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Comparison of Liquid Water Content Measurement Technquies in an Icing Wind Tunnel

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COMPARISON OF LIQUID WATER CONTENT MEASUREMENT TECHNIQUES IN AN ICING WIND TUNNEL

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ABSTRACT

This paper compares the results of liquid water content measurements by various means in an icing wind tunnel. The techniques/instruments tested are the icing blade, a single rotating cylinder, the Johnson-Williams and CSIRO-King hot-wire probes, the Nevzorov LWC/TWC probe and the liquid water content calculated from the combined droplet distributions of two droplet sizing probes - the Forward Scattering Spectrometer probe and the Optical Array probe.

A large range of icing conditions was used for this study. The liquid water content ranged from 0.1 to 1.25 g/m^3 and the median volumetric droplet diameters (MVD) ranged from 10 to 270 μm. Airspeeds of 50 to 250 mph (22 to 112 m/s) were used.

This study shows the degree of agreement between the various liquid water content measurement methods over the normal cloud MVD range of 10 to 50 micrometers and over several supercooled large droplet (SLD) conditions. It shows that the Nevzorov LWC/TWC instrument has the potential for measuring the LWC in SLD clouds as well as normal droplet size cloud conditions. It reveals a large disagreement between the droplet sizing probe results and the other methods. The implications and possible causes of this disagreement are discussed. Recommendations for additional investigations to resolve disagreements are included.

INTRODUCTION

Liquid water content (LWC), along with airspeed, air temperature and water droplet size is one of the important parameters that affects icing on aircraft. It affects the rate of ice accretion on the aircraft, the type of icing (i.e. rime, mixed or glaze) and whether there will be water runback that might freeze aft of protected areas. LWC therefore has a large impact on an aircraft's potential loss of performance in an icing encounter.

There are many ways that the LWC of icing clouds has been measured. The early icing cloud characterization work in the 1940's and early 1950's employed the rotating multicylinder technique (ref 1) which was used to measure both the liquid water content and the droplet size. The results of this work were used in large part to establish the current FAA aircraft icing certification criteria. Since then other methods of measuring LWC have been developed. These methods fall into three categories based on the basic principle of operation: ice accretion methods, hot-wire methods and droplet sizing/counting methods.

This report compares results of LWC measurements made in an icing wind tunnel using several methods. The methods are the icing blade, a single rotating cylinder, three hot-wire instruments, and a pair of droplet sizing instruments.

DESCRIPTION OF TEST FACILITY

Testing was conducted in the NASA Glenn Icing Research Tunnel. A plan view of the tunnel is shown in figure 1. The icing tunnel is a closed-loop refrigerated design with a test section that is 6 feet high by 9 feet wide (1.8 x 2.7 m). It has a spray system containing approximately 100 air-assist type spray nozzles installed in eight horizontal spraybars. The tunnel is capable of running at airspeeds of 50 to 400 mph (22 to 179 m/s) at temperatures down to –40 °F (–40 °C). It can produce clouds of super-cooled water over a LWC range from approximately 0.1 to greater than 3.0 g/m^3 although this range is airspeed dependent. Two different spray nozzles, called Standard and Mod 1, are used to produce this LWC range. The normal range of cloud droplet sizes is median volumetric diameters (MVD)[1] of 10 to 50 μm. The MVD capability of the tunnel has been extended to 270μm in response to the interest in performing icing tests at super-cooled large droplet conditions.

The relative humidity in the test section of the IRT is very near and sometimes above saturation, depending on airspeed. After the tunnel has been humidified by the first spray the dew point at the spray location is less than 7 °F (3.9 °C) below the air temperature. As the air passes through the 14:1 contraction it speeds up resulting in a decrease in the static air temperature. Above 200 mph (89 m/s) the test section air is saturated, even assuming none of the water from the spray is evaporated. At all airspeeds the test section relative humidity is greater than 75 percent. This high relative humidity reduces droplet evaporation and contributes to very repeatable spray conditions in the test section.

All tests reported here were conducted in the center of the tunnel to avoid questions about the spatial variations in the LWC of the cloud affecting the results.

DESCRIPTION OF MEASUREMENT TECHNIQUES

Icing Blade

The icing blade is a very simple device. It consists of a piece of aluminum that is 6 inches long, 0.125 inches wide and 0.75 inches thick. The blade is placed behind a shield in the center of the tunnel. After the desired spray condition has been stabilized the shield is raised, exposing the 6-inch by 0.125-inch face of the blade to the cloud for a predetermined time. The appropriate exposure time results in an ice accretion that is less than 0.2 inches thick. The icing blade was used at an air temperature of 0 °F (–18 °C) to ensure that rime icing occurred thereby minimizing the width of the ice, which would change the collection efficiency. The LWC is determined from the ice thickness by the following equation:

$$LWC = \frac{C * \rho_{ice} * \Delta S}{E_b * V * t} \qquad (1)$$

[1]MVD is defined as the diameter at which an equal volume of water is contained in droplets with diameters smaller (and larger) than this value.

where:	C	is a constant
	ρ_{ice}	is the density of ice
	ΔS	is the ice thickness on the blade
	E_b	is the blade collection efficiency
	V	is the airspeed
	t	is the exposure time.

The ice density is assumed to be a constant, $\rho_{ice} = 0.88$. The collection efficiency of the blade, which is a function of the airspeed and the droplet size, was calculated using the FWG two-dimensional trajectory code (ref. 2). This code uses a Hess-Smith panel code for the flowfield prediction and a C.W. Gear stiff equation scheme to integrate particle trajectories.

Rotating Cylinder

The rotating cylinder used for this testing was 1.5 inches in diameter and was six feet long. It was rotated at approximately 60 rpm. All testing was performed at a temperature of 0 °F (–18 °C) to minimize the possibility of water run-off. The tunnel spray system was turned on for a predetermined time and the resulting iced diameter of the cylinder was then measured. Equation (1) was used to calculate LWC with the exceptions that (1) exposure time was divided by two since only one-half of the cylinder is exposed to the cloud at any given time, (2) the ice thickness was calculated by dividing the change in diameter of the cylinder by two.

Hot-Wire LWC Instruments

The Johnson-Williams (J-W) instrument, also known as a Cloud Technology probe, uses two heated wires in a balanced bridge circuit. The main sensing wire is 0.55 mm in diameter and is mounted perpendicular to the airstream. It is heated at a constant voltage to a temperature above the boiling point of water. Cloud droplets impinging on the wire are evaporated, causing the wire to cool and its electrical resistance to decrease. This change in resistance causes an imbalance in the bridge circuit; the degree of imbalance is related to the LWC. The second wire is mounted parallel to the airstream and is shielded from droplet impingement. This wire is connected to the opposite side of the bridge and compensates for small changes in air temperature, air density and speed.

The CSIRO-King instrument employs a sensor composed of three wire coils wound around a small hollow tube. The slave coils on each side of the master coil are connected in series and minimize the longitudinal heat conduction from the master coil. The sensor element is 1.9 mm in diameter and 1.5 inches long. Unlike the J-W instrument the CSIRO-King is a constant temperature device. The total heat transfer rate from the coil is determined from the power required to keep the sensor coil at a constant temperature. This heat transfer rate is composed of the "dry" term, which is a function of airspeed, air density and air temperature, and a "wet" term, which is a function of airspeed and LWC.

The Nevzorov instrument is also a constant temperature device which consists of two separate hot-wire sensor systems that are intended to measure liquid water content and total water content (i.e., liquid plus ice crystal water content). The sensing elements are mounted on a vane that is designed to keep the sensors aligned into the airflow. Each sensor system consists of two heated wires —a sensing wire and a compensating wire. The liquid water content sensor consists of the sensor wire coil of 1.8-mm diameter mounted on the leading edge of the vane and the compensating wire mounted on the trailing edge of the vane. The total water sensor consists of a wire mounted inside a cylindrical cone of 8-mm diameter and the compensating wire wound in a groove around the cylinder. Each set of wires is controlled and monitored by its own set of electronics.

Droplet Sizing Probes

There are two instruments that are commonly used to measure cloud water droplet sizes in flight programs and some icing facilities. They are the Forward Scattering Spectrometer Probe (FSSP) and the Optical Array Probe (OAP)[2]. The FSSP is used to measure the smaller droplets in the range of 2 to 47 μm and the OAP used in this study measures droplets in the range of 15 to 450 μm.

The FSSP determines droplet diameter by measuring the intensity of light scattered in the near-forward direction when the droplet passes through a focused laser beam. It is assumed that only one droplet is within the depth of field of the probe optics at a time. Each measured droplet is then classified into one of fifteen size bins, which for a range of 2 to 47 μm means each bin is 3 μm wide. The standard corrections for "activity" and "ratio of total counts to total strobes" as described in the instrument manufacturer's manual (ref. 3) are applied in calculations of number density and LWC. In order to average out any fluctuations in the cloud and to obtain a good statistical sampling of droplets each cloud measurement is made for a duration of 50 seconds.

The OAP determines droplet diameter by measuring the diameter of a shadow of the particle formed as it passes through a collimated laser beam. The shadow is expanded by optical lenses and projected on a linear photodiode array. The droplet diameter is determined from the number of diodes shadowed and the magnification of the system. The OAP used in this study has 30 size bins and a range of 15 to 450 μm, each bin having a width of 15 μm. As in the FSSP it is assumed that only one droplet is within the probe's depth of field at a time. The standard calculations for sample area for each bin as contained in the manufacturer's manual (ref. 4) were used in calculations of number density and LWC.

In order to average out any fluctuations in the cloud and to obtain a good statistical sampling of droplets, particularly for the larger droplets measured by the OAP, each cloud measurement is made for a duration of 100 seconds.

LWC is calculated from the combined droplet distributions of the FSSP and OAP using the following equation:

$$LWC = \frac{\rho * \pi}{6} * \Sigma \frac{N_i * d_i^3}{SA_i * V * t} \quad (2)$$

where:

- ρ is the density of water
- N_i is the number of particles in bin i
- d_i is the mid-bin diameter of bin i
- SA_i is the sample area for bin i
- V is the airspeed
- t is the total sample time.

[2]The FSSP and OAP are manufactured by Particle Measuring Systems, Inc. of Boulder, Colorado.

For the FSSP the sample area, SA_i, is the same for each bin. For the OAP the sample area is a function of bin number (or droplet diameter). Data from the OAP below 47 micrometers (i.e., the upper limit of the FSSP) was disregarded because these bins tend to under-sample.

ICING TUNNEL CALIBRATION

The LWC calibration of the icing tunnel is established by making measurements of numerous spray conditions over the full operating range of the tunnel using the icing blade technique. This covers an airspeed range from 50 to 350 mph and a droplet size (MVD) range from 10 to 50 μm. Water spray settings also cover the complete range of atomizing air pressures and water flow rates. It should be noted that all data are taken at an air temperature of 0 °F to assure that the water droplets freeze on impact with the blade. The blade results are then used to establish an equation that accounts for the interplay of these variables. The equation takes the form:

$$LWC = A*\left(\frac{V}{150}\right)^{x}*\left(\frac{P_{air}}{40}\right)^{y}*\frac{\sqrt{dP}}{V} \qquad (3)$$

where: A, x and y are constants
V is tunnel airspeed
P_{air} is the spray nozzle air pressure
dP is the nozzle water pressure minus the air pressure.

Figure 2 shows a comparison of the icing blade measurements to the tunnel calibration (i.e., equation 3). It can be seen that the majority of the data is well within the +/–10 percent agreement lines. This plot is typical of the agreement to be expected from the tunnel as demonstrated by the twice-yearly calibration checks.

Icing Blade and Rotating Cylinder

To date five large droplet (i.e., MVD>50 μm) conditions have been established in the tunnel. They have nominal droplet size (MVD) values of 70, 100, 125, 175 and 270 μm. For these large droplet clouds it was initially felt that the icing blade normally used for tunnel LWC calibrations might not be appropriate since its surface area is so small. Therefore the initial measurements of LWC for large droplet conditions were made with a 1.5-inch diameter rotating cylinder at airspeeds of 125, 163 and 195 mph. The icing blade was then used to measure the LWC of these clouds as a source of comparison to the rotating cylinder measurements. Figure 3 shows the results of this comparison between the rotating cylinder and icing blade measured LWC at an airspeed of 195 mph. It can be seen that there is reasonable agreement between the two methods. Only two points are significantly outside the +/– 0.1 g/m^3 band. Figure 4 shows the same data, this time plotted as the ratio of the blade measured LWC to the cylinder LWC versus the nominal droplet size. It can be seen that reasonable agreement exists until the MVD exceeds 175 μm. At this droplet size it is possible that the larger droplets of the distribution are breaking up and splashing off the surface of the icing blade. The vertically adjacent points at 100, 175 and 270 μm are repeat runs with the rotating cylinder and serve to demonstrate the repeatability of the tunnel sprays and the cylinder measurement method in terms of LWC.

COMPARISON OF OTHER LWC INSTRUMENTS/TECHNIQUES

Hot-Wire LWC Instruments

Figure 5 shows a comparison of the LWC measured by the Johnson-Williams hot-wire instrument to the tunnel calibration over normal FAA Appendix C droplet conditions (i.e., 10<MVD<50 μm). This data was obtained over an airspeed range of 75 to 250 mph and air temperatures of 20 and 30 °F. It shows that on average the J-W measured LWC was 0.07 g/m^3 higher than the tunnel value. No trends due to airspeed or droplet size were evident in the data and are therefore not presented here.

Figure 6 shows a comparison of the CSIRO-King hot-wire results to the tunnel calibration. The data on this plot were obtained over an airspeed range of 75 to 250 mph, a droplet size (MVD) range of 10 to 40 μm and a temperature range of –15 to 40 °F. This instrument's results show good agreement with the tunnel calibration. Only a small percentage of the data are outside the +/– 0.1 g/m^3 band. This plot also demonstrates that there is no effect of air temperature on the tunnel LWC. This is an important piece of information since the LWC calibration of the tunnel was developed using the icing blade at a single air temperature of 0 °F. As with the J-W, no trends due to airspeed or droplet size were evident in the data from this test.

Figure 7 shows a plot of the test results for the J-W and CSIRO-King hot-wire instruments for the large droplet cases. For this plot the J-W data has been corrected by subtracting 0.07 g/m^3 from the data to account for the offset seen in figure 5. It can be seen that there is considerably more scatter for the CSIRO-King data than is seen with the J-W instrument but both instruments show almost the same decrease in response as the droplet size increases. The slope of the J-W is –0.022 as compared to the CSIRO-King slope of –0.0018. This is surprising because the sensing wire of the J-W is less than one-third the diameter of the CSIRO-King sensing wire.

Figure 8 shows a comparison of the Nevzorov LWC results to the tunnel calibration. Testing was performed with three different sensing vanes. Although the scatter in the data on this plot is approximately the same as that experienced with the J-W and CSIRO-King hot-wire instruments this instrument only indicated 75 to 90 percent of the tunnel LWC values, depending on sensor vane. Figure 9 shows the same comparison for the Nevzorov TWC, where it can be seen that the data scatter is very small but the sensors indicate only 76 percent of tunnel LWC values.

Unlike the other two hot-wire instruments the Nevzorov results showed a very strong influence due to changes in airspeed. Figure 10 shows that as the airspeed was increased the LWC measured by the Nevzorov also increased but the TWC decreased. During testing there was insufficient time to further investigate these trends.

Figures 11 and 12 show the response of the Nevzorov to the large droplet clouds. The data contained in these plots have been corrected by dividing the actual measurements by a factor of 0.76 to account for the instrument response shown in figures 8 and 9. It can be seen from figure 11 that the Nevzorov measured LWC under these conditions is very similar to the J-W and CSIRO-King instruments, having a slope of –0.0023. However, as seen in figure 12 the TWC sensor indicates no drop-off in response as droplet size increases. This lack of drop-off indicates that the Nevzorov TWC sensor has the potential for use in measuring the LWC of clouds containing large droplets.

Another test performed with the Nevzorov was intended to determine its ability to measure glaciated and mixed-phase icing conditions. The air and water temperatures supplied to the spraybars was gradually increased from 75 °F to 185 °F. The effect of these temperatures is that at the colder spraybar temperature virtually all of the water droplets freeze when exiting the nozzle. Then as the spraybar temperatures are increased fewer droplets freeze until at temperatures above approximately 175 °F none of the droplets are frozen. Figure 13 shows the response of the Nevzorov LWC and TWC sensors to these temperature changes. It can be seen that the LWC sensor does not respond to the frozen particles but its response increases as the amount of liquid water increases. The TWC sensor indicates an almost constant response—it measures the particles whether they are solid or liquid.

The results of the two tests described above shows that a comparison of the LWC and TWC from the Nevzorov could be used as an indication of clouds containing either ice crystals or large droplets. But it cannot be used to determine which of these cases exists.

Droplet Sizing Instruments

The droplet size (MVD) calibration of the icing tunnel is established by making hundreds of measurements of droplet distributions over different spray nozzle air and water pressure settings. Measurements are made with the Forward Scattering Spectrometer Probe (FSSP) and the Optical Array Probe (OAP). The LWC can be calculated from these droplet distributions as previously described. Figure 14 shows a comparison of the calculated LWC from these instruments to the icing tunnel LWC as determined by the icing blade for MVD's less than 50 μm and the rotating cylinder for MVD's greater than 50 μm. All LWC values from the droplet sizing instruments are significantly greater than the actual LWC. Figure 15 shows the same data plotted as a ratio of the LWC calculated from the FSSP plus OAP measured droplet distribution to the tunnel LWC plotted against droplet size. The plot shows that the ratio of LWC is between 1.5 for the smaller droplet cases and 2.5 for some of the larger droplet size cases. It should be noted that for the smallest MVD of 15 μm all of the calculated LWC comes from the FSSP. As the MVD increases more of the LWC is contained within the range of the OAP. Figures 14 and 15 demonstrate that both the FSSP and the OAP cause the LWC discrepancy.

In the legend of figures 14 and 15 symbols are shown to differentiate between "half spraybars" and "all spraybars". In the half spraybar cases even numbered spraybars were turned off in order to reduce the droplet number density and hence the FSSP "activity" level (ref. 5). All spraybars means that all eight spraybars were spraying. Measurements made during the half-spraybar tests did show a factor of 2 or more decrease in measured number density and FSSP activity but as can be seen in figure 15 the ratio of the LWC calculated from the FSSP and OAP compared to the tunnel LWC did not change significantly. In fact, for the larger droplet sizes, the LWC ratio is higher for the half-spraybar cases.

The most probable reason for the overestimation of LWC is oversizing by the droplet sizing instruments. This oversizing could be caused by either spectral broadening or coincidence errors or more probably both. Spectral broadening is caused by a droplet being sized differently depending on where it passes through the sample volume.

Coincidence errors result when more than one droplet is in the sample volume at the same time. This results in the two or more droplets being sized as one larger droplet. Although this results in a reduced number of droplet counts the calculated LWC would still increase because it is a function of the droplet diameter to the third power. The probability of coincidence errors is much greater in a tunnel than in most clouds in the atmosphere because of the much higher droplet number densities that exist in the tunnel environment.

These sizing errors would effect both the LWC and the MVD calculated from the instruments. Table 1 contains a listing of droplet sizes (diameters) and the measured size that would be required for the LWC to be overestimated by 50, 100, and 150 percent as was shown to be the case in figure 8. A monodispersed droplet distributions is assumed for this simplified example. The table illustrates that in at least some cases the oversizing would have to be very significant.

OTHER OBSERVATIONS DURING TESTING

All of the instruments tested had some degree of problems in the icing environments. The J-W sensor had sufficient heating to remain ice-free in all but the most severe icing cases. However, at colder temperatures (<0 °F) and high LWC ice could form on the front support for the compensating wire. The ice would build up and then shed, causing fluctuations in indicated values of LWC.

The CSIRO-King sensor has no heating on most of its surface area and therefore is subject to ice build-up over time. This limits the amount of time the probe can be used in icing conditions before the ice blockage would affect the measured LWC. While this isn't a significant problem in icing tunnel testing because the sensor can be easily accessed, it could cause problems when used on aircraft in extended icing conditions.

The unheated sides of the Nevzorov sensor vane had a significant icing problem that limited testing to temperatures just below freezing. Ice would build up on the sides of the vane and cause a change in the LWC indications within one minute. Therefore, all testing of this instrument except the droplet freeze-out test were conducted at total temperatures from 28 to 35 °F.

Icing of the FSSP was always a problem. Ice builds up on a small protrusion within the sampling tube of the probe. This ice growth causes local blockage of the airflow, which causes the airflow and the smaller droplets to concentrate towards the center of the sampling tube. This results in an increase in measured number density and a decrease in measured droplet size with time. In the icing tunnel, the ice had to be removed after only five minutes.

Icing was generally not a significant problem with the OAP. Although ice builds up on the front hemisphere and the cross-brace between the probe arms it does not cause measurement errors until the ice becomes large enough to seriously affect the airflow through the sample area of the probe.

DISCUSSION OF MAJOR RESULTS

It was shown that the icing blade, rotating cylinder, J-W and CSIRO-King hot-wire probes agreed well in the NASA Glenn Icing Research Tunnel when the droplet sizes (MVD) were within the "normal" range of 10 to 40 μm as defined by the FAA's FAR Part 25, Appendix C envelopes. It was also shown that good agreement was achieved between the rotating cylinder and the icing blade measured LWC values for the larger droplet sprays with MVD's of 70 to 175 μm.

The Nevzorov LWC instrument only indicated 76 percent of the actual LWC when the droplet sizes (MVD) were within the range of 10 to 40 μm. The TWC sensor indicated approximately 76 percent of tunnel LWC values for all droplet sizes (MVD) from 10 to 270 μm.

The calculated LWC from the droplet distributions measured by the FSSP and OAP severely overestimate the LWC. The LWC was overestimated by 50 percent for MVD's up to 50 μm and 100 to 150 percent for higher MVD's.

CONCLUSIONS

1. Good agreement was shown between the LWC derived from icing blade technique and the J-W and CSIRO-King hot-wire LWC instruments for $10<MVD<40$ μm.
2. The Nevzorov instrument only indicated 76 percent of the actual LWC when the droplet sizes were within the range of 10 to 50 μm.
3. Good agreement was shown between the LWC derived from the icing blade and the rotating cylinder techniques for $15<MVD<175$ μm.
4. The response of the J-W, CSIRO-King and Nevzorov LWC instruments had approximately the same drop-off in response as the droplet size was increased above 50 μm. The slope of the drop-off was between –0.0018 and –0.0023.
5. The Nevzorov TWC sensor showed no drop-off in response as the droplet size was increased above 50 μm. It shows a good potential for use in measuring LWC in SLD clouds.
6. A comparison of the measured LWC and TWC from the Nevzorov could be used to indicate when an aircraft is flying in large droplet, mixed-phase or glaciated clouds.
7. The LWC calculated from the droplet distributions measured by the FSSP and OAP severely overestimated the actual LWC.

RECOMMENDATIONS

1. Additional testing in a controlled environment should be conducted with the Nevzorov LWC/TWC instrument to gain additional experience and to further evaluate its accuracy.
2. The sides of the Nevzorov sensing vane should be heated to avoid serious icing problems.
3. The cause(s) of the overestimation of LWC by the FSSP and OAP should be further investigated.

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Table 1

Actual droplet diameter	Measured droplet diameter if LWC were overestimated by:		
	50 percent	100 percent	150 percent
10	11.4	12.6	13.6
20	22.9	25.2	27.1
40	45.8	50.4	54.3
50	57.2	63.0	67.9
100	114.5	126.0	135.7
200	228.9	252.0	271.4

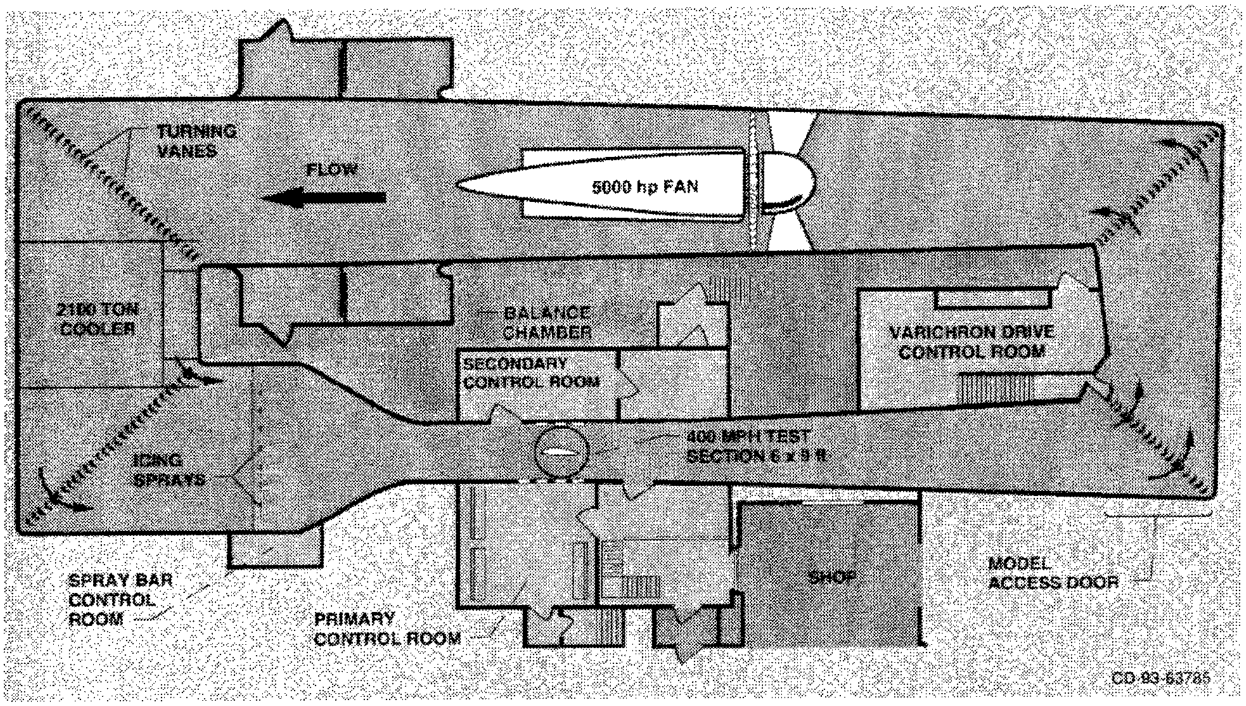

Figure 1.—Plan view of the NASA Glenn Icing Research Tunnel.

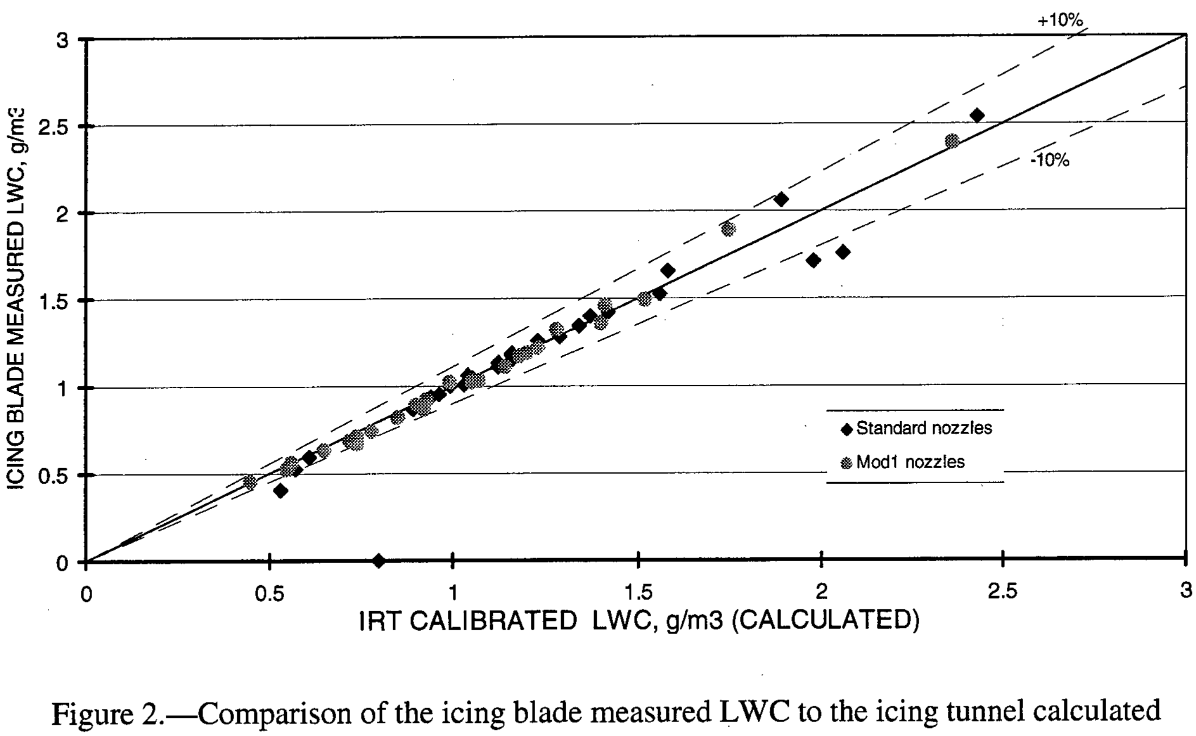

Figure 2.—Comparison of the icing blade measured LWC to the icing tunnel calculated LWC for 50<Airspeed<350 mph, 14<MVD<50 μm and an air temperature of 0 °F.

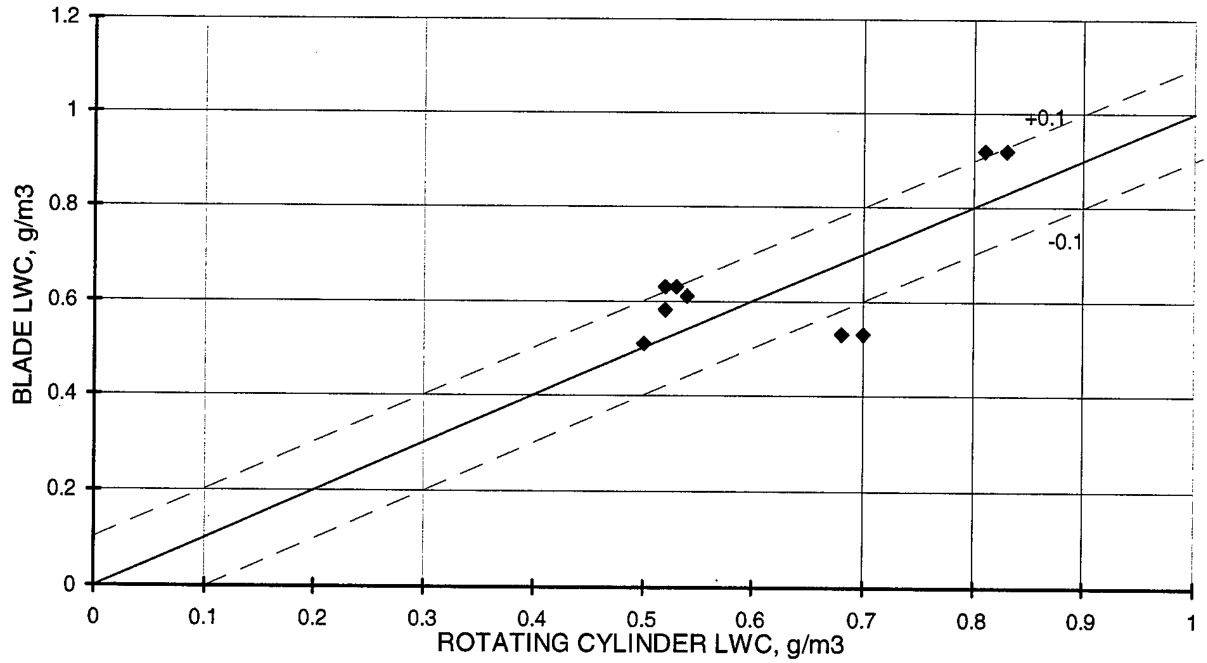

Figure 3.—Comparison of the icing blade measured LWC to the rotating cylinder LWC for droplet sizes (MVD) from 15 to 270 μm.

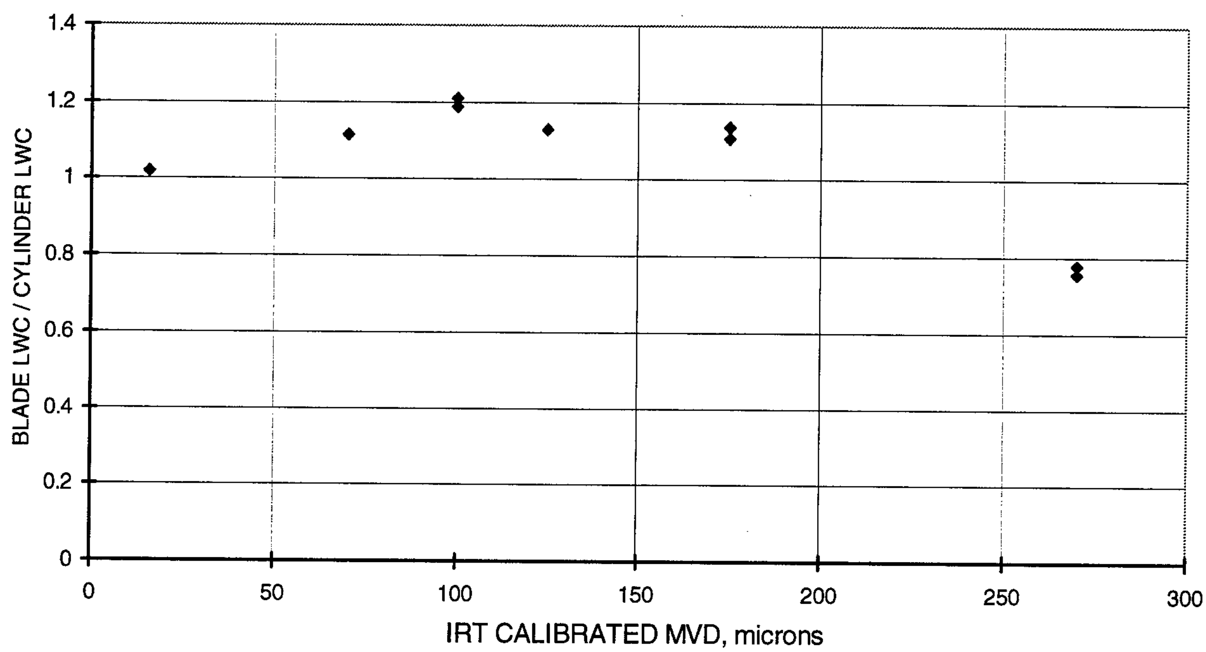

Figure 4.—Ratio of the icing blade measure LWC to the rotating cylinder LWC for a range of droplet sizes (MVD) from 15 to 270 μm.

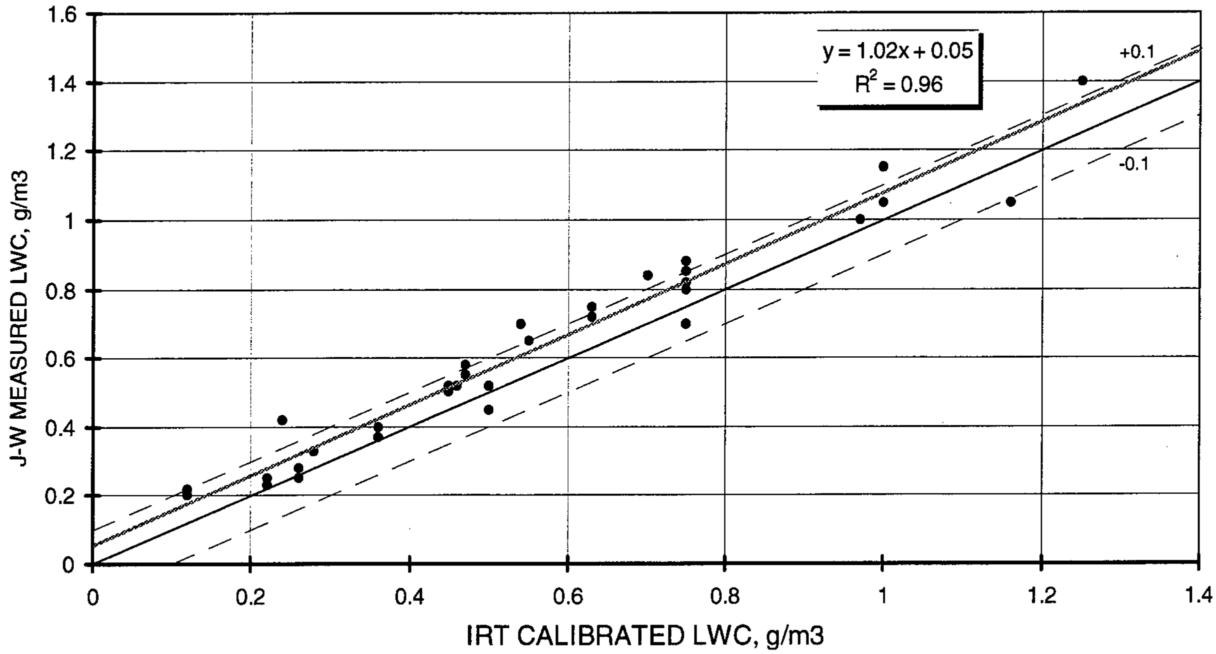

Figure 5.—Comparison of Johnson-Williams measured LWC to the IRT calibrated LWC for 75<Airspeed<250 mph, 10<MVD<40 μm and air temperatures of 20 and 30 °F.

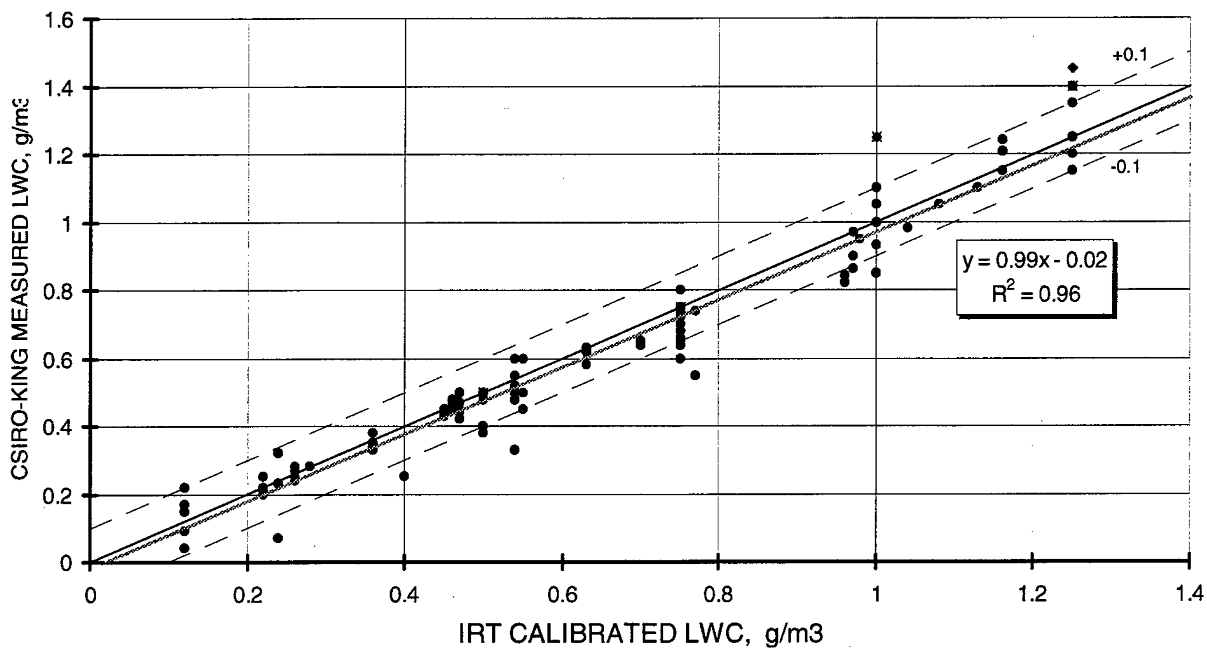

Figure 6.—Comparison of CSIRO-King measured LWC to the IRT calibrated LWC for 75<Airspeed<250 mph, 10<MVD<40 μm and –15<Temp<40 °F.

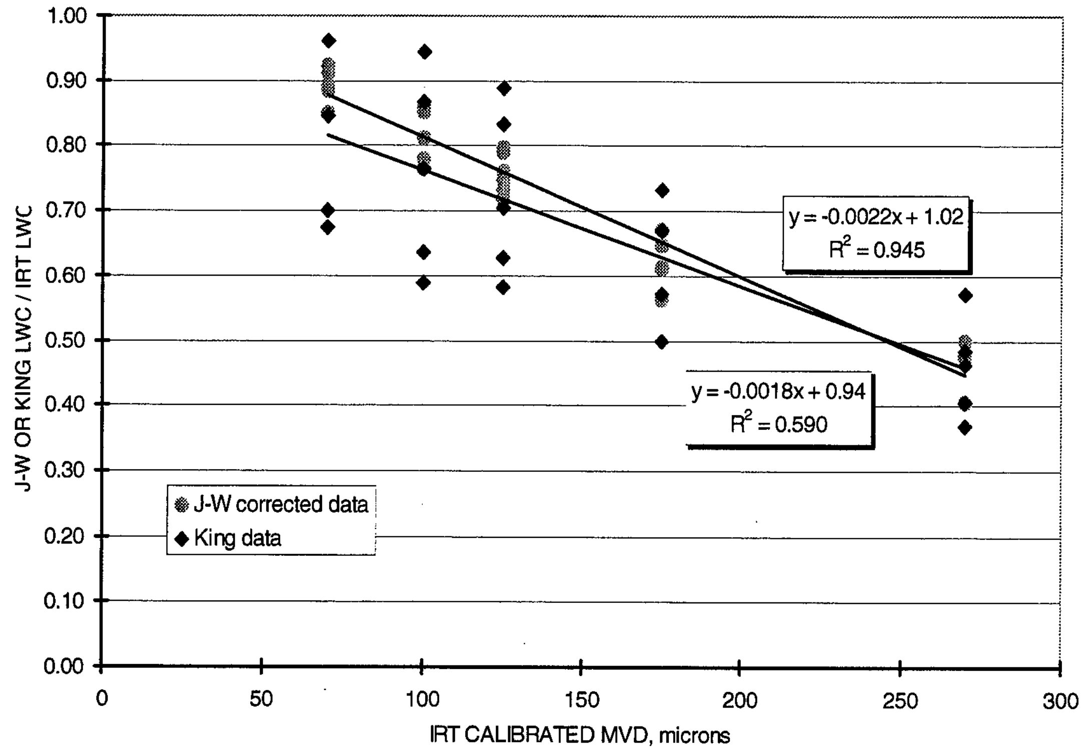

Figure 7.—Ratio of the corrected Johnson-Williams and CSIRO-King measured LWC to the IRT calibrated LWC for large droplets at airspeeds of 125, 163, and 195 mph.

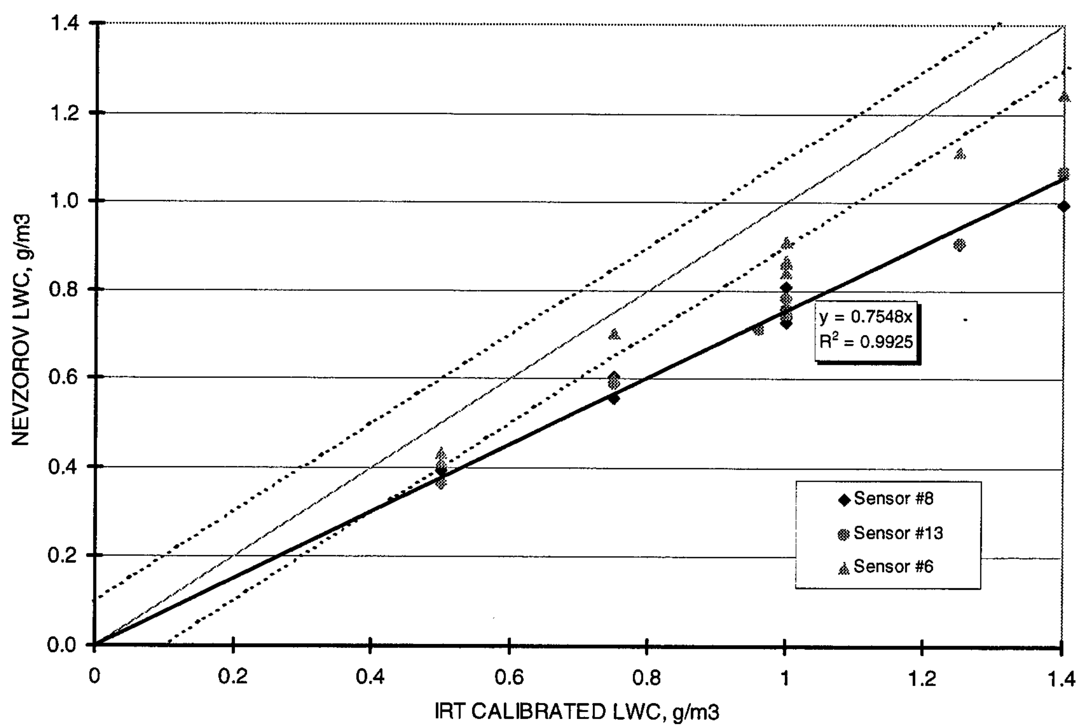

Figure 8.—Comparison of the Nevzorov measure LWC to the IRT calibrated LWC at an airspeed of 150 mph, MVD of 20 μm and air temperature of 28 to 40 °F.

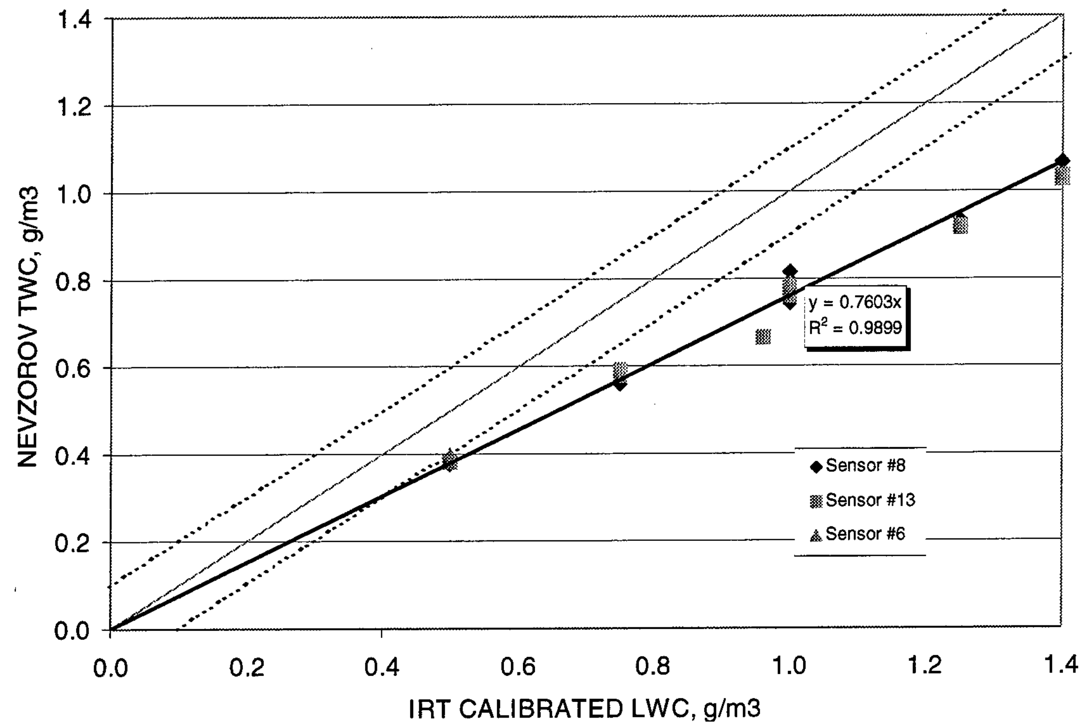

Figure 9.—Comparison of Nevzorov measured TWC to the IRT calibrated LWC at an airspeed of 150 mph, MVD of 20 μm and air temperature of 28 to 40 °F.

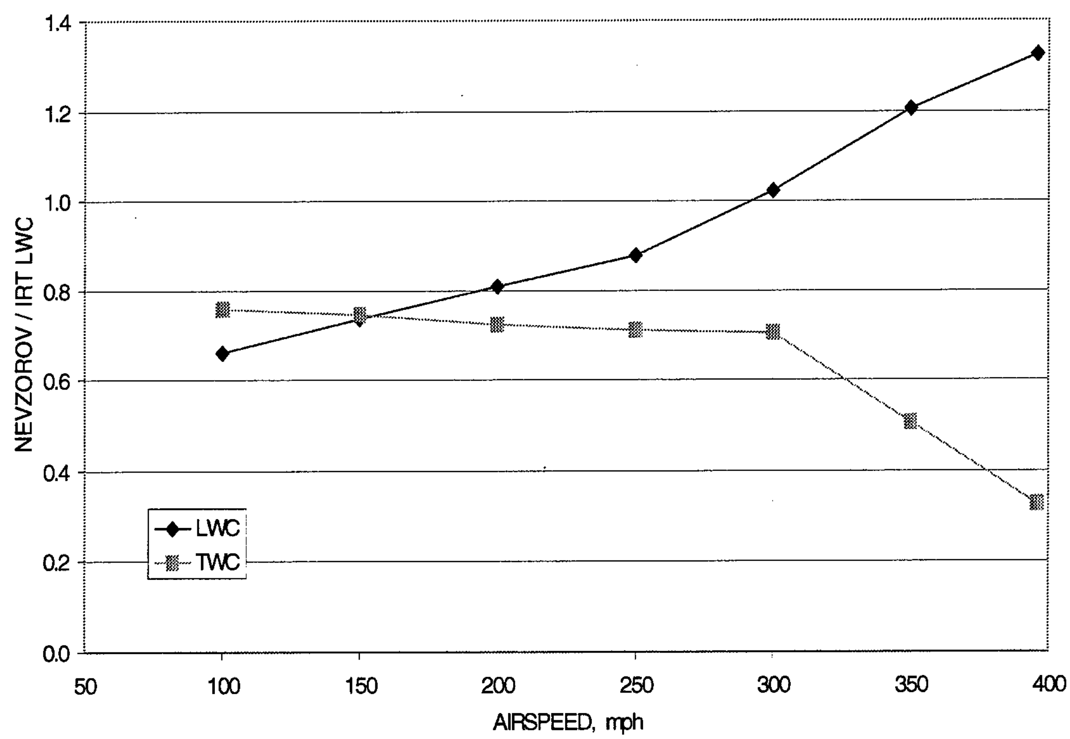

Figure 10.—Ratio of the Nevzorov measured LWC and TWC to the IRT calibrated LWC as a function of airspeed. The tunnel temperature was 33 °F and the MVD was 20 μm.

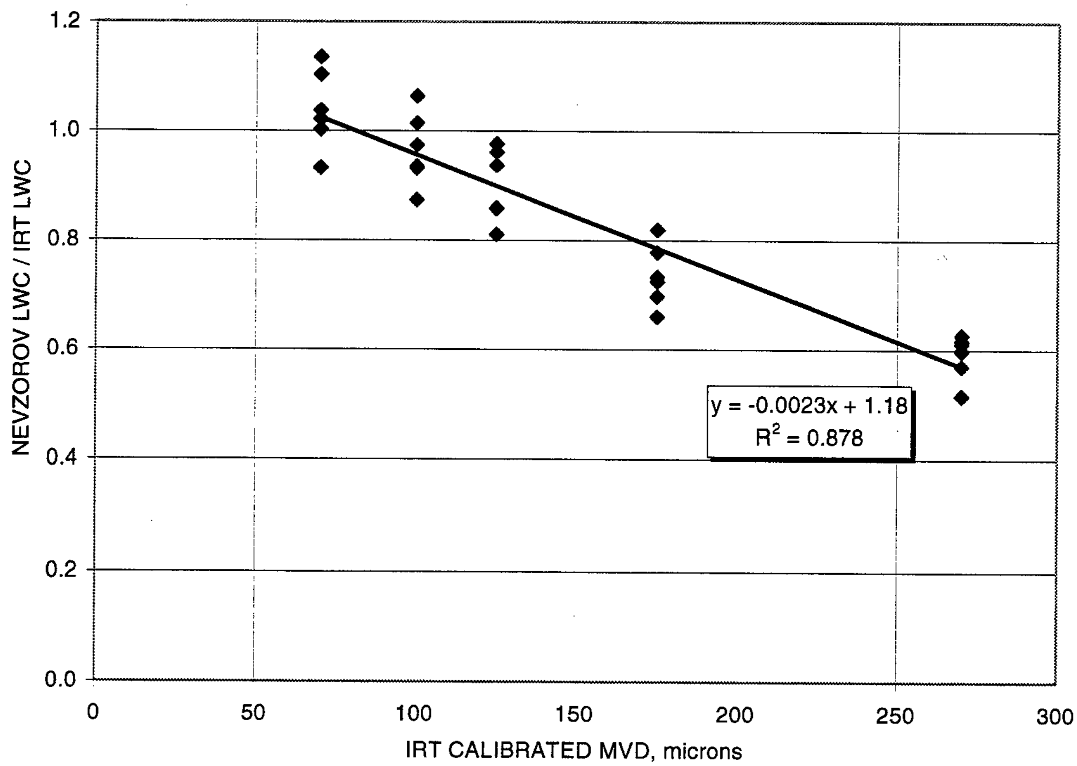

Figure 11.—Ratio of the corrected Nevzorov measured LWC to the IRT calibrated LWC for large droplets at airspeeds of 125, 163, and 195 mph.

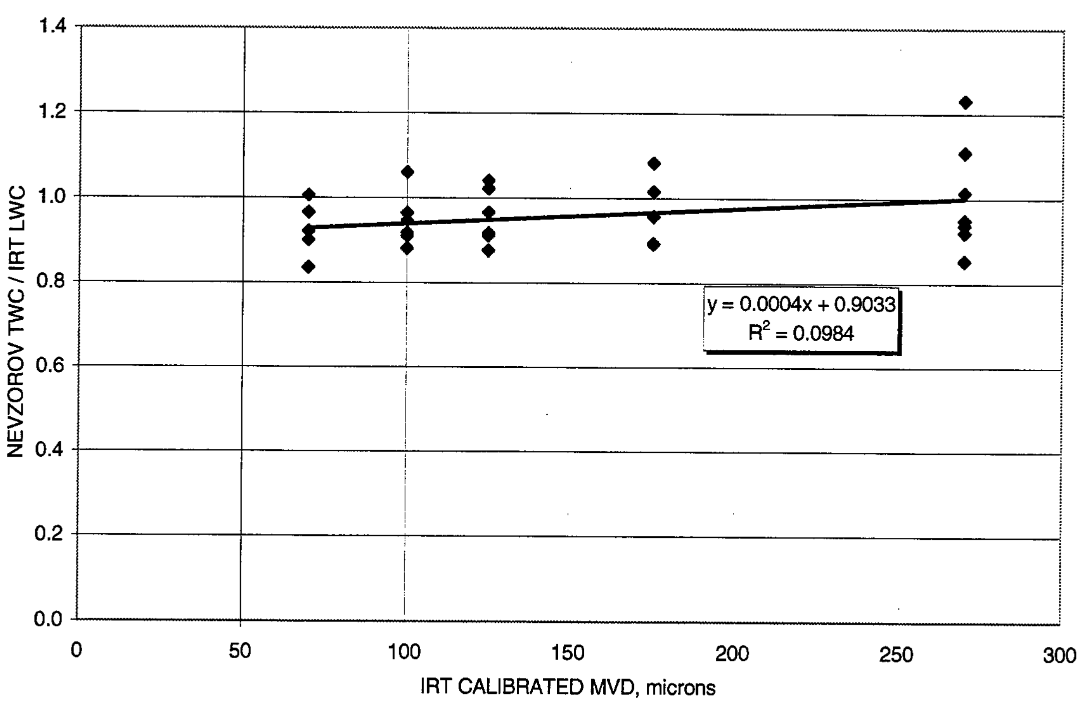

Figure 12.—Ratio of the corrected Nevzorov measured TWC to the IRT calibrated LWC for large droplets at airspeeds of 125, 163, and 195 mph.

