Total Water Content Measurements With an Isokinetic Sampling Probe

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Abstract

The NASA Glenn Research Center has developed a Total Water Content (TWC) Isokinetic Sampling Probe. Since it is not sensitive to cloud water particle phase nor size, it is particularly attractive to support super-cooled large droplet and high ice water content aircraft icing studies. The instrument is comprised of the Sampling Probe, Sample Flow Control, and Water Vapor Measurement subsystems. Analysis and testing have been conducted on the subsystems to ensure their proper function and accuracy. End-to-end bench testing has also been conducted to ensure the reliability of the entire instrument system. A Stokes Number based collection efficiency correction was developed to correct for probe thickness effects. The authors further discuss the need to ensure that no condensation occurs within the instrument plumbing. Instrument measurements compared to facility calibrations from testing in the NASA Glenn Icing Research Tunnel are presented and discussed. There appears to be liquid water content and droplet size effects in the differences between the two measurement techniques.

Introduction

The need for a new form of water content measurement instrument became apparent as NASA became deeply involved with the study of hazards associated with super-cooled large droplets (SLD) flight conditions (Ref. 2). As NASA began experimental studies in SLD conditions, it became apparent that the current liquid water content (LWC) instrumentation would be inadequate. Existing instrumentation was designed and intended for cloud measurements of cloud droplet size distributions with a typical median volumetric diameter (MVD) of <50 μm. When the larger droplets associated with SLD conditions impact the existing instrumentation, the measured LWC could be significantly in error due to droplet breakup, splashing, and bouncing (Ref. 3).

In addition to the inadequacies of current LWC instrumentation for SLD conditions, a new need for improved water content measurement of mixed-phase and high ice water content (HIWC) conditions has also more recently come to the attention of NASA. Cruise altitude engine icing caused by flight into HIWC conditions has been shown to be a serious flight hazard (Ref. 4). To date, there is limited data available to quantify this environment, in part because of the lack of adequate water content instrumentation. Due to its basic design, existing water content instrumentation suffers the effects of ice particle bouncing and inadequate heater capacity when tasked to measure HIWC conditions.

One solution option that eliminates droplet splash, bounce, and breakup effects of SLD conditions and ice particle bounce effects for HIWC conditions is a heated isokinetic cloud particle sampler. Isokinetic Sampling is defined as "Any technique for collecting airborne particulate matter in which the collector is so designed that the air stream entering it has a velocity equal to that of the air passing around and outside the collector" (Ref. 5). By its nature, a properly functioning heated isokinetic cloud particle sampler should not be influenced by the size or phase of the cloud particle. By sufficiently heating the sampling probe, all water particles sampled (ice and liquid) are evaporated into the air sample. An additional benefit of this heating is that the exterior of the probe remains free of ice accretion. When all of the water is evaporated, the cloud's total water content (TWC) can be calculated for a known air sample flow rate by differencing the measurement of the absolute humidity of the sampled air from the measurement of the absolute humidity of the ambient air.

Nomenclature

A_{inlet} inlet area (m^2)

d_{ref} reference distance (m)

d_{part} particle diameter (m)

LWC   liquid water content (g/m^3)

MVD   median volumetric diameter (μm)

Stk   Stokes number: $\tau\, V/d_{ref}$ (from Ref. 1)

TWC   total water content (g/m^3), water content made up of both liquid and ice particles

$V_{external}$ ambient external free-stream air velocity (m/s)

$\rho_{external}$ ambient external free-stream air density (kg/m^3)

ρ_{dryair} dry air density (kg/m^3)

ρ_{part} water particle density (kg/m^3)

μ air viscosity (Pa s)

τ relaxation time: $\rho_{part} * d_{part}^2/18\,\mu$ (from Ref. 1)

Instrument Concept

The concept behind a total water content (TWC) instrument based on heated isokinetic cloud particle sampling is relatively straightforward. This form of TWC instrument can be broken into 3 subsystems: (1) Sampling probe (2) Sample flow control, and (3) Water vapor measurement. A block diagram of such an instrument is shown in Figure 1.

Sampling Probe

The sampling probe must be designed to ensure isokinetic sampling is possible and must provide sufficient heat to completely evaporate the ingested moisture. To ensure isokinetic sampling capability, the probe would ideally satisfy the thin-wall assumption. Uncorrected isokinetic sampling theory is valid for probes with an outer diameter to inner diameter ratio of 1.1 (Ref. 6). This ensures that when the probe inlet is properly aligned with the external flow velocity vector and that the probe internal velocity matches the external velocity, the flow entering the probe will not have been disturbed. An extreme example of this criterion not being satisfied is a sampling orifice in a flat plate. Even if the orifice is aligned with the flow and the internal velocity is set equal to the external velocity, the flow about the flat plate will influence the incoming streamlines such that a significant number of the particles intended for sampling will be deflected away from the probe inlet. In the same situation, a probe satisfying the thin-wall assumption would not disturb the incoming streamlines and the probe will ingest all particles within the incoming stream-tube.

Sample Flow Control

The objective of this kind of instrument is to obtain a sample with the same ratio of constituents as the ambient free-stream conditions. If the particles of interest have no mass, then they will always follow the air streamlines and a sample with proper particle to air ratio can always be obtained regardless of the inlet velocity. However, since we are interested in sampling water particles that can have significant inertia
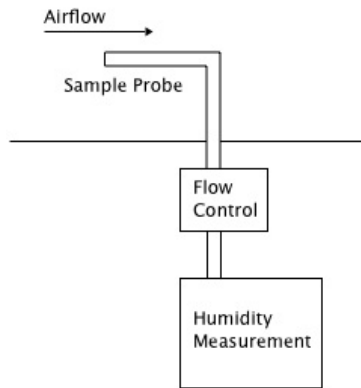
Figure 1.—Basic block diagram
of sampling total water content
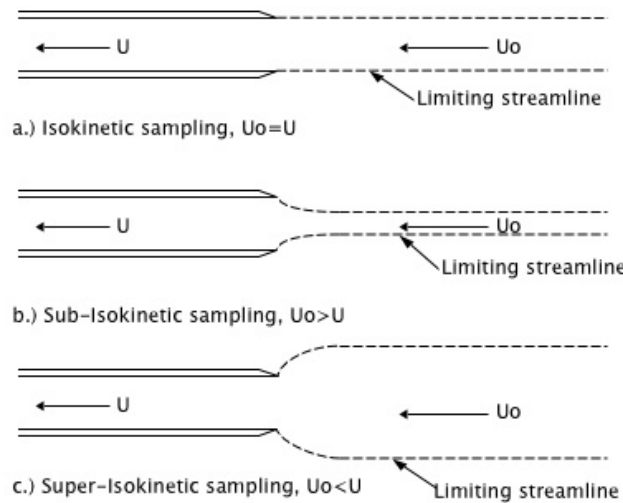(TWC) instrument subsystems.

