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2006 Icing Cloud Calibration of the NASA Glenn Icing Research Tunnel

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May 2008

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I wish to thank the IRT crew for the excellent support I received during the 3-plus months of testing required to perform this cloud calibration.

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Abstract

In order to improve icing cloud uniformity, changes were made to the tunnel at the NASA Glenn Research Center in the vicinity of the spray bars. These changes necessitated a complete recalibration of the icing clouds. This report describes the methods used in the recalibration, including the procedure used to optimize the uniformity of the icing cloud and the use of a standard icing blade technique for measurement of liquid water content. The instruments and methods used to perform the droplet size calibration are also described. The liquid water content/droplet size operating envelopes of the icing tunnel are shown for a range of airspeeds and compared to the FAA icing certification criteria.

Introduction

Changes were made to the area in the vicinity of the spray bars of the Icing Research Tunnel (IRT) at NASA Glenn Research Center in late 2005. These changes were made in an attempt to improve the mixing of the spray, thereby improving the icing cloud uniformity in the test section.

The changes in the icing tunnel necessitated a recalibration of the icing clouds. The recalibration included: (1) establishment of spray nozzle locations in the spray bars to generate a uniform icing cloud in the test section and documentation of the resulting clouds at various airspeeds and drop sizes; (2) measurement of the droplet size distributions over the complete range of nozzle air and water pressures; and (3) measurement of the liquid water content to determine the effects of spray air pressure, water pressure and tunnel airspeed.

This paper describes the methods used in the recalibration of the icing tunnel and presents the results of these calibrations.

Facility Description

A plan view of the IRT loop is shown in figure 1. The tunnel is of the closed-loop design. The test section is 9 ft wide, 6 ft high and is approximately 20 ft long. The tunnel fan is powered by a 5000 horsepower electric motor, which can generate maximum airspeeds of almost 350 knots. The tunnel contains a flat-faced heat exchanger, which allows testing over a temperature range of 40 to –22 °F.

The tunnel water spray system consists of 10 spray bars, which are located in the low-speed section of the tunnel just upstream of the contraction. Each spray bar has positions for up to 55 spray nozzles. Each nozzle location is supplied by two independent water manifolds through individually controllable electrically activated solenoid valves. Two different nozzles are used to increase the LWC range of the tunnel. They are referred to as the Standard and Mod 1 nozzles. They are both of the same air-assist configuration, the only difference being the diameter of the water tubes. The Standard nozzles have a water tube diameter of 0.025 in.; the Mod 1 nozzles have a water tube diameter of 0.0155 in. This difference causes the Mod 1 nozzles to have approximately 30% of the water flow of the Standard nozzles at the same water pressure. The nozzles used in the spray system have matching water flow coefficients to within ±5%.

Two different types of devices were installed within the icing tunnel to improve icing cloud uniformity. Six columns of struts were installed between the spray bars. These struts, shown in figure 2, were added to generate unstable wakes which interact with the spray plumes to cause more mixing of the individual plumes. The geometry of the struts is similar to the spray bar center support.
It was found through experiments that these struts did indeed improve the uniformity of the clouds in the test section and that this improvement seemed to be independent of airspeed. However the struts had the negative affect of "shrinking" the cloud vertically, i.e., the cloud did not extend as far toward the floor and ceiling.

Ramps were installed on the floor and ceiling of the tunnel approximately 7.5 ft upstream of the spray bars. The ramps are made from a 13 in. long plate that is inclined at a 45° angle. The ramps had the desired effect of extending the cloud to within 2 in. of the floor and ceiling in the test section.

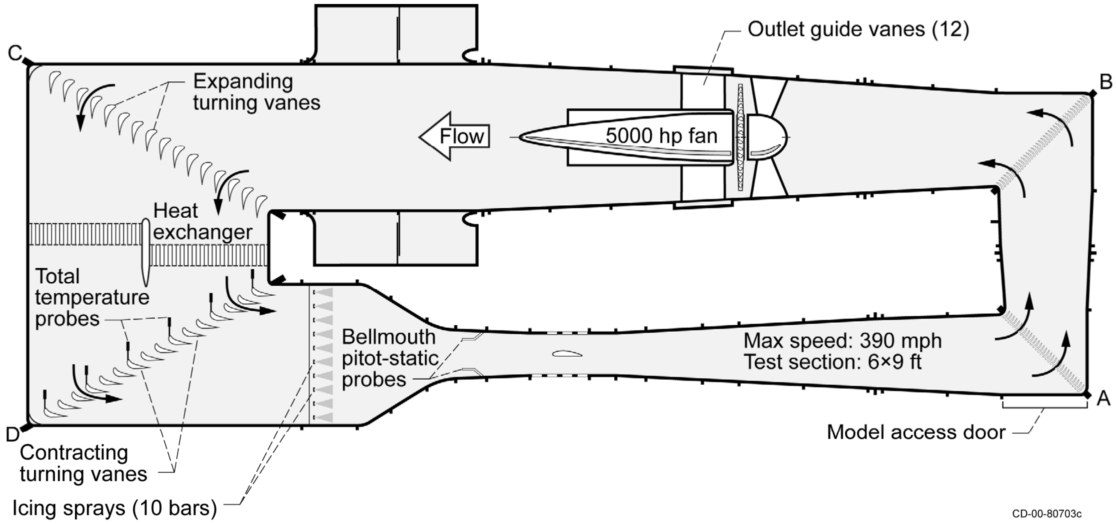

Figure 1.—Plan view of the NASA-Glenn Icing Research Tunnel.