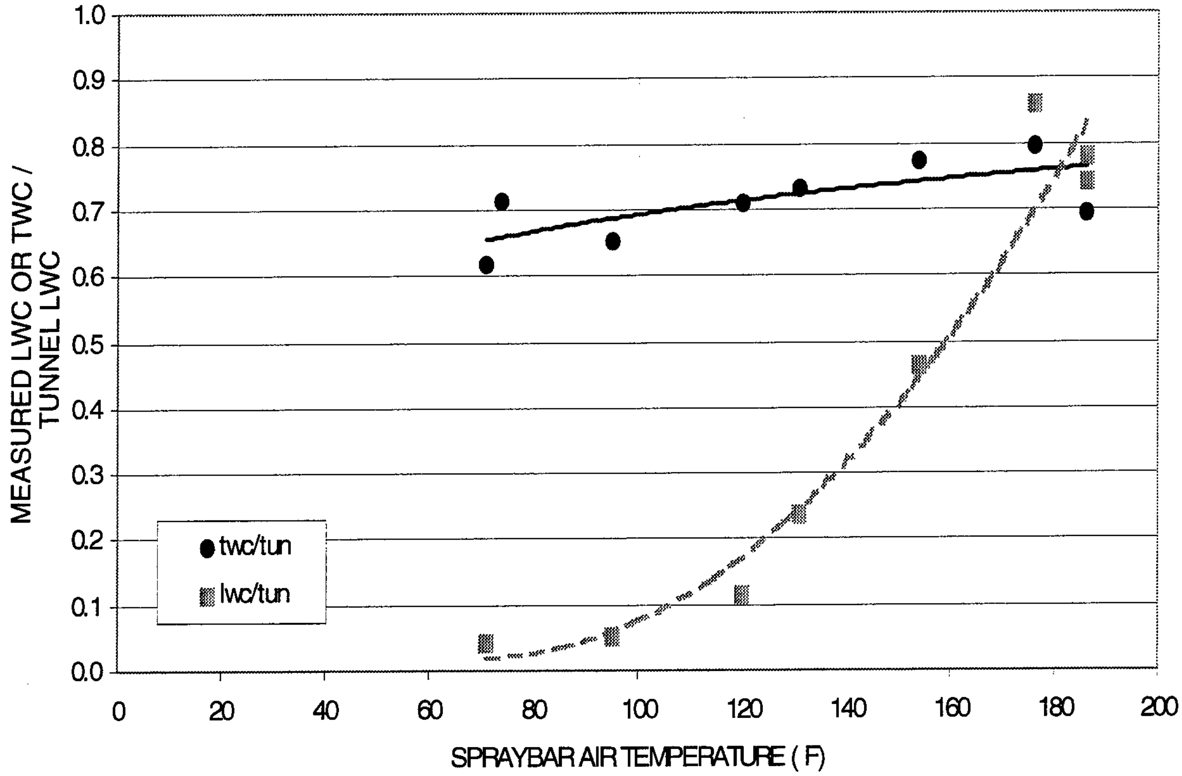

Figure 13.—Comparison of Nevzorov LWC and TWC response to glaciated and mixed-phase icing clouds. The air temperature was 15 °F and the MVD was 16 μm.

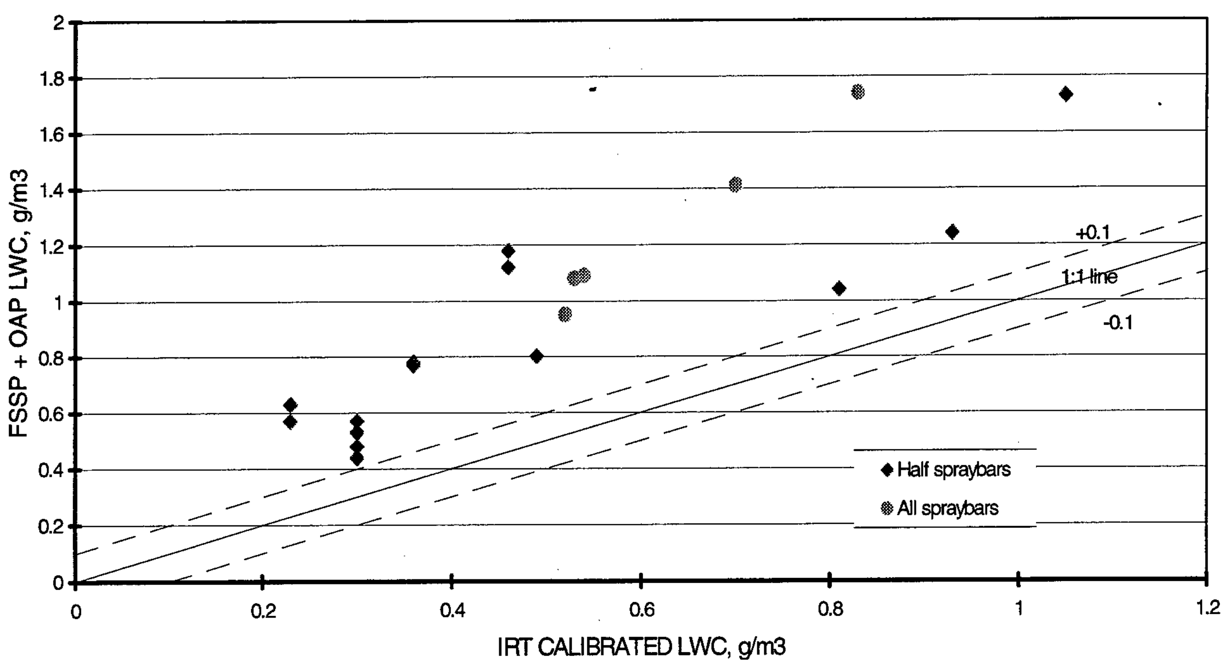

Figure 14.—Comparison of the LWC calculated from the FSSP and OAP to the IRT calibrated LWC at speeds of 150 and 195 mph. The droplet sizes (MVD) range from 15 to 270 μm.

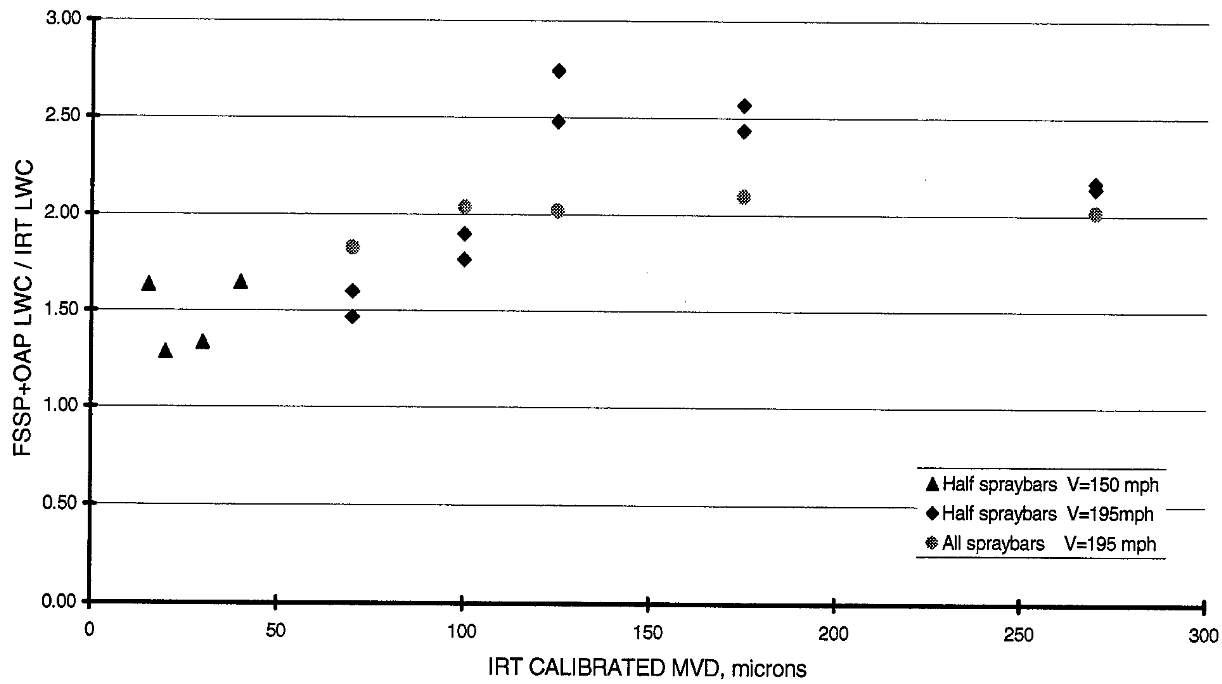

Figure 15.—Ratio of the LWC calculated from the FSSP and OAP to the IRT calibrated LWC as a function of droplet size (MVD).

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13. ABSTRACT ***(Maximum 200 words)***

This paper compares the results of liquid water content measurements by various means in an icing wind tunnel. The techniques/instruments tested are the icing blade, a single rotating cylinder, the Johnson-Williams and CSIRO-King hot-wire probes, the Nevzorov LWC/TWC probe and the liquid water content calculated from the combined droplet distributions of two droplet sizing probes - the Forward Scattering Spectrometer probe and the Optical Array probe. A large range of icing conditions was used for this study. The liquid water content ranged from 0.1 to 1.25 g/m^3 and the median volumetric droplet diameters (MVD) ranged from 10 to 270 μm. Airspeeds of 50 to 250 mph (22 to 112 m/s) were used. This study shows the degree of agreement between the various liquid water content measurement methods over the normal cloud MVD range of 10 to 50 micrometers and over several supercooled large droplet (SLD) conditions. It shows that the Nevzorov LWC/TWC instrument has the potential for measuring the LWC in SLD clouds as well as normal droplet size cloud conditions. It reveals a large disagreement between the droplet sizing probe results and the other methods. The implications and possible causes of this disagreement are discussed. Recommendations for additional investigations to resolve disagreements are included.

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