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Ice Detector Evaluation for Aircraft Hazard Warning and Undercooled Water Content Measurements

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A Rosemount ice detector was installed on a Research Aviation Facility Queen Air for evaluation. It was used during a winter stratus cloud experiment at Muskegon, Mich. (1978) and during a cumulus cloud experiment (HIPLEX) in 1980 at Big Spring, Tex. Results indicate that the detector is an extremely sensitive instrument with a reasonable dynamic range. The instrument will provide a measure of icing severity and valid computed water content values only for conditions of small water content and/or low temperature. The dynamic range of this measurement technique for stratus cloud studies is probably adequate; its use at temperatures of −5 to −10°C in cumulus clouds will provide only a relative measure of icing severity and large underestimates of the computed liquid water content.

Introduction

THE accretion of ice on the surface of an aircraft and its external stores is caused and controlled by several meteorological and aerodynamical variables. These include undercooled water content (UWC); cloud droplet size; temperature of the unheated surface; size, shape, and collection efficiency of the collecting surface; and aircraft speed.

A threefold need exists in aeronautical and meteorological research with regard to instruments for measuring icing severity in flight: 1) a continual update of design requirements for aircraft ice protection systems, e.g., protection systems for rotary wing vehicles, which are increasingly operating in all weather conditions; 2) measurements of the composition and water content of the particles in different cloud systems; and 3) a reliable sensor that may be used on fixed and rotary wing aircraft to identify a wide variety of icing conditions for improving flight safety. In reviewing the literature on methods of ice detection, it is clear that no single instrument will satisfy the three requirements.

This report presents an evaluation of the Rosemount 871 ice detector for use as an aircraft hazard instrument and for determining liquid undercooled water content. Ice detector measurements are compared with those obtained by the more conventional heated-wire cloud water probe for −10°C stratus and −5°C cumulus icing events.

The Rosemount Ice Detector

The sensing element (Fig. 1) is a cylindrical assembly that vibrates axially at a resonant frequency of 40 kHz; the sensing probe is an exposed cylinder 2.54 cm long and 0.635 cm in diameter. Once ice begins to bond to the sensor and to accumulate, the added mass decreases the resonant frequency of the cylinder; this frequency is compared to a reference frequency-limiter amplifier network to provide an output signal proportional to the accumulated mass. When the preset ice accumulation trip point has been reached, the strut airfoil and the sensing probe are deiced by an internal heater for 7 s and a new icing cycle begins.

This assembly operates as an oscillator microbalance and by convention

$$\Delta f/\Delta t = (\Delta m_d/\Delta t)K$$

where Δf is the frequency change in interval Δt, $\Delta m_d/\Delta t$ the mass deposited in Δt, and K the unit sensitivity in Hz/g.

Unfortunately, the sensitivity (Hz/g) is proprietary information; however, state-of-the-art quartz-crystal microbalances often exhibit sensitivities of 7×10^8 Hz/g and microbalance long-term drifts of 0.2 Hz/min.[1] Such a sensor would be capable of detecting microgram deposits. For example, at an airspeed of 70 m/s the volume sampled of 0.01129 m^3/s will provide data on water deposits (in milligram/second) to the detector from water contents of 0.1-0.5 g/m^3. Thus the sensitivity required of the detector appears well within the limits of the state-of-the-art of oscillator microbalance technology.

The 871 ice detector was part of the instrument complement on a Queen Air aircraft operated by the National Center for Atmospheric Research for cloud physics research. The icing flights on which this evaluation is based were experienced during a study of snow and urban plumes near Muskegon, Mich. in the winter of 1978 and during cumulus cloud research in west Texas in 1980.

The detector was installed on the top forward fuselage, 1.65 m aft of the nose and 0.56 m forward of the bottom of the windshield. The sensing cylinder was 10 cm from the aircraft skin, outside the aircraft boundary layer. The considerations in determining an optimum location for the sensor were primarily related to sampling representativeness. The local aircraft boundary-layer thickness should be less than the sensor height and known stagnation or flow separation areas are to be avoided for optimum operation. Zones of increased droplet concentration (shadow zones) should be avoided when practical.

Calculation of Undercooled Water Content

A quantitative mass calibration of the 871 ice detector was performed by considering the system principles and theory. The sensing surface is the entire circumferential area of the cylinder; i.e., a mass m on the cylinder has the same influence on the frequency change despite the density of the accumulation or the geometry of its distribution about the surface. The technique of calibration consisted of securely bonding small objects to the cylinder and measuring the output voltage for each simulated mass. Two separate calibration data sets were taken and combined to provide the following second-order transfer function:

$$m_d = 0.0019143\times v^2 + 0.0064756\times v - 0.008447 \qquad (1)$$

where m_d = the mass of the bonded material in grams and v = the system output in volts. The rate of change of m_d with respect to time (t) provides the measured rate of ice accretion in terms of $\Delta v/\Delta t$, which is obtained from a 1 s data rate of v. The physical significance of $(\Delta m_d/\Delta t)$ is of interest only when

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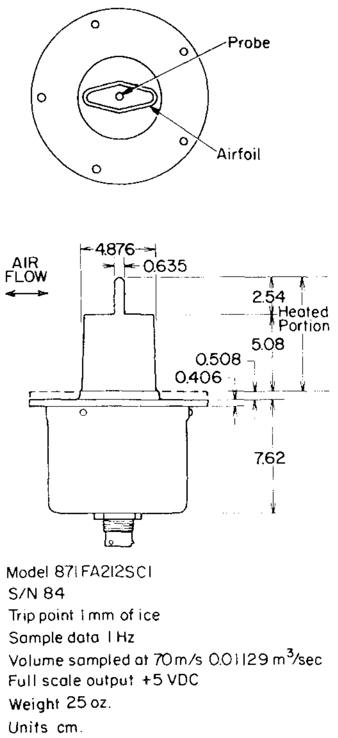

Fig. 1 Ice detector dimensions and specifications.

$\Delta v/\Delta t \geq 0$; when sublimation is occurring or the detector is deicing, $\Delta v/\Delta t < 0$.

The rate of water drop impingement Q for a cylinder 2.54 cm long is expressed in grams/second/2.54 cm of span and may be calculated from the general equation of Bowden[2]

$$Q = 2.54 \times 10^{-4} \times V \times W \times E \times D, \text{ g/s/2.54 cm of span} \quad (2)$$

where

V = true air speed, m/s

W = liquid water content, g/m^3

D = cylinder diameter, 0.635 cm

E = cylinder collection efficiency (dimensionless)

The rate of change of Eq. (1) for an icing event is interpreted as the mass deposited per unit time over the detector length, i.e., g/s/2.54 cm; note that these units are equivalent to those of Eq. (2). Equating $\Delta m_d/\Delta t$ with Eq. (2) and solving for W provides an expression for calculating "undercooled water content" (UWC) from the ice detector signal. The collection efficiency of the probe is calculated by the method of Langmuir and Blodgett.[3] For the conditions that true air speed = 70 m/s, pressure altitude = 2500 m, and droplet median volume diameter = 8 μm, by this method $E = 0.83$ and the algorithm for UWC reduces to

$$\text{UWC} = 7.4698 \times 10^3 \times \frac{\Delta m_d}{\Delta t} \Big/ V, \text{ g/m}^3 \quad (3)$$

Dynamic Range Estimate

The sensing cylinder as a stand-alone heat sink must be sufficient for freezing various quantities of water under different conditions. What conditions limit the utility of the device and what are the limits? The ice accumulation range of the detector is estimated for two conditions from an analysis of the heat-transfer mechanisms of a rimed cylinder.[4] The heat transfