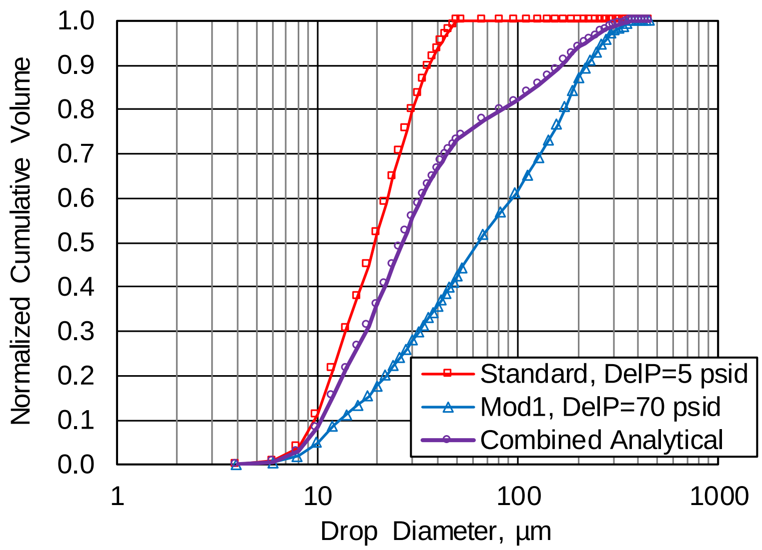

Figure 7. Analytical drop-size distribution created by combining two spray conditions (also included) that were measured during the IRT 2014 Full Calibration. This is the most "stark" bimodal distribution that can currently be created, using the lowest air pressure that is common to both nozzle sets, Pair = 10 psig, and the greatest difference in MVD.

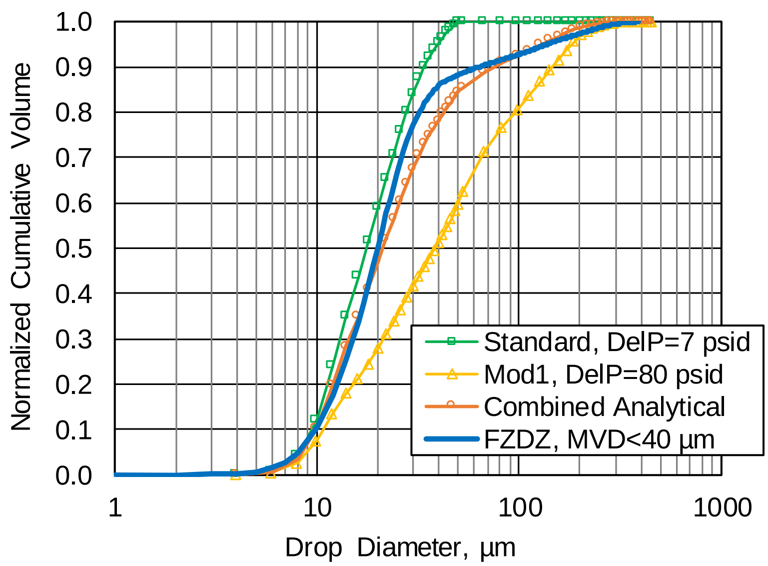

Figure 8. Analytical drop-size distribution created by combining two spray conditions at Pair = 15 psig (also shown) that were measured during the IRT 2014 Full Calibration. Individual distributions were chosen to match the Appendix O, FZDZ, MVD<40 µm distribution, which is also shown.

the Normalized Cumulative Volume plot shown in Fig. 6. From this we can see the Median Volumetric Diameter is 19.6 µm: the diameter at which 50% of the volume is contained in smaller drops. This graph can also be used to find Dv90 and Dv99, which are the diameters at which 90% and 99% of the volume is contained in smaller drops.

Note that the distribution in Fig. 6 is also the one given in Ref. 3 as the closest to the FZDZ, MVD<40 µm distribution, which is also included in the figure. At all MVD values, the two curves match within 10% of their normalized cumulative volumes, but the larger drop diameters that are present in the FZDZ, MVD<40 µm distribution are clearly missing from the compared IRT distribution.

IV. Creating Bimodal Distributions, Analytically

To create an analytical drop-size distribution to compare to the FAA FZDZ, MVD<40 µm distribution, two selected drop-size distributions (one from Mod1 nozzles and one from Standard nozzles) were superimposed by adding the liquid water content values for respective bin sizes. Once the new LWC values were obtained, new cumulative volumes were calculated for each bin and normalized by the new total water content. The distributions that were used were from the 2014 IRT full calibration[3,5]. Because the IRT spray bars have only one air manifold, both conditions had to have the same P_{air}. An example distribution is given in Fig. 7, which shows the two individual drop size distributions as well as the combined distribution.

As would be expected, the effect on the overall drop-size distribution is more noticeable when there is larger difference in MVD between the two individual conditions. Since the lower nozzle air-pressures generate a wider range of MVD values with varying water pressure, these lower air pressures create more "stark" bimodal conditions. Figure 7 was created with the lowest P_{air} that has been calibrated for both nozzle sets (10 psig), with the highest DelP from the Mod1 nozzles and the lowest DelP from the Standard nozzles, hence it is the most distinctly bimodal distribution that could be created at the time.

Several different combinations of drop sizes were tried to ultimately obtain Fig. 8, which was found to be the best match to the Appendix O FZDZ, MVD<40 µm distribution. Figure 8 also shows the individual distributions that were combined, as well as the FZDZ, MVD<40 µm distribution. It can be seen here that for all drop diameters, the normalized cumulative volumes of the two distributions match within 10%, and the larger drops are present in both the IRT distribution and the FZDZ, MVD<40 µm distribution.

V. Measuring Bimodal Distributions, Experimentally

A. Test Procedures

The two drop-sizing probes were run separately so that each could be mounted in the center of the test section; thus, each condition was sprayed twice—once for each probe. The two bimodal conditions that were examined were those shown in Figures 7 and 8. This test collected spray data for the Mod1 + Standard nozzle combined sprays as well as the individual Mod1- and Standard-nozzle conditions that were used in the combination.

Typically, when a drop-sizing calibration is done in the IRT, only half the spray bars are run in order to decrease number density and prevent coincidence error from the probes. At each calibration cycle, a drop-size comparison is made between running all spray bars, running only the even-numbered spray bars, and running only the odd-numbered spray bars. The different conditions are examined to see which condition shows a reasonably strong number density (approximately above 1000 /cm^3) without showing effects of coincidence error. Coincidence error would be indicated by very high number densities coupled with larger-than-expected MVD values that occur as a result of multiple drops being measured at the same time. Based on the results of the previous calibration, the majority of conditions for the bimodal test were collected using only the even-numbered spray bars. However, for the sake of completeness, the combined Mod1 + Standard cloud was also measured using all bars for the P_{air}=15 psig distribution.

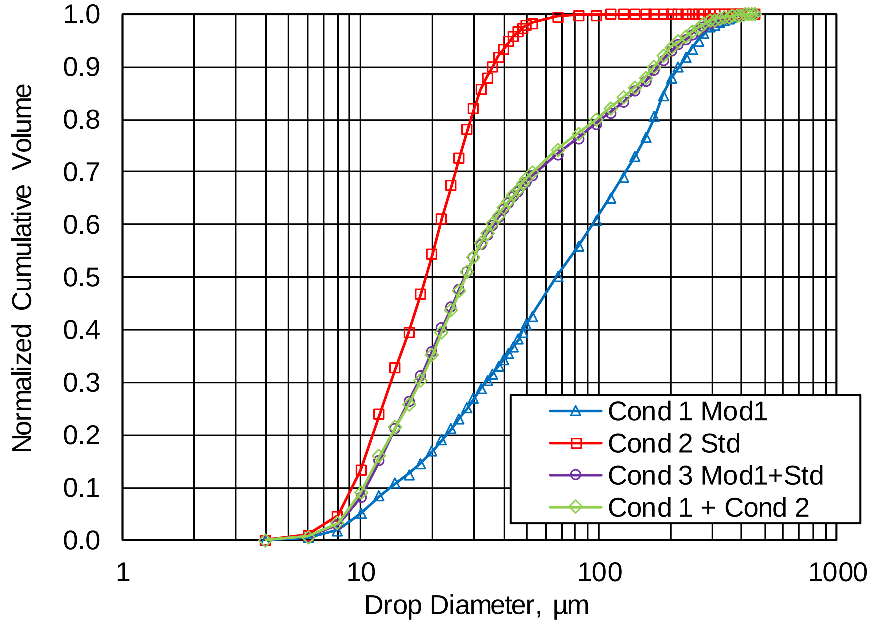

Figure 9. Experimental results for the "stark" bimodal condition, i.e., the distribution from combining two distributions at the minimum air pressure, Pair = 10 psig and the largest difference in MVD value. Shown here is the distribution from the combined spray, the two individual conditions that were combined to create it, and also the distribution from the mathematical summation of the two individual conditions. It is evident that the analytical matches well to the experimental.

B. Experimental Results

Figure 9 shows the measured drop-size distributions corresponding to the combined spray with a P_{air} of 10 psig, i.e., the "stark" bimodal distribution. This plot shows the measured distribution for simultaneously spraying the Mod1 and Standard nozzles (indicated as "Mod1+Std") as well as the two individual spray conditions from the respective Mod1 and Standard nozzles. All conditions were created using only the even-numbered spray bars. Lastly, this plot shows the drop-size distribution created mathematically by superpositioning the two individual spray bar conditions, using the same calculation procedures described earlier. Figure 10 is shown in the same format, except with the addition of the simultaneous Mod1+Std spray that was created using all spray bars. Clearly, there is good comparison between these two distributions, whether they were created by measuring both nozzle sets sprayed simultaneously or by mathematically adding the two individual conditions together.

Further analysis was done to determine how closely the analytical vs. experimental distributions match, which is

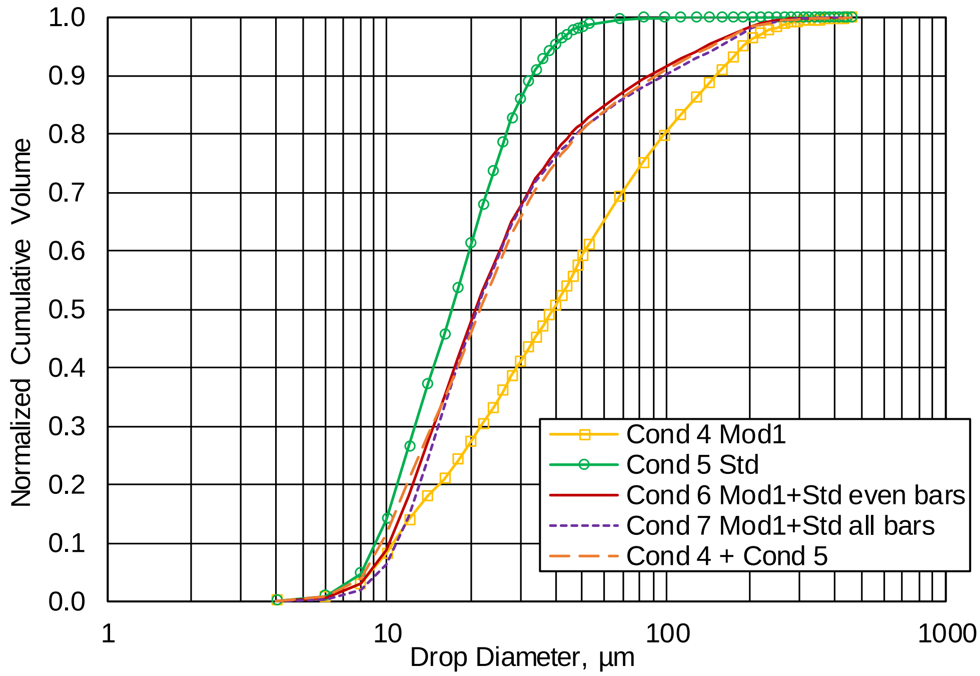

Figure 10. Experimental results for the attempted FZDZ, MVD<40 µm bimodal condition. Shown here are two distributions from the combined spray (one spraying only even-numbered bars, one spraying all bars), as well as the two individual conditions that were combined to create it (even-numbered bars only), and also the distribution from the mathematical summation of the two individual conditions. It is evident that all three methods for creating the combined spray match well to each other.

shown in Table 1. The first two columns of the table indicate which two distributions are being compared. The nomenclature "Mod1+Std expt" means conditions that were measured experimentally by simultaneously spraying the Mod1 and Standard nozzles, and are indicated as having been created from even-numbered spraybars or all bars. Distributions described as "sum of Mod1 and Std" were created by mathematically combining two individual spray conditions that were sprayed with only the even-numbered bars. In the last three columns, the difference (Diff.) values shown examine the differences in (percent) cumulative volume across all bin sizes, and the values indicated are the mean and maximum of these differences. Essentially, the percent differences described in Table 1 simply refer to the y-axis value differences between the two compared distributions for any given drop diameter on the normalized cumulative volume plot. "Diam. at Max. Diff." is the drop-size diameter at which the two distributions have the greatest difference.

Table 1: Comparison of Bimodal Drop-Size Distributions

Compared Distributions			Mean Diff.	Max Diff.	Diam. at Max Diff.
Pair=10, sum of Mod1 and Std	vs	Pair=10, Mod1+Std expt, even bars	0.3%	1.0%	10 µm
Pair=15, Mod1+Std, expt., all bars	vs	Pair=15, Mod1+Std expt, even bars	0.7%	3.5%	12 µm
Pair=15, sum of Mod1 and Std	vs	Pair=15, Mod1+Std expt, even bars	0.6%	2.2%	26 µm
App. O., FZDZ, MVD<40 µm	vs	Pair=15, Mod1+Std expt, even bars	2.7%	9.6%	36 µm

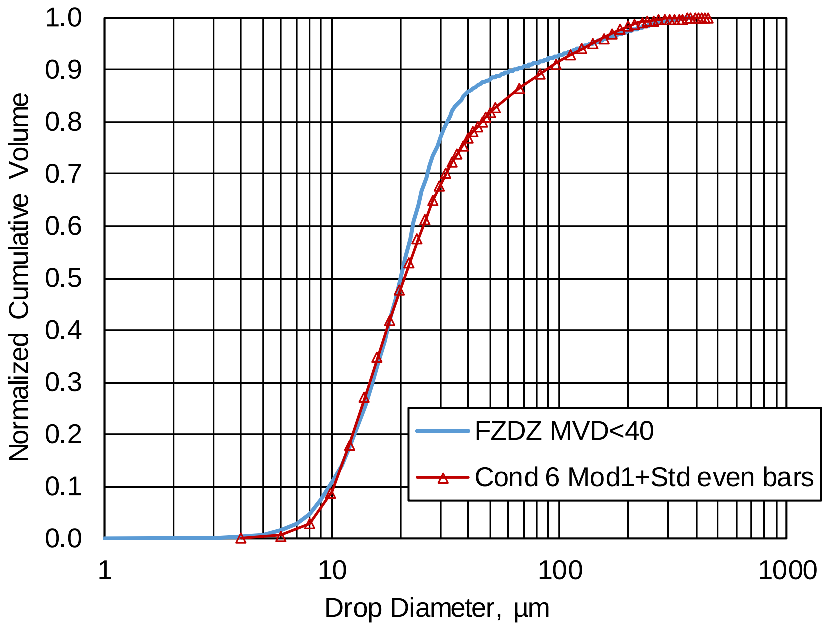

Figure 11. Comparison of the combined IRT Mod1+Standard-nozzle spray to the Appendix O, FZDZ, MVD<40 µm distribution. The two distributions match within 10% of their total LWC at all drop sizes.