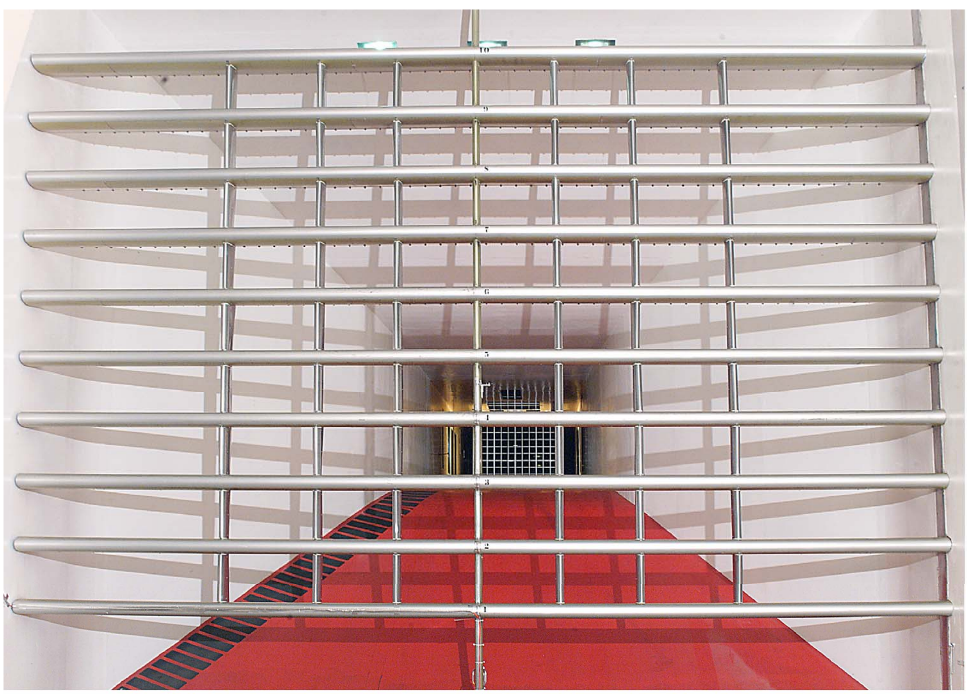

Figure 2.—View of spray bars with six columns of struts installed. View is from upstream of the spray bars looking toward the test section.

Purpose of Calibration

Calibration of the icing clouds consists of three parts. The first part is to determine the locations of the spray nozzles and the number of nozzles required to generate as uniform an icing cloud as possible in the tunnel test section. The next two parts are to make measurements of the drop sizes and liquid water contents (LWC) at many different combinations of spray air and water pressures.

The drop size and LWC data are used to develop curve fits that relate these parameters to the spray air and water pressures. During actual icing tests the drop size and LWC are not measured. Instead, the spray air and water pressure are calculated for the desired drop size and LWC conditions.

The operating range of the tunnel is as follows:

Airspeed: 50 to 300 knots
Air Temperature: Ambient to –22 °F
Spray Air Pressure: 10 to 60 psig
Spray ΔP: 5 to 150 psid (Standard nozzles)
5 to 250 psid (Mod 1 nozzles)

The spray ΔP is the water pressure minus the air pressure. This is the parameter, rather than water pressure, that is used in calculations of drop size and LWC since the water flow rate is proportional to $\Delta P^{0.5}$.

Icing Cloud Uniformity

The term icing cloud uniformity refers to the degree of liquid water distribution over the area of the tunnel test section. It is desirable that the liquid water within the cloud be uniformly distributed from wall to wall and from floor to ceiling. However, due to limitations in possible nozzle locations within the spray bar system, limited mixing/spreading of the spray plumes and variations in airflow (wakes, corner vortices, flow angularity, etc) the icing cloud generated in a tunnel always has variations. The goal of establishing nozzle locations to establish a uniform cloud is to generate as large a cloud as possible with as little variation as possible. The current criteria for a "uniform" icing cloud are that variations in LWC of $\pm$ 20% are acceptable.

The first step in trying to establish a uniform icing cloud was to determine where the spray from each area of the spray bars ended up in the test section. A 6-ft by 6-ft stainless steel grid was placed in the test section, centered horizontally within the 9-ft wide test section. The grid, a picture of which is shown in figure 3, has 6-in. vertical and horizontal spacing. The tunnel was cooled to 0 °F and the airspeed was set to 150 knots. Once the tunnel had stabilized at this temperature and airspeed, water spray was initiated from two widely spaced spray bars. Ice was allowed to accrete on the grid for several minutes. The peaks of the ice accretions as well as the widths of the iced bands were then documented This test was repeated for all of the spray bars. It was also performed for 16 (vertical) columns of nozzles. The data from the spray bar and column tests were used to generate a map of spray nozzle location to ice accretion location in the test section.

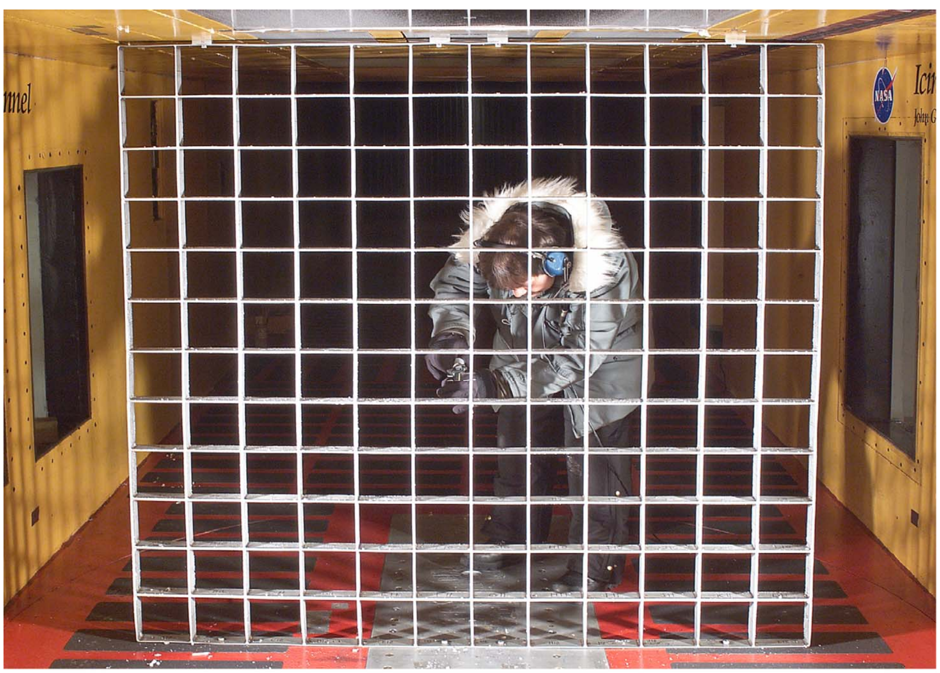

Figure 3.—A technician measuring the ice thickness on the icing grid used to determine icing cloud uniformity.

Following this test a uniform pattern of spray nozzles was installed in the spray bars. The tunnel was stabilized at an airspeed of 150 knots and a temperature of 0 °F. All nozzles were activated and ice was allowed to accrete on the grid. The ice thickness was then measured at 6-in. vertical intervals, starting 3 in. from the test section ceiling. The data gathered was then used to construct a contour plot. This plot along with the results from the single spray bar/single column tests was used to guide the process of adding or changing nozzle locations to improve the cloud uniformity. Airspeeds of 50 to 250 knots were also used to guide this process, with emphasis placed on airspeeds of 150 and 200 knots, where most "real life" testing is performed. The process of optimizing the cloud uniformity involves a considerable amount of trial and error and is very time consuming.

Since the spray bars contain two water manifolds and each nozzle location is controlled by individual solenoid valves, two sets of nozzles can be installed in the bars at the same time. Based on the Mod 1 nozzle locations, the Standard nozzles were positioned between these locations, with somewhat closer spacing. After about 30 iterations of changes in some Mod 1 and Standard nozzle positions, the final nozzle positions for both nozzle sets were established. The final nozzle arrays contained 165 Standard nozzles and 101 Mod 1 nozzles.

Figure 4 shows the LWC uniformity for the Standard nozzles at an airspeed of 150 knots. The contour intervals on this plot are in 10% bands. The blue area represents values within ±10% of the averaged center values. The green areas are lower and the red areas are higher LWC compared to the central region. It can be seen from this plot that the icing cloud covers almost the entire grid area and that the vast majority of the area is within ±10%. This could be considered to be an "ideal" cloud.

Figure 5 shows contour plots of the LWC cloud uniformity for various airspeeds. All of these tests were run with the Mod 1 nozzles at a nozzle air pressure of 20 psig. At 100 knots (figure 5(a)) the LWC of the icing cloud is within ±10% over the 5.5-ft vertical by 6-ft wide central region of the test section except for a few spots along the edges. At 150 knots (figure 5(b)) the cloud looks slightly more uniform than at 100 knots. At 200 knots (figure 5(c)) the cloud has larger low areas but most of the cloud is still within ±10%. Note that the cloud looks like it may be shrinking slightly in the vertical direction. Finally, at 250 knots the cloud has some high spots on the sides but the vast majority of the area is still within ±10%.

For comparison with the new data figure 6 shows the LWC uniformity plots generated from the 2000 tunnel calibration (ref. 1). The cloud at 100 knots was more uniform in 2000 but the clouds at all of the higher airspeeds are more uniform in the 2006 calibration. When compared to the 2000 calibration it can be seen that the high and low spots in the new clouds are much broader and less frequent than the small areas of the old clouds. This is an indication that the mixing of the spray from individual nozzles is greatly improved by the use of the struts on the spray bars.

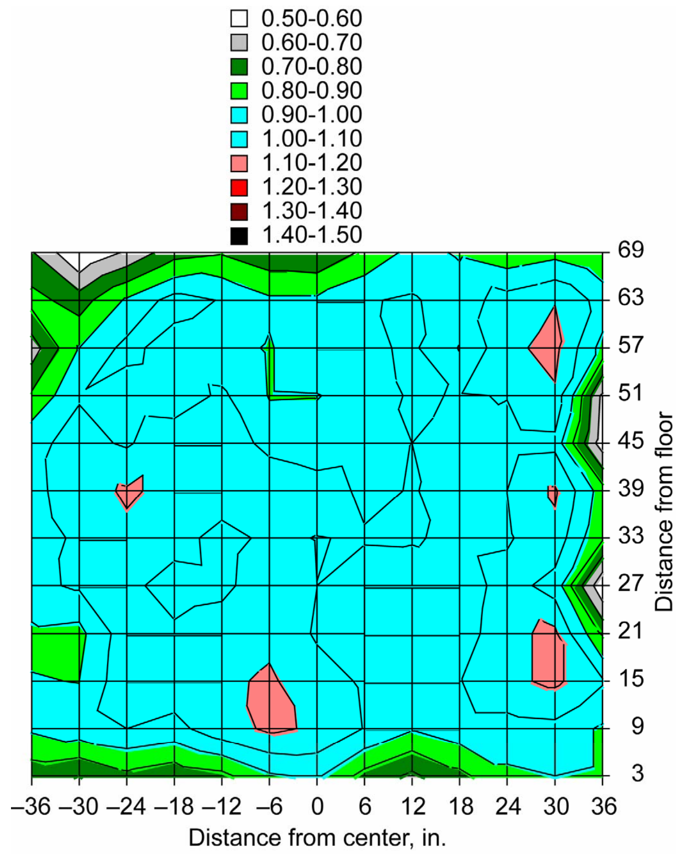

Figure 4.—LWC uniformity contour plot for the standard nozzles. Airspeed = 150 knots, MVD = 20 um, nozzle air pressure = 20 psig. The legend applies to all plots in figures 6 to 8.

There is some concern that the presence of the struts and ramps may increase turbulence levels in the test section enough to affect icing test results (i.e., ice shapes, heat transfer rates) and aerodynamic measurements. A standard ice shape repeatability test was run after completion of the cloud calibrations. This test showed no change in ice shapes due to the installation of the struts and ramps. Further tests are planned to investigate any issues.

Droplet Size Calibration

Two droplet sizing instruments were used in the droplet size calibration of the icing research tunnel. These were the Forward Scattering Spectrometer Probe (FSSP) and the Optical Array Cloud Droplet Spectrometer Probes (OAP). These are aircraft type instruments manufactured by Particle Measuring Systems, Inc. of Boulder, Colorado.

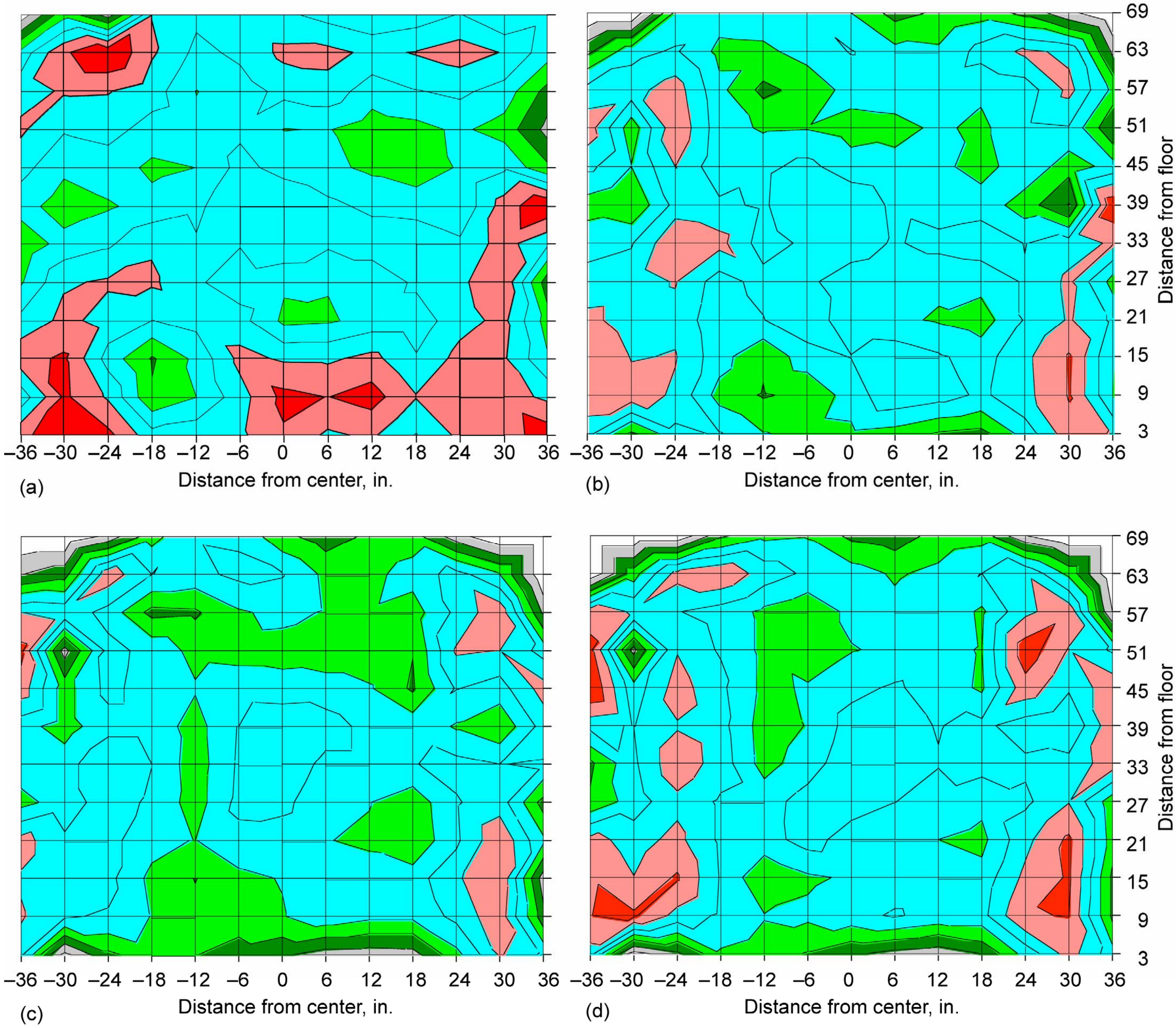

Figure 5.—Mod 1 nozzle LWC uniformity plots for several airspeeds. MVD = 21 μm, nozzle air pressure = 20 psig. (a) Airspeed = 100 knots. (b) Airspeed = 150 knots. (c) Airspeed = 200 knots. (d) Airspeed = 250 knots.

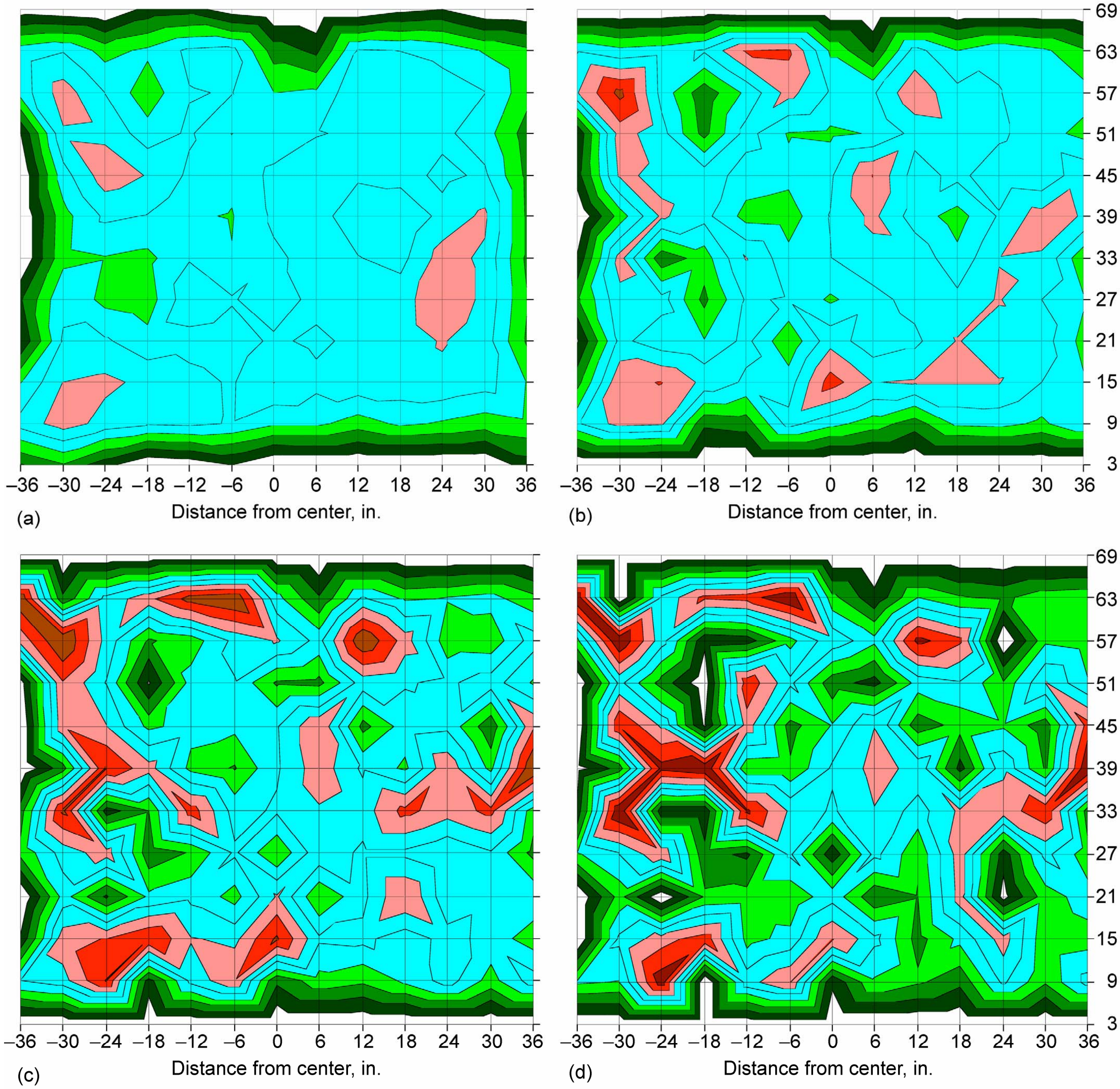

Figure 6.—2000 Cloud uniformity plots with Mod 1 nozzles for several airspeeds. MVD = 21 μm, nozzle air pressure = 20 psig. (a) Airspeed = 100 knots. (b) Airspeed = 150 knots. (c) Airspeed = 200 knots. (d) Airspeed = 250 knots.

Figure 7.—Picture of the FSSP droplet sizing instrument mounted in the test section of the IRT.

The FSSP (refs. 2 and 3) was used to measure droplets with diameters of 2 to 47 μm. In this instrument a laser beam is used to illuminate single particles as they traverse the sample volume. The intensity of the forward scattered light is measured to determine the particle size. Larger particles generate greater intensity. The instrument counts each particle passing through the laser beam and places the count in one of 15 size bins. The nominal bin width for the FSSP is 3 μm. Over time a number versus particle size histogram is obtained. A data analysis program is used to convert the number histogram into a volume histogram and to calculate other characteristics of the droplet distribution such as the median volume diameter.

The OAP (ref. 3) was used to measure droplets with diameters of 9.5 to 457.5 μm. This instrument uses a collimated laser beam to illuminate particles creating a shadow, which is magnified and projected onto a linear photodiode array. The number of diodes shadowed determines into which particle size bin the particle will be placed. The diode spacing and the system magnification determine the size definition of each size bin. The nominal bin width for this OAP is 15 μm.

The particle sizing instruments were mounted in the tunnel on the centerline of the test section one at a time to ensure that each instrument was measuring the same part of the cloud. The FSSP is shown in Figure 7. Various spray conditions (i.e., air pressure and water pressure) were set and allowed to stabilize. The sample time used for the FSSP was 50 seconds and the sample time for the OAP was 100 seconds. In general, measurements were made with the FSSP first for all the spray conditions covering the air pressure and water pressure range of the facility. The OAP was then used for those spray conditions where it appeared that the FSSP had not captured the complete droplet size distribution. Approximately 100 test conditions were measured for the Standard nozzles and 150 test conditions were measured for the Mod 1 nozzles.

Data Processing of Droplet Size Distributions

The median volume diameter (MVD) is used to characterize the droplet size distribution. The MVD is defined as the diameter where half of the volume of water is contained in droplets with diameters smaller (or larger) than this diameter. To calculate a meaningful MVD, it is often necessary to combine the droplet size distributions from more then one instrument. The procedure used to calculate the total volume was to calculate the total volume of the droplets from the FSSP and to add to this the additional volume of the droplets from the OAP that exceed the range of the FSSP. Thus in the overlap size region of the FSSP and OAP the FSSP measurements are used. This provides an effective droplet size range for the OAP of 47 to 457.5 μm. Figure 8 shows an example of the combined distributions from the FSSP and OAP. This distribution is a droplet number density distribution versus droplet diameter that has been normalized by each instrument's bin width and sample volume. The square symbols are from the FSSP and the triangles are from the OAP. The two filled triangles are the data from the OAP that are in the overlap region with the FSSP that are discarded. In this example the two instruments combine to form a smooth continuous curve from 3.5 to 300 μm with a large dynamic range in number density of $1E^2$ to $1E^{-5}$.

Figure 9 shows the cumulative percent volume (or percent LWC) curves for MVD values of 15, 20, 30 and 40 μm. These curves are formed by calculating the percentage of the total droplet volume (or LWC) contained in each size bin of each instrument and then summing them. It can be seen from these curves that as the MVD increases the droplet distribution becomes broader. Note that the 40 μm MVD distribution has droplets with diameters exceeding 200 μm.

Droplet Size Equation

The MVD data from the droplet size calibrations was fit to an equation for each nozzle type so that the tunnel cloud MVD can be directly calculated for any pair of spray bar air pressure and water pressure settings. These equations are valid over a range of air pressures from 10 to 60 psig; ΔP range of 10 to 150 psid for the Standard nozzles and 10 to 250 psid for the Mod-1 nozzles. The calculation of MVD is valid for MVD up to 50 μm.

For each nozzle type (Mod-1 and Standard) the MVD data was tabulated as a function of spray bar P_{air} and ΔP. A commercially available software program (ref. 4) was used to fit these data using least-squares procedures to a large number of candidate equations. These equations were then ranked based of the root mean square error (MSE). The top several ranked equations were reviewed for both nozzle types in order to select the best equation that could be used for both the Mod-1 and Standard nozzles. The equation has the following form:

$$MVD = (a + bx^c + dy^e + fx^c y^e)$$

where x is the air pressure in psig, and y is the ΔP in psid. The coefficients a thru f for the Mod 1 and Standard nozzles are listed in Table 1. Figures 10 and 11 show these equations for the Standard and Mod 1 nozzles plotted as a function of MVD versus ΔP for the series of air pressures between 10 and 60 psig.

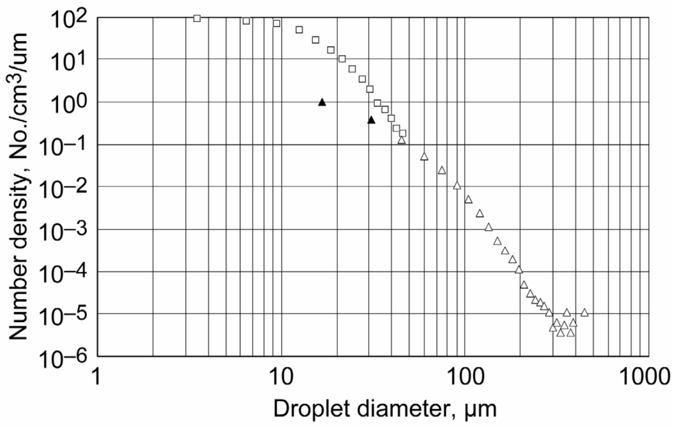

Figure 8.—Number density drop distribution measured by the FSSP and OAP. MVD = 25 μm.

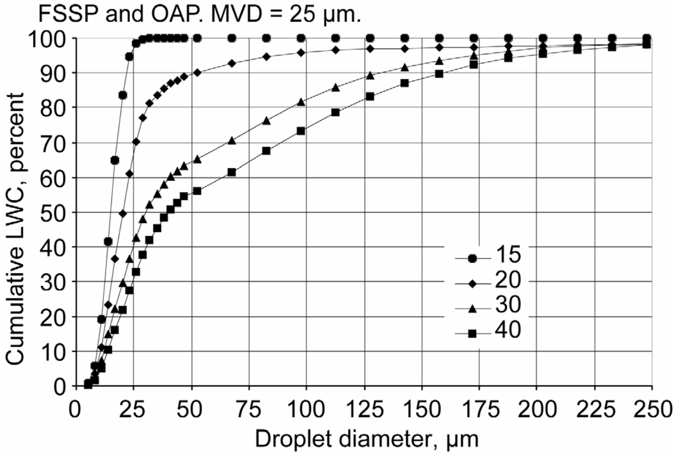

Figure 9.—Cumulative percent LWC droplet distributions for MVD values of 15, 20, 30, and 40 μm. These distributions are from measurements of the Mod 1 nozzles.