Figure 2.—Schematic of possible probe inlet flow
conditions. (a) Isokinetic sampling. (b) Sub-isokinetic
sampling. (c) Super-isokinetic sampling.

(such that their paths can deviate from turning air streamlines), we must be careful to properly set the probe's inlet flow conditions. When a probe's mean inlet face velocity is equal to the external free-stream conditions, we have isokinetic sampling (Fig. 2(a)). When the internal flow is too slow, the condition is considered to be sub-isokinetic (Fig. 2(b)). When the internal flow is too fast, the condition is considered to be super-isokinetic (Fig. 2(c)).

Sub-isokinetic sampling results in elevated concentration measurements since too little air is being ingested relative to the number of particles captured. Super-isokinetic sampling results in low concentration measurements since too much air is being ingested relative to the number of particles captured.

Water Vapor Measurement

When the sampling probe is properly designed and aligned, and the sample flow rate is properly controlled, the sample obtained will have the same constituents as the external conditions. Since our probe is assumed to be sufficiently heated, all of the captured sample moisture is evaporated to water vapor. Therefore, the determination of TWC with this probe comes down to subtracting the ambient water vapor from the sample water vapor and converting the result into the desired water content units.
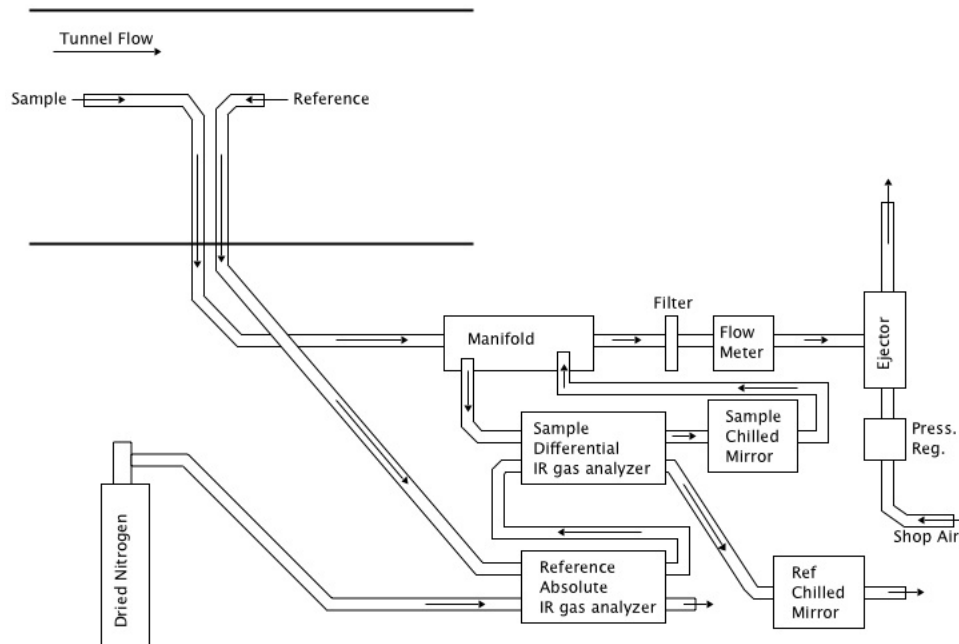
Figure 3.—Detailed block diagram of NASA TWC Isokinetic Probe.

Apparatus

The NASA Isokinetic TWC instrument is based upon the concept described above. A detailed block diagram of the instrument is seen in Figure 3. While this diagram may seem rather complicated, the system can still be broken down to the subsystems described above.

The forward and backward facing tubes within the tunnel flow in Figure 3 make up the Sample Probe subsystem. The forward facing tube collects the ambient air and cloud particle (Sample) and the rear facing tube collects only the ambient air (Reference).

The Filter, Flow Meter, Shop Air source, Pressure Regulator, and Ejector in Figure 3 make up the Flow Control subsystem. Airflow through the Sample probe is set by adjusting the amount of suction. Introducing a regulated air source to an ejector (Ref. 7) creates the required suction. The suction driven flow is filtered and measured with a thermal mass flow meter (Ref. 8). By monitoring the sample flow rate, the ejector source air can be adjusted until the target flow rate is achieved.

The Infrared (IR) Gas Analyzers and the Chilled Mirror hygrometers in Figure 3 make up the Humidity Measurement subsystem. Two differential, nondispersive, IR gas analyzers (Ref. 9) are utilized to make the primary water vapor concentration measurements for both the sample and the reference air sources. This form of gas analyzer measures the difference in infrared absorption between two sampling cells. To make an accurate, absolute measurement of its water vapor concentration, the reference is compared to dry nitrogen (high precision nitrogen source dried with a magnesium perchlorate dessicant). The second water vapor concentration gas analyzer makes an accurate differential measurement between the sample and reference air sources. To maximize the systemic accuracy of the water vapor measurements, the measured absolute water vapor concentration of the reference source is passed electronically to the differential unit. Two chilled mirror hygrometers are used as backups for the water vapor measurements. While chilled mirror hygrometers can be quite accurate, their time response is relatively poor, and thus not as attractive as the IR gas analyzers. Since the air flow rates through the IR gas analyzers and the chilled mirror hygrometers are not as high as the required isokinetic sampling flow rate, the sample air source for the water vapor measurements is drawn from the manifold in the suction line upstream of the flow meter. Since we are making very accurate flow rate measurements to ensure isokinetic sampling, after passing through the water vapor instruments, the sample air is dumped back

into the manifold (downstream of where it is drawn) to ensure no leakage. After passing through the water vapor instruments, the reference air and the dry nitrogen are vented to the room.

The installation in the NASA Glenn Icing Research Tunnel (IRT) is shown in Figures 4 and 5. Figure 4 shows the sampling probe within the wind tunnel test section and Figure 5 shows the remainder of the instrument system in the wind tunnel control room.

The control and measurements of the TWC Isokinetic Probe are handled with a data acquisition program written in the LabVIEW programming environment (Ref. 10), running on a laptop computer. Data signal input, control output, and analog-to-digital conversion is performed with an Ethernet-based portable data acquisition system (Ref. 11). Some of the calculations made in the LabVIEW program are described in the Appendix.

Figure 4.—TWC Isokinetic Probe in the IRT.

Figure 5.—NASA TWC Isokinetic System equipment in the IRT. Left, on desk, is controlling PC laptop; Center, in tall rack, are the Chilled Mirror hygrometers, the data acquisition hardware, and the IR Gas Analyzers; Right, on table, power supply that provides current for sampling probe heat.

Results and Discussion

Potential Error Assessment

Early in the development of this instrument system, it became apparent that there were several potential sources for error. The potential error sources align with the subsystems described earlier.

For the Sample Probe subsystem, a concern was violating the thin-wall assumption. As discussed earlier, to satisfy the thin-wall assumption the ratio of the outer diameter to the inner diameter of the probe inlet needs to be 1.1 or less. For the probe used in this work, that ratio was 1.33. To examine this further, a computer analysis was performed using PMARC (Ref. 12) to provide the flow solution and LEWICE3D (Ref. 13) to provide the droplet trajectory analysis (Fig. 6). The trajectories calculated by LEWICE3D were then used to calculate inlet catch efficiency for a range of droplet size, external flow velocity, and probe flow angularity. The inlet catch efficiency data and the approximation used to correct the experimental TWC Isokinetic Sampling probe data is shown in Figure 7. To improve the accuracy of the instrument this correction is applied, but as one can see, the corrections are quite small for all but the smallest droplet sizes (error caused by flow angularity between 0 and 5° was considered negligible, so no flow angularity correction is applied).
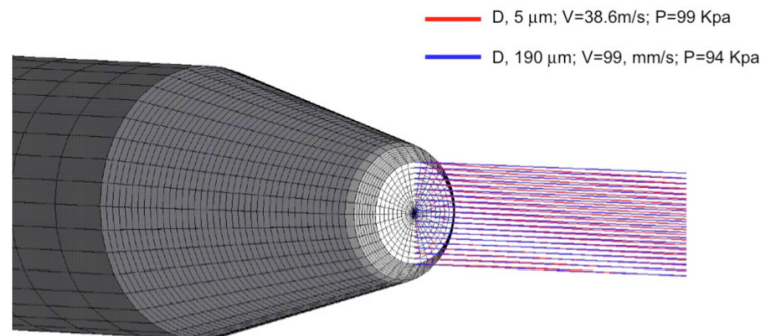

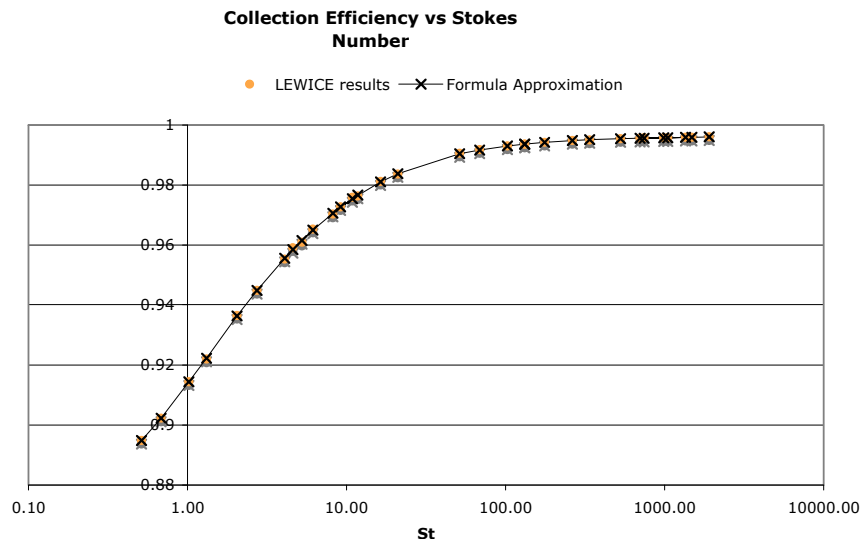Figure 6.—LEWICE3D calculated droplet trajectories for NASA TWC Isokinetic Sampling Probe.

Figure 7.—LEWICE3D calculated TWC Isokinetic Sampling Probe collection efficiency and the related Stokes Number formula approximation.

For the Humidity Measurement subsystem, the main concern was the accuracy and proper calibration of the IR gas analyzers. To help assess the accuracy of the IR gas analyzers, the chilled mirror hygrometers were added to the system. And to examine the accuracies of the humidity measurements in a controlled manner and to assess various calibration techniques, a bench test was performed. For bench testing the system, the probe head was replaced with a chamber that could heat and evaporate very controlled amounts of water. The system software was modified to time-integrate the total amount of water sampled, thus providing a controlled end-to-end system check of most of the TWC instrument (water vapor measurements, the flow control and measure, analog-to-digital signal conversion, data acquisition, and system software). Using the bench test, the instrument was found to be very repeatable and accurate to within 5 percent.

Early bench testing pointed to a problem in the Sample Flow Control subsystem. The bench testing and further flow meter comparison tests led to the rejection of one of the original two flow meters. While the rejected flow meter was designed to be temperature and pressure compensated, it was found to have significant error when operating in a suction driven flow. The thermal mass flow meter that is used today has been checked against a differential pressure volumetric flow meter with excellent agreement and receives annual NIST traceable calibration.

Another finding of the bench testing is that for this kind of instrumentation, it is very important to monitor the sample's dew point and temperature and the temperature of the tubing and instrument surfaces exposed to the sample (the sample path). If the sample's dew point goes above the temperature of the sample path, condensation will take place and the measured water vapor will be incorrect. For the NASA TWC instrument system, this is handled by using a heated hose to transport the sample from the probe to the individual humidity instruments. Also the tubing length is kept to a minimum. The use of tubing that is resistive to water absorption is also obviously very important.

Icing Wind Tunnel Condensation Cloud

In the course of the development and testing of the TWC Isokinetic Sampling Probe, the authors experienced several instances of apparent elevated icing wind tunnel LWC (above the wind tunnel's calibrated spray LWC). Upon further consideration, it has been theorized that a condensation process, not unlike that which causes cap clouds above mountaintops, caused these events. This additional cloud generation can occur when the humidity, heat exchanger temperature, and air speed conditions within any icing wind tunnel are suitably combined. To help illustrate this formation process, Figure 8 displays a conceptual icing wind tunnel layout. Flow, which is from the left, passes through the heat exchanger and on through the contraction into the test section. In region A, the airspeed is V_a, static temperature is Ts_a, and the dew point is Dew_a. As the flow goes through the heat exchanger, the airspeed remains steady ($V_b = V_a$); if the heat exchanger is cooling the airflow, then Ts_b will be less than Ts_a; and if the heat
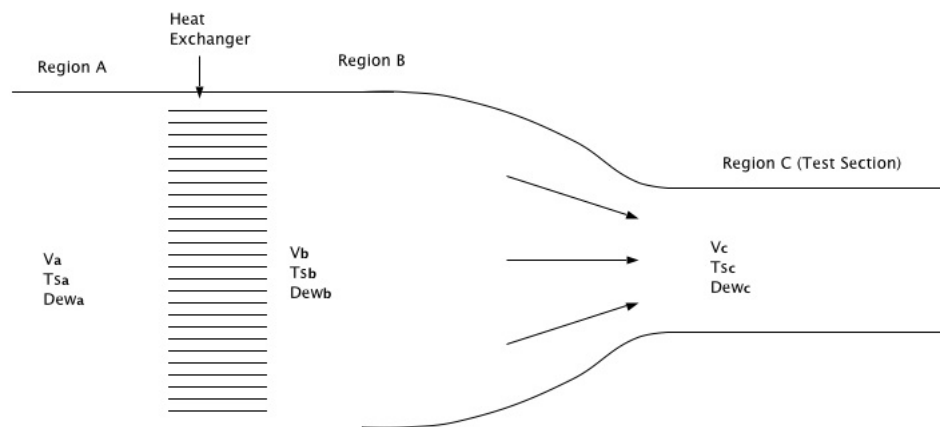

Figure 8.—Conceptual icing wind tunnel layout.

exchanger temperature is below Dew_a, then the flow will be dried ($Dew_b < Dew_a$). As the flow accelerates through the contraction into the test section, the velocity increases ($V_c > V_b$) and the static temperature drops ($Ts_c < Ts_b$). If the static temperature drops below the dew point, the air becomes supersaturated and a spontaneous condensation cloud begins to form. As water vapor condenses into liquid water, the dew point decreases ($Dew_c < Dew_b$). If the dew point in regions B and C are known, then the LWC of resultant condensation cloud can be calculated (described in Appendix). The MVD of mountaintop cap clouds are on the order of 10 μm with a rather narrow size spectra as a result of direct condensation with little or no coalescence (Ref. 14). This paper's authors theorize that the MVD of an icing wind tunnel condensation cloud would be 5 μm or smaller since the growth time within the region of supersaturation (from the end of the contraction through the test section) is a fraction of a second. It should be noted that droplets such as these with very low inertial parameters would not significantly contribute to wing ice accretions nor be detectable by instruments requiring particle impact. Depending on the icing wind tunnel conditions, the LWC of a condensation cloud can be significant. Since the TWC Isokinetic Sampling Probe would not discriminate between condensation cloud and the normal spray cloud of the IRT, the data presented in the next section has been corrected for the presence of condensation cloud.

NASA Glenn Icing Research Tunnel (IRT) Data

The instrument system as described above was tested in the IRT in January and again in May 2008. The test condition matrices for these two tests are found in Tables 1 and 2. The conditions run in the May 2008 test were selected from the IRT calibration conditions. These conditions were used to ensure that there was no calibration interpolation error possible. Because of this, the May 2008 data is considered our best set of data and is emphasized here.

All of the TWC Isokinetic Sampling Probe data presented here has been corrected for collection efficiency as described earlier. Each of the TWC data points has been time averaged over a stable period of output of at least 1 minute. The data stability depended on both spray and instrument output stability (the chilled mirror hygrometers would typically require several seconds to reach a stabilized value following spray activation while the IR gas analyzers had no apparent stability issues). All of the IRT LWC data presented is the sum of the IRT LWC calibration and the calculated condensation cloud LWC (if a condensation cloud was calculated to be present). The condensation term is calculated using a pre-spray measured facility dew point temperature, and is assumed to be constant throughout the spray.

Figure 9 presents all of the data gathered in the May 2008 IRT test (see the test matrix in Table 2). The linear fit of the IR gas analyzer data results in a slope of 1.1886, and the similar slope for the chilled mirror hygrometer data is 1.1485. The chilled mirror TWC data shows better agreement to the condensation cloud corrected IRT LWC calibration data. But this is largely because the chilled mirror hygrometer data was gathered after it had settled to steady values. If data were recorded from spray-on to spray-off, chilled mirror derived TWC data would certainly have degraded accuracy.

There is a significant amount of spread to the data in Figure 9. As an attempt to understand the variations in the TWC to LWC comparisons, a calculation of the TWC to IRT LWC difference as a percentage of the IRT LWC was made and plotted versus IRT LWC, spray MVD, and IRT airspeed. Figure 10 displays the percent difference versus the IRT calibration plus condensation cloud LWC for the May 2008 test data. A linear fit trend line was calculated for the IR gas analyzer and chilled mirror hygrometer based TWC measurements. Based on the trend line data, it appears that there is a significant dependency of the measured water content differences on the facility LWC.

Figure 11 presents the percent water content differences versus the spray MVD. Based on the calculated trend lines, there appears to be a strong correlation between the measured water content differences and the tunnel spray's MVD.

The final error examination in Figure 12 is of the percent water content differences versus the test section airspeed. There does not appear be any correlation in this data.

TABLE 1.—JANUARY 2008 IRT TEST MATRIX

Condition number	Airspeed (m/s)	Total temp (^{o}C)	LWC (g/m^3)	MVD (μm)
1	51.4	−2.7	0.55	15.9
2	51.4	−2.7	0.99	18.9
3	51.4	−2.7	1.53	21
4	51.4	−2.7	1.01	47.2
5	77.2	−1.0	0.52	18.7
6	77.2	−1.1	1.01	19.4
7	77.2	−1.1	0.52	78.2
8	77.2	−1.0	0.73	191.5
9	90.0	−0.2	1	40
10	77.2	−7.0	1.01	19.4
11	77.2	−12.0	1.01	19.4
12	38.6	−2.9	0.55	15
13	38.6	−3.1	1	19
14	38.6	−2.9	1.5	21
15	51.4	−1.1	0.3	14.4
16	77.2	−1.1	1.22	21.5
17	51.4	−2.2	0.7	20
18	51.4	−9.0	0.3	14.4
19	51.4	−9.1	0.55	15.9
20	51.4	−8.9	0.7	20
21	51.4	−14.0	0.3	14.4
22	51.4	−14.0	0.55	15.9
23	51.4	−14.0	0.7	20
24	51.4	−14.0	1.1	156

TABLE 2.—MAY 2008 IRT TEST MATRIX

Condition number	Airspeed (m/s)	Total temp. (^{o}C)	LWC (g/m^3)	MVD (μm)
1	25.7	−10.0	2.48	20.5
2	38.6	−10.0	1.73	20.5
3	51.4	−10.0	1.45	20.5
4	64.3	−10.0	1.3	20.5
5	77.2	−10.0	1.21	20.5
6	90.0	−10.0	1.03	20.5
7	102.9	−10.0	0.98	20.5
8	115.7	−10.0	0.89	20.5
9	128.6	−10.0	0.79	20.5
10	77.2	−10.0	0.55	14.3
11	77.2	−10.0	1.03	24
12	77.2	−10.0	1.32	33.9
13	77.2	−10.0	0.18	13.8
14	77.2	−10.0	0.92	47.2
15	77.2	−10.0	0.63	13.2
16	51.4	−10.0	0.7	14.3
17	51.4	−10.0	1.46	24
18	52.5	−10.0	1.67	33.9
19	129.1	−9.8	0.37	14.3
20	128.6	−10.0	0.76	24
21	128.6	−3.4	0.37	14.3
22	129.1	−5.9	0.37	14.3

Catch Corrected Isokinetic TWC vs Total IRT LWC
assumes pre-spray D-corner dewpoint remains constant through spray

y = 1.1485x
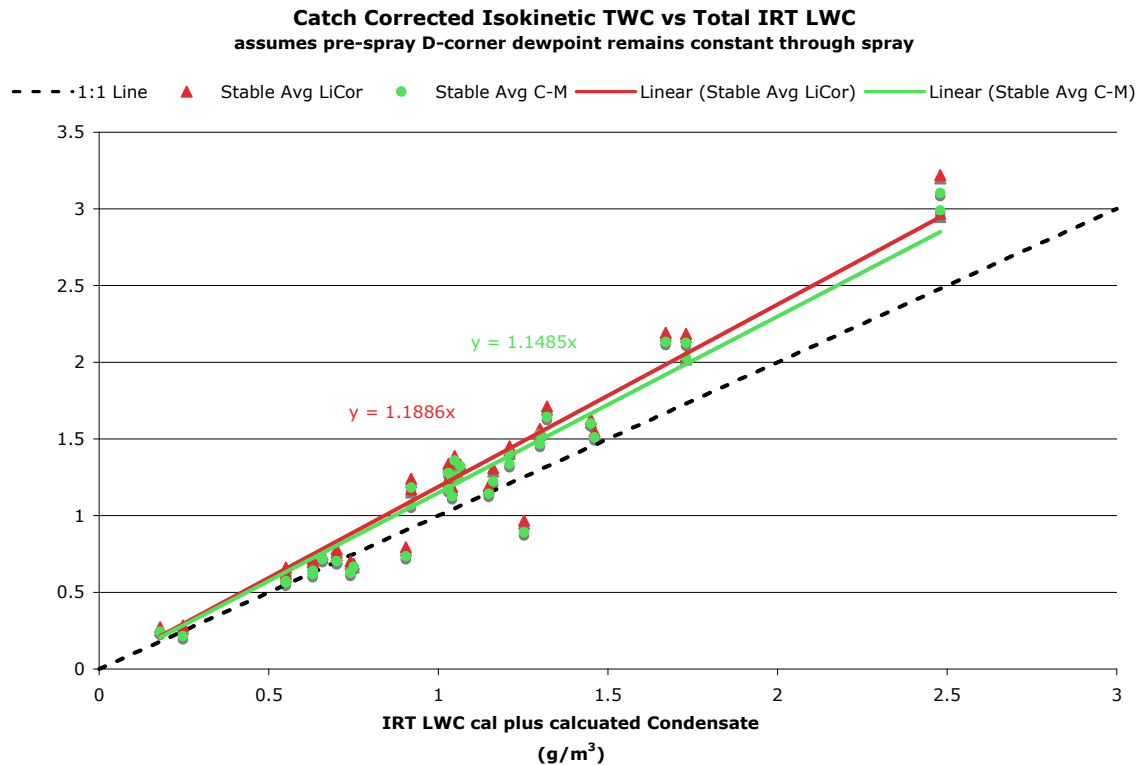
y = 1.1886x

IRT LWC cal plus calcuated Condensate
(g/m³)

Figure 9.—Catch corrected TWC measurements versus IRT calibration plus calculated condensation cloud LWC for May 2008 test.

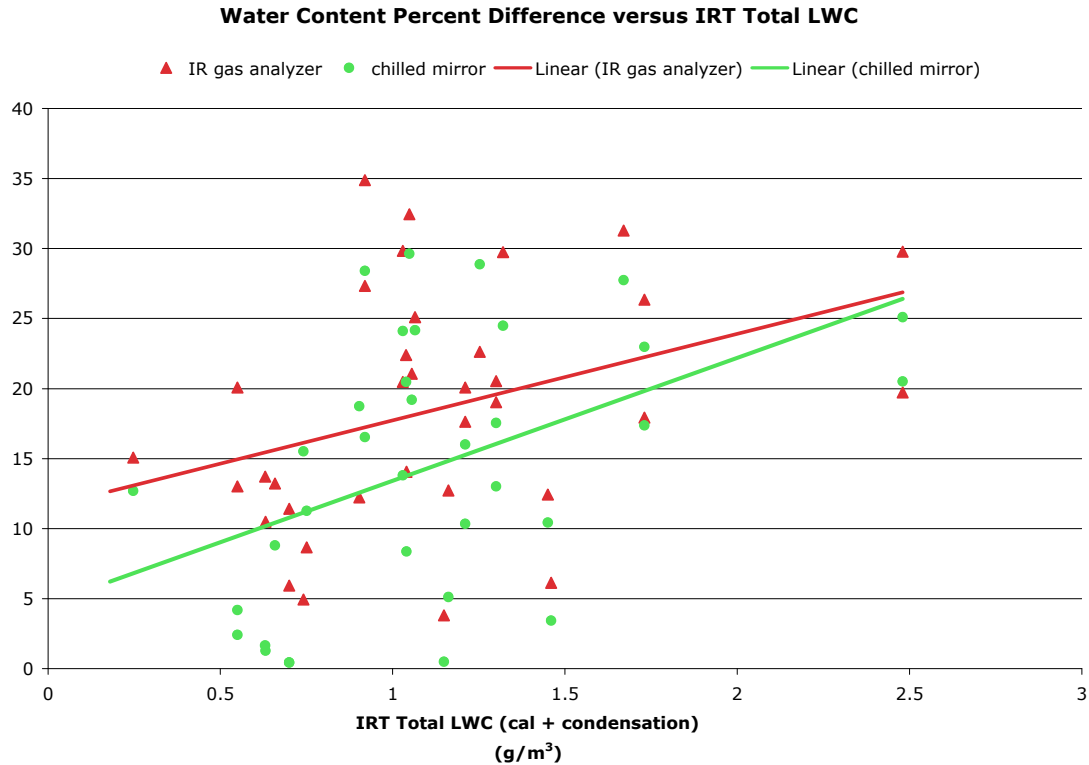**Water Content Percent Difference versus IRT Total LWC**

IRT Total LWC (cal + condensation)
(g/m³)

Figure 10.—Water content percent difference versus IRT calibration plus calculated condensation cloud LWC, for May 2008 test.

Water Content Percent Difference versus MVD
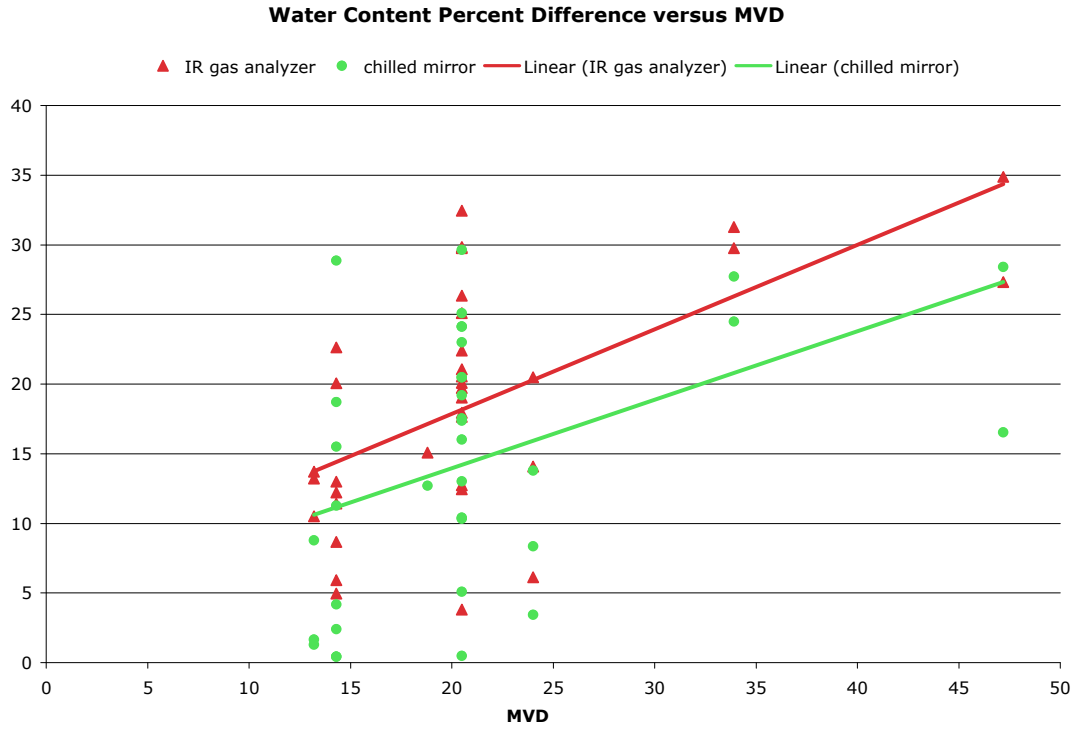
Figure 11.—Water content percent difference versus IRT MVD, for May 2008 test.
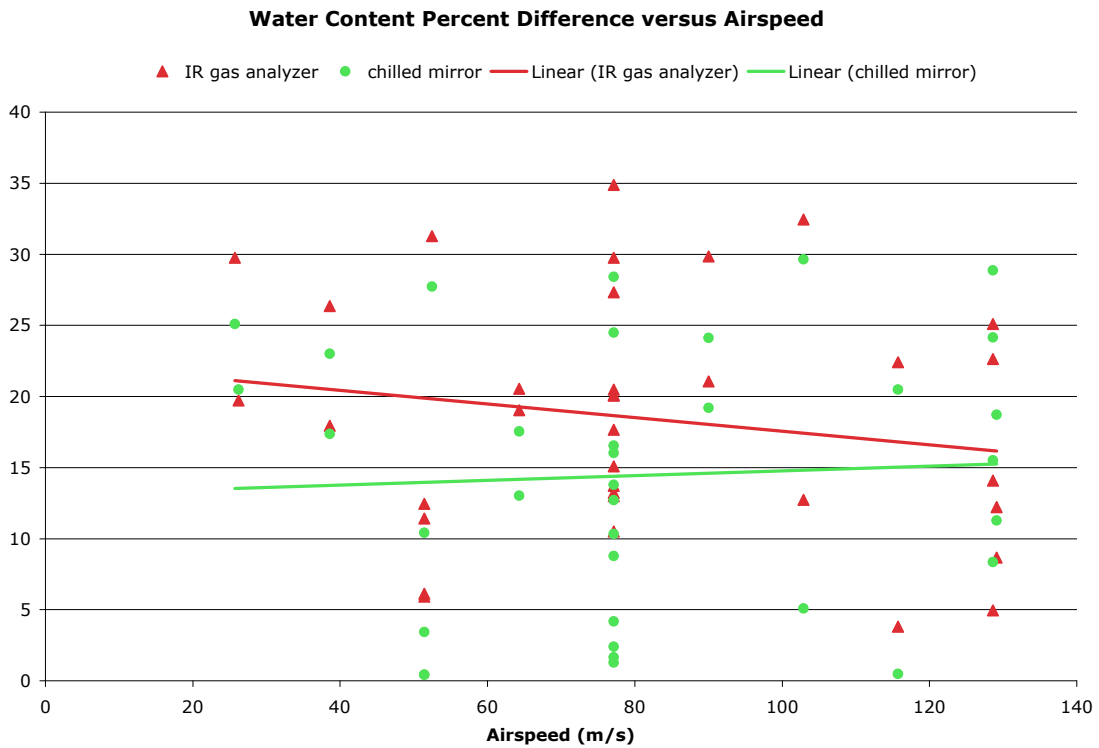
Water Content Percent Difference versus Airspeed

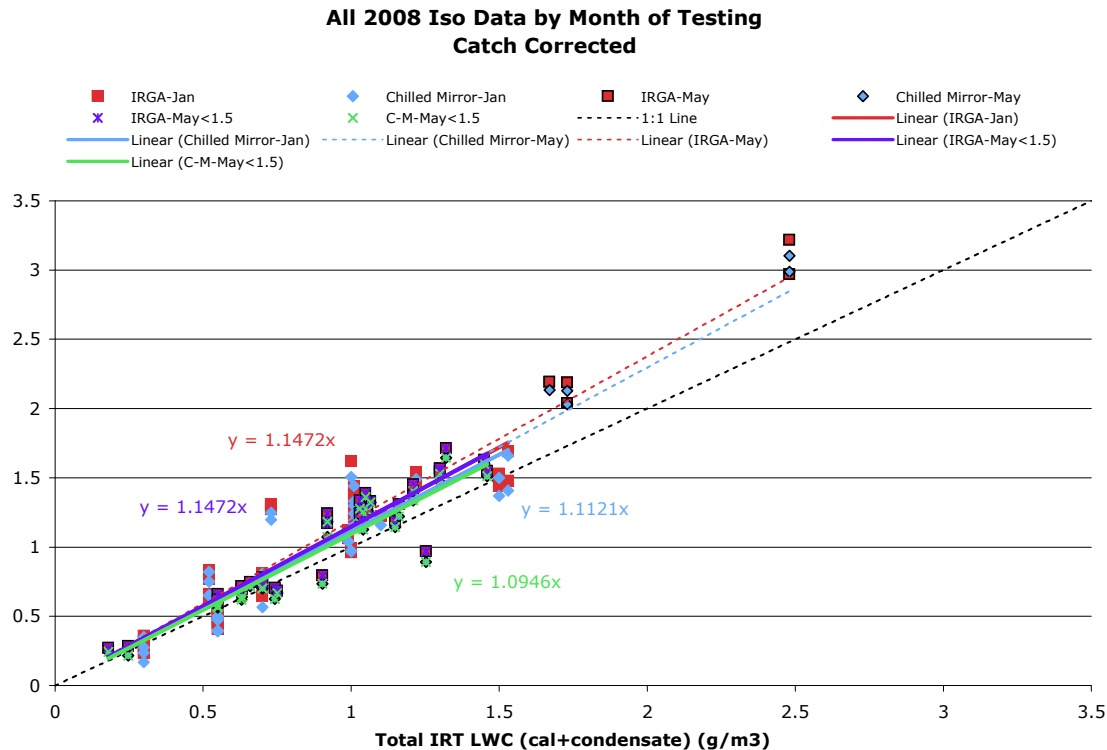Figure 12.—Water content percent difference versus airspeed, for May 2008 test.

Figure 13.—Catch corrected TWC measurements versus IRT calibration plus calculate condensation cloud LWC, for both January and May 2008 tests. Data fit for May data is for LWC values <1.5 g/m^3 (to match range of January data).

One final plot (Fig. 13) is included that shows the data from both the January and May IRT tests. The data fits for the May data were limited to 1.5 g/m^3 to match the range of the January LWC data. The data from the two test entries agree very well (the IR gas analyzer data's fit matches to 4 decimal places). This is particularly interesting since the test matrix for the two tests were significantly different and provides an indication of the general repeatability of the measurement system.

Conclusions

Overall it appears that the TWC Isokinetic Sampling Probe is working quite well. In bench tests it has been able to repeatedly measure evaporated water mass within 5 percent. The probe head has been checked with accepted computational tools to have a minimal level of required correction. And the flow system has been independently checked against other flow measurement sources. The differences that remain are likely the cause of two dramatically different measurement methods measuring somewhat different parameters. The TWC Isokinetic Sampling Probe by design should measure all water particles (liquid and frozen) within its sample volume. The IRT calibration is based upon "accretable" moisture, since it is the timed measurement of ice accretion thicknesses formed on a small radius leading edge collector. While actions are taken to make these timed accretion measurements very accurately, the accretion process itself is dependent on particle phase, droplet size, and to a lesser degree, cloud LWC. And while the IRT calibration method has long been accepted and is very appropriate for the work normally performed in the IRT, it is not completely surprising to the authors that there could be a difference between the two measurement techniques. Further, it is also very possible that at elevated LWC and MVD values that the accretion calibration method is under measuring due to droplet breakup, splashing, and bouncing.

Appendix A.—Calculations

A.1 Flow Rate Calculations

To set the probe sampling flow rate to ensure isokinetic conditions, the desired sample air mass flow rate is calculated as:

$$\text{Target Dry Air Mass Flow Rate (kg/s)} = V_{external} \text{ (m/s)} * A_{inlet} \text{ (m}^2\text{)} * \rho_{external} \text{ (kg/m}^3\text{)}$$

where
    $V_{external}$ and $\rho_{external}$ are based upon wind tunnel test section values.

Since the thermal mass flow meter used to monitor the sample flow rate (Ref. 8) operates in standard flow units, we make the following conversion:

$$\text{Target Dry Airflow Rate (Std L/min)} = \text{Target Dry Air Mass Flow Rate (kg/s)/Standard Conditions Air Density (kg/L)} * 60 \text{ (s/min)}$$

where
    standard conditions are T = 21.1 °C and P_s = 101.3 kPa
(Note: These standard conditions are defined by the air flow meter's manufacturer.)

By adjusting the shop air pressure entering the ejector, the sample flow rate is adjusted until it matches the target isokinetic condition.

A.2 Water Concentration Calculations

After the sample flow rate has been set ensuring isokinetic sampling, the TWC can be calculated based upon the sample and reference water vapor measurements.

Cloud water concentration = Sample water vapor measurement – Reference water vapor measurement
(Note: these measurements are made in $mmol_{wv}/mol_{dryair}$ units.)

Next, the molar based units need to be converted to mass units:

$$\text{Cloud mixing ratio } (g_{wv}/kg_{dryair}) = \text{Cloud humidity } (mmol_{wv}/mol_{dryair}) * 18.02/28.97$$

where
    water vapor molar mass = 18.02 g/mol
    dry air standard conditions molar mass = 28.97 g/mol

Finally,

$$\text{TWC (g/m3)} = \text{cloud mixing ratio } (g_{wv}/kg_{dryair}) * \rho_{dryair} \text{ (kg/L)} * 1000 \text{ (L/m}^3\text{)}$$

Where
    ρ_{dryair} is at wind tunnel test section pressure and temperature

A.3 Condensation Cloud LWC

To calculate the LWC of a condensation cloud in the IRT, first the initial saturation partial pressure of water vapor (WVPP) is calculated from the facility dew point measurement (measured just downstream of the heat exchanger):

$$WVPP_i \text{ (kPa)} = a_o + T (a_1 + T (a_2 + T (a_3 + T (a_4 + T (a_5 + T * a_6)))))/10$$

where
- T — dew point temperature in °C
- a_o — 6.107799961
- a_1 — $4.436518521 \times 10^{-1}$
- a_2 — $1.428945805 \times 10^{-2}$
- a_3 — $2.650648471 \times 10^{-4}$
- a_4 — $3.031240396 \times 10^{-6}$
- a_5 — $2.034080948 \times 10^{-8}$
- a_6 — $6.136820929 \times 10^{-11}$

(From Lowe, P.R. and Ficke, J.M., "The computation of saturation vapor pressure," Tech paper No. 4–74, Environmental Prediction Research Facility, Naval Postgraduate School, 1974.)

Then, with a known air pressure (P), the initial absolute water vapor concentration (WVC) is calculated:

$$WVC_i \text{ (mmol}_{wv}/\text{mol}_{dryair}) = WVPP \text{ (kPa)} / P \text{ (kPa)} * 1000$$

From this term we need to subtract the water vapor concentration from the test section to determine the excess moisture (which we assume has all become condensation cloud). This can either be similarly calculated from dew point, or we can use the direct output of the IR gas analyzer (in $mmol_{wv}/mol_{dryair}$ units).

$$WVC_{excess} = WVC_i - WVC_{testsection}$$

We then convert to Mixing Ratio (as we did on the previous page):

$$\text{Cloud mixing ratio (g}_{wv}/\text{kg}_{dryair}) = WVC_{excess} \text{ (mmol}_{wv}/\text{mol}_{dryair}) * 18.02 / 28.97$$

where
    water vapor molar mass = 18.02 g/mol
    dry air standard conditions molar mass = 28.97 g/mol

Finally we calculate the condensation cloud LWC:

$$\text{LWC (g/m3)} = \text{cloud mixing ratio (g}_{wv}/\text{kg}_{dryair}) * \rho_{dryair} \text{ (kg/L)} * 1000 \text{ (L/m}^3)$$

Where
    ρ_{dryair} is at wind tunnel test section pressure and temperature

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
The NASA Glenn Research Center has developed a Total Water Content (TWC) Isokinetic Sampling Probe. Since it is not sensitive to cloud water particle phase nor size, it is particularly attractive to support super-cooled large droplet and high ice water content aircraft icing studies. The instrument is comprised of the Sampling Probe, Sample Flow Control, and Water Vapor Measurement subsystems. Analysis and testing have been conducted on the subsystems to ensure their proper function and accuracy. End-to-end bench testing has also been conducted to ensure the reliability of the entire instrument system. A Stokes Number based collection efficiency correction was developed to correct for probe thickness effects. The authors further discuss the need to ensure that no condensation occurs within the instrument plumbing. Instrument measurements compared to facility calibrations from testing in the NASA Glenn Icing Research Tunnel are presented and discussed. There appears to be liquid water content and droplet size effects in the differences between the two measurement techniques.

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