It is of particular interest to note that the calculated sum of the individually-sprayed Mod1- and Standard-nozzle conditions is always within 2.2% of the corresponding distribution (Mod1+Std) that was measured experimentally. This suggests that the drops from the two individual sprays are not interacting with each other (coalescing), and that other bimodal conditions may be created in the same manner. It is also worth noting that the bimodal condition sprayed with all spraybars compares within 3.5% of the same condition sprayed only with the even-numbered bars. This suggests there was little interference due to coincidence error, and is further confirmation that spraying only half the spray bars is still adequate for measuring drop size in the IRT.

Table 1 also gives the comparison between the Mod1+Std nozzle condition for P_{air}=15 psig (even bars) and the Appendix O, FZDZ MVD<40 µm distribution. These two distributions are shown alongside each other in Fig. 11, and are found to match within 10%.

Further comparison between the conditions that resemble FZDZ, MVD<40 µm is shown in Table 2. In this table, Dv0.95 is the diameter at which 95% of the volume is contained in smaller drops. The distribution "P_{air} = 15, Mod1 nozzles only (mono-modal)" is the one previously shown in Fig. 6. In examining the Dv0.95 comparisons, it should be noted that the gradual slope of the graph in this region means that small changes in the y-axis values lead to much larger changes in the x-axis values. For example, the "all bars" condition has a Dv0.95 that is 15 µm larger than the "even bars" condition, which is a drop diameter difference of about 10%. However, at a drop size of 150 µm, the "all bars" condition has a normalized cumulative volume of 94.7%, and the "even bars" condition has a normalized cumulative volume of 95.8%, for a difference of only 1.1%.

Table 2: Distributions resembling FZDZ, MVD<40 µm

Distribution Name	MVD (µm)	Dv0.95 (µm)	Number Density (#/cm^3)
P_{air} = 15, Mod1 nozzles only (mono-modal)	19.3	58.0	492
P_{air} = 15, Mod1+Std expt, even bars	20.8	138.4	1692
P_{air} = 15, Mod1+Std expt, all bars	21.0	153.8	2671
P_{air} = 15, sum of Mod1 and Std	21.6	143.2	1670
App. O., FZDZ, MVD<40 µm	20.0	137.1	--

VI. Cloud LWC Uniformity

Further measurements were made of the cloud uniformity for the FZDZ, MVD<40 µm condition using the 1.83 x 1.83 m (6 by 6 ft) grid. The grid mesh is 15.2 by 15.2 cm (6 by 6 in). Mesh elements are 5.1 cm (2 in.) deep with a flat 3.2 mm (1/8 in.) face for ice accretion. Digital calipers were used to measure the ice thickness accreted at the center mesh points of the vertical elements. An image of a technician measuring ice on the grid is shown in Fig. 12. A more detailed documentation of cloud uniformity measurements during cloud calibration procedures can be found in References 3 and 5. For this report, measurements were made of the same nozzle air and water pressure settings at three airspeeds: 100, 150, and 250 kts.

The results of the cloud uniformity measurements are shown in Fig. 13. The legend on this plots indicates a ratio of the local LWC measured on the grid compared to the average of the central twelve values. The pale green (nearly white) color shows that most of the map is within ±10%. The uniformities shown here look much more like the typical Standard-nozzle cloud uniformities seen in the IRT,[3] which indicates that the Standard nozzles give the greatest contribution to the cloud uniformity. This makes sense because the Standard nozzles also contribute the majority of water for this spray condition (54% at all speeds).