TABLE 1.—VALUES FOR COEFFICIENTS IN DROPLET SIZE (MVD) EQUATIONS.

Coefficient	Mod 1 Nozzles	Standard Nozzles
a	10.86055522	14.32728174
b	82.70313916	–656.427533
c	–1.85363921	–1.97675308
d	0.00100127	–0.00237495
e	1.198684321	1.422620275
f	18.46437591	88.49911787

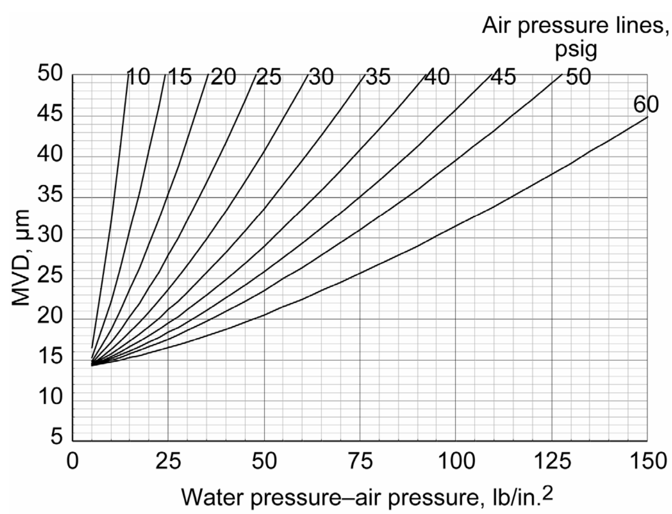

Figure 10.—The droplet size calibration curves for the standard nozzles plotted as MVD versus ΔP for the complete range of air pressures.

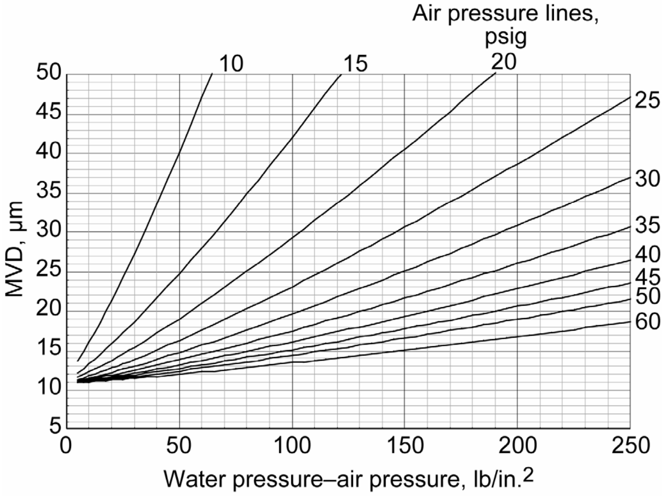

Figure 11.—The droplet size calibration curves for the Mod 1 nozzles plotted as MVD versus ΔP for the complete range of air pressures.

Liquid Water Content Calibration

A standard icing blade technique (ref. 5) was used to measure the liquid water content in the center of the test section. The blade is made of stainless steel and is 6-in. long, 3/4-in. deep and 1/8-in. thick. All tests were run at an air temperature of 0 °F to insure that the ice that formed on the thin eighth inch face would have minimal width so that the blade collection efficiency would not have to be adjusted.

The collection efficiency, E_b, of the blade was calculated for the full range of airspeeds and droplet sizes used for this testing. The computer code used, the FWG two-dimensional droplet trajectory code (ref. 6), uses a Hess-Smith panel code for the flowfield prediction and a C. W. Gear stiff equation scheme to integrate particle trajectories.

After the tunnel temperature and desired airspeed were stabilized the water spray was turned on at the desired air and water pressure for a predetermined time. The thickness of ice on the blade was measured using a chilled micrometer. The ice thickness and the exposure time were used in the equation below to calculate the liquid water content.

$$LWC = \frac{C \times \rho_{ice} \times \Delta S}{E_b \times V \times t} = \frac{4.34 \times 10^4 \times \Delta S}{E_b \times V \times t}$$

In this equation C is a unit conversion constant, ρ_{ice} is the density of ice which is assumed to be constant (i.e., $\rho_{ice} = 0.88$), ΔS is the thickness of ice in inches, E_b is the blade collection efficiency, V is the free-stream airspeed in knots and t is the spray time in seconds.

The icing blade was used to measure liquid water content values over a range of spray air pressures from 10 to 60 psig, airspeeds from 50 to 300 knots and droplet sizes from 14 to 50 µm. It was known from past experience that the liquid water content calibration is a function of both air pressure and airspeed, that is:

$$LWC = K(f(P_{air}, V) \times \frac{\sqrt{\Delta P}}{V}$$

where ΔP is the spray bar water pressure minus the air pressure and is proportional to the water flow rate.

The first series of tests involved varying the spray bar air pressure while holding the airspeed and droplet size constant. The results of these tests are shown in figure 12 for both nozzle sets. It can be seen from this plot that the liquid water content decreases as the air pressure increases. There are two possible causes for this decrease - droplet freeze-out and evaporation. Droplet freeze-out is caused by the temperature decrease of the compressed air as it undergoes an isentropic expansion at the exit of the nozzles (refs. 7 and 8). Evaporation of some of the water is also very possible since the air used in the spray system is very dry, having a dew point of approximately –30 °F and is heated to a temperature between 165 and 190 °F. And since the airflow increases with air pressure an increase in evaporation would be expected with increasing air pressure.

The next series of tests involved varying the airspeed from 50 to 300 knots while holding the air and water pressures and the droplet size constant. Figure 13 shows the results of these tests.

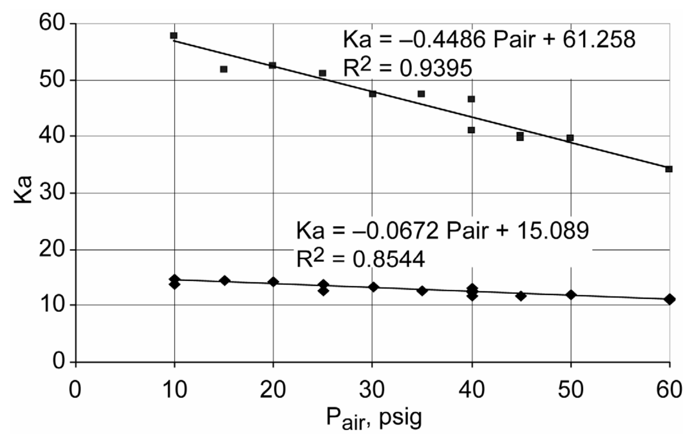

Figure 12.—Effect of nozzle air pressure on “K” for the standard (upper curve) and Mod 1(lower curve) nozzles.

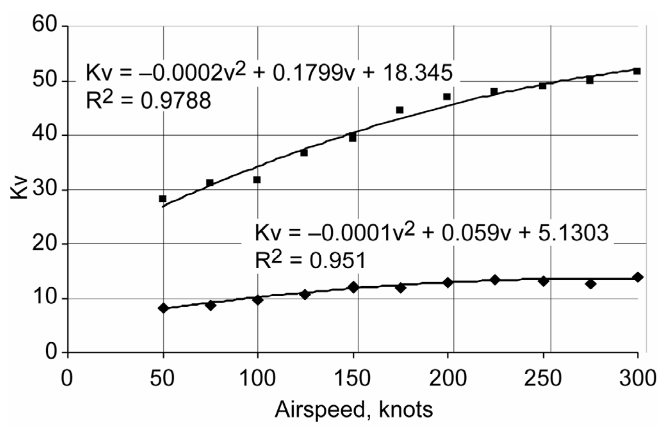

Figure 13.—Effect of tunnel airspeed on “K” for the standard (upper curve) and Mod 1 (lower curve) nozzles.

The effect of droplet size was also investigated, but no significant effects were found within the droplet size range of 14 to 50 μm.

The two equations for "K" generated from the air pressure and airspeed tests were combined to generate the calibration equations for each nozzle set. The final equations are:

Standard Nozzles:

$$LWC = (-0.0002V^2 + 0.18V - 0.449P_{air} + 39.0)\frac{\sqrt{\Delta P}}{V}$$

Mod 1 Nozzles:

$$LWC = (-0.0001V^2 + 0.059V - 0.08P_{air} + 9.0)\frac{\sqrt{\Delta P - 1}}{V}$$

Figure 14 shows the comparisons of the *LWC* data taken with the icing blade (Measured *LWC*) to the values calculated from the equations above (Curve Fit *LWC*) for the Standard and Mod 1 nozzles. Almost all of the data is within a ±10% band, indicating a reasonable fit of the equations to the data.

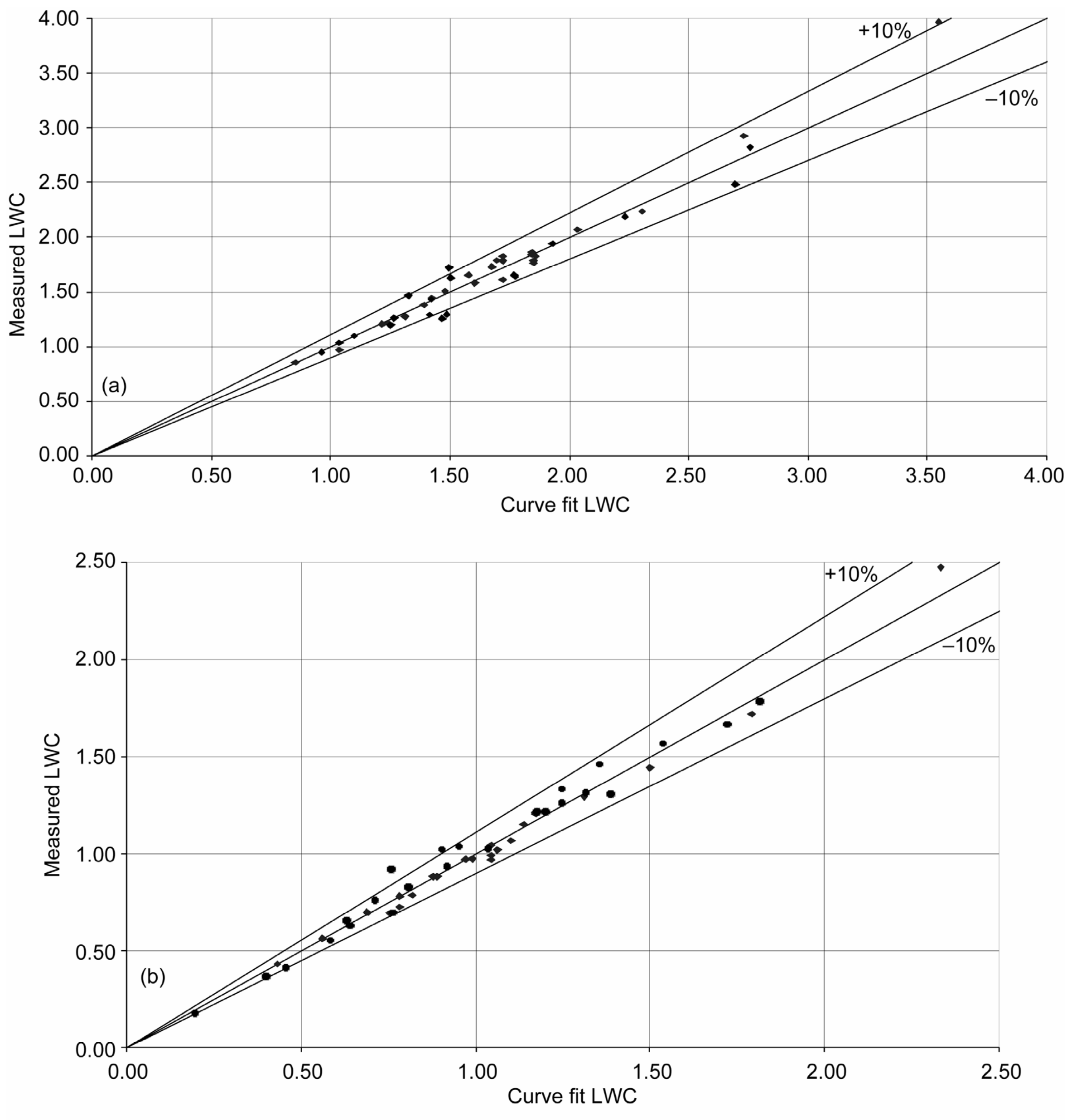

Figure 14.—A comparison of the LWC measured by the icing blade to the LWC calculated from the calibration equations for the (a) Standard and (b) Mod 1 nozzles.