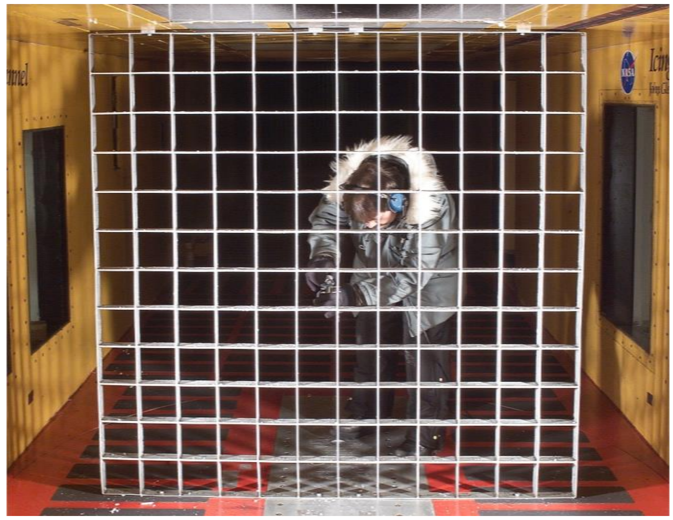

Figure 12. A technician measures the thickness of ice accreted on the Grid.

VII. Conclusions

Two bimodal drop size distributions have been created in the Icing Research Tunnel by spraying the Mod1 and the Standard nozzles simultaneously at the same nozzle air pressure and different water pressures. One of these distributions matches the Appendix O, FZDZ, MVD<40 μm distribution within 10% of the normalized cumulative volume for all drop sizes, and provides a better match to the larger drop-sizes than what could be done with only one nozzle set. The cloud water content uniformity for this combined spray condition has also been found to be very good, within ±10%.

These tests also suggest that the IRT's capability to create bimodal distributions can be analytically determined by mathematically combining individual spray conditions from the Mod1 and Standard nozzles, and that this mathematical summation will match the combined spray condition within approximately 2%.

Further comparisons suggest that spraying only the even-numbered bars in the IRT (under our current spray nozzle configuration) results in a drop-size distribution that is adequately comparable (within 4%) to the distribution that would be measured by spraying all bars. This is helpful because the measurement needs to be representative of what is created when all bars are spraying (since this is normal operating procedure), but the large number densities in the IRT have in the past sometimes resulted in coincidence error from other probes, such as the Forward Scattering Spectrometer Probe (FSSP). It has been shown that spraying only half the spraybars can reduce this effect and still provide accurate measurement for a particle size distribution. It should be noted, though, that this technique of only spraying half the bars is only utilized when making measurements of the particle size distribution.

VIII. Further Considerations

In examining this means of creating a bimodal condition, it is critical to note that combining a Mod1- and a Standard-nozzle spray results in a cloud liquid water content that is much higher than described by the Appendix O criteria. For the condition described in Fig. 11, at 250 knots, the expected liquid water content would be 1.45 g/m^3 (and higher at lower airspeeds) which is 3-5 times as much as the 0.29 – 0.44 g/m^3 that is given in Appendix O. Thus, the authors expect that valuable information may be gathered from this distribution, but proper scaling laws must be applied in order for these drop sizes to be tested as Appendix O distributions.

Since one of the purposes of creating a bimodal drop size distribution in the IRT is to determine the effect a bimodal versus a single mode distribution has on icing characteristics of an airfoil, further testing would be expected to understand this drop size distribution and understand the impact of including the larger drop sizes. Initial testing has already been completed in this regard, which includes the scaling work that was just referred to, and it is described in a separate conference paper.[2]

Lastly, it is worth stating again that in order for a ground-test facility to replicate the conditions described in Part 25 Appendix O, along with drop size distribution and maximum drop size, consideration must be given to the drop-size uniformity, liquid water content, drop temperature, and drop breakup. All these parameters are likely to have an effect on the replicated conditions and impact the ice accretion on an airfoil. And without creating these conditions in a ground-test facility, there is also no way of validating computer codes that seek to simulate these conditions. Hence, the IRT has been continuing efforts towards understanding these parameters and considering additional options to expand its capabilities towards creating a means of compliance for the new FAA and EASA rules in Appendix O.