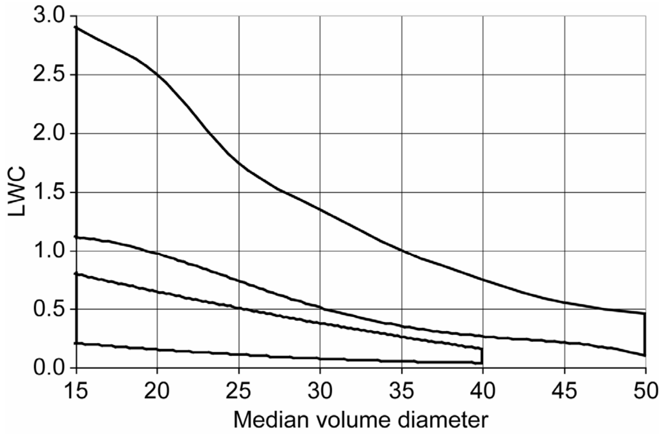

Figure 15.—The LWC/MVD icing certification criteria from FAA FAR Part 25, Appendix C.

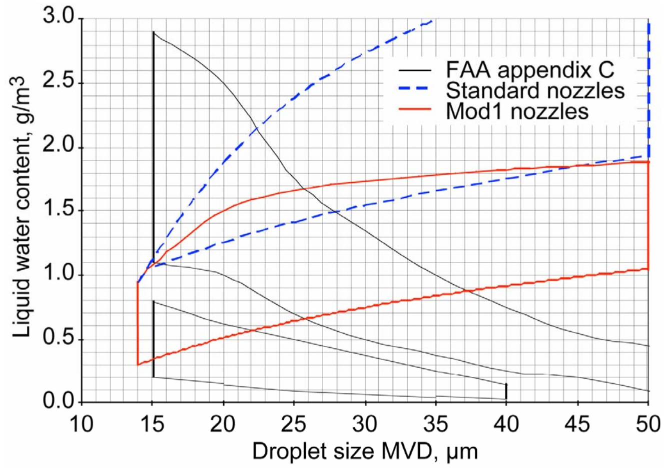

Figure 16.—Comparison of the LWC/MVD operating envelopes for the IRT to the FAA icing certification criteria for an airspeed of 100 knots.

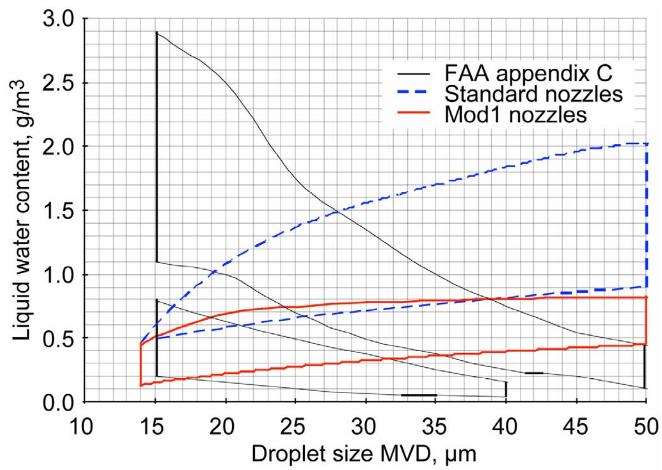

Figure 17.—Comparison of the LWC/MVD operating envelopes for the IRT to the FAA icing certification criteria for an airspeed of 300 knots.

Icing Cloud Operating Range

The results of the liquid water content and droplet size calibrations were combined to establish the operating envelopes of the spray system. Since the liquid water content is a function of airspeed in the tunnel, these operating envelopes are also a function of airspeed.

The goal of any icing tunnel is to be able to duplicate as fully as possible the Federal Aviation Administration (FAA) aircraft icing certification standards contained in FAR Part 25, Appendix C. These icing envelopes are shown in figure 15. The upper envelope is called the intermittent maximum envelope applicable to flight in cumulus clouds while the lower envelope, the continuous maximum envelope, is applicable to flight in stratus-type clouds.

Figure 16 shows the capabilities of the NASA Glenn IRT at an airspeed of 100 knots compared to the FAA icing criteria. The figure illustrates that the IRT has the capability to cover much of the higher LWC conditions of the intermittent maximum envelope at the smaller droplet size end but does a poor job of covering the lower LWC range of the intermittent maximum envelope at droplet sizes above 35 µm. The IRT at this speed can duplicate very little of the continuous maximum envelope.

Figure 17 shows the capabilities of the IRT at an airspeed of 300 knots. At this airspeed it can be seen that the IRT does a better job of duplicating the lower LWC values of the continuous maximum envelope but cannot duplicate the higher LWC values at smaller droplet sizes of the intermittent maximum criteria.

The number of nozzles in the spray bars could be adjusted to expand the amount of overlap between the tunnel capabilities and the FAA criteria. In fact the IRT can now spray the Standard and Mod 1 nozzles simultaneously. This improves the tunnel's ability to cover more of the high LWC cases. A reduction in the number of Mod 1 nozzles in the spray bars would help to reduce the LWC to cover more of the continuous maximum envelope. However a significant reduction in the number of nozzles will have the tendency to degrade the LWC uniformity, particularly at high airspeeds.

Another possible approach of increasing the amount of overlap between tunnel capability and the FAA criteria is to use a different type of spray nozzle. However, no nozzle that is clearly superior to the NASA nozzles has been found.

Conclusions and Recommendations

(1) The use of spray bar mounted struts and floor and ceiling mounted ramps greatly increased the amount of mixing of the icing sprays. The LWC uniformity in the tunnel test section was greatly improved, particularly at higher airspeeds.

(2) The probable increase in turbulence in the tunnel due to the presents of the struts and ramps should be investigated for

any negative influence to icing test results including changes in ice shape, heat transfer, and aero performance measurements.

(3) Methods of increasing the LWC/MVD coverage of the FAA icing test criteria contained in FAR Part 25 Appendix C should be investigated. This should include considering other types of spray nozzles.

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14. ABSTRACT
In order to improve icing cloud uniformity, changes were made to the tunnel at the NASA Glenn Research Center in the vicinity of the spray bars. These changes necessitated a complete recalibration of the icing clouds. This report describes the methods used in the recalibration, including the procedure used to optimize the uniformity of the icing cloud and the use of a standard icing blade technique for measurement of liquid water content. The instruments and methods used to perform the droplet size calibration are also described. The liquid water content/droplet size operating envelopes of the icing tunnel are shown for a range of airspeeds and compared to the FAA icing certification criteria.

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