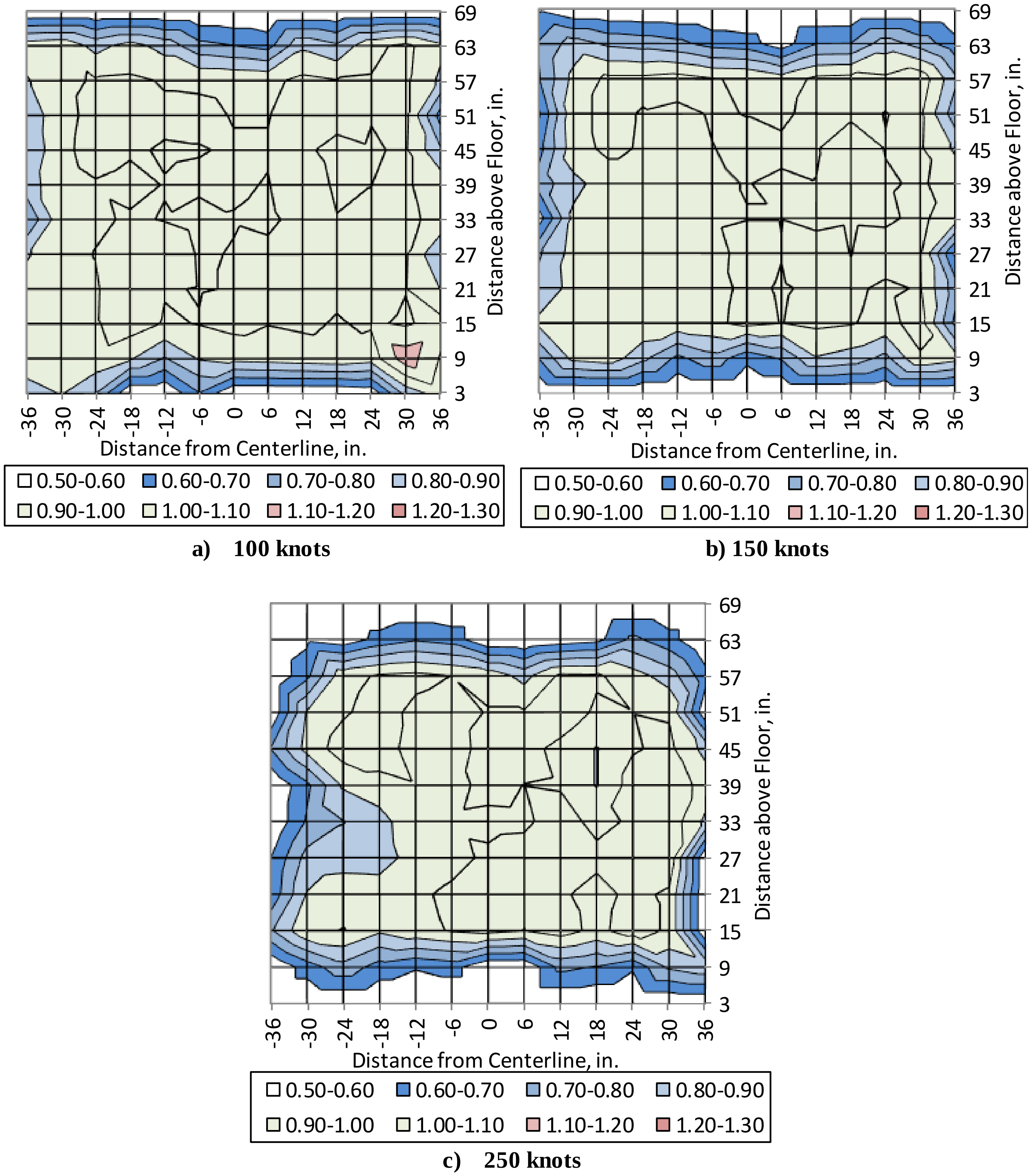

Figure 13. Cloud liquid water content uniformities at three airspeeds, for IRT condition matching most closely to the Appendix O, FZDZ, MVD<40 µm distribution. Uniformity is plotted as the ratio of the local LWC measured on the grid compared to the average of the central twelve values. All maps can be seen to have a uniformity of ±10%.

References

[1]CFR 14, Part 25, Appendix O, "Supercooled Large Drop Icing Conditions" http://www.ecfr.gov/cgi-bin/text-idx?SID=259d868888112fec2583fa3951738ebd&mc=true&node=ap14.1.25_11801.o&rgn=div9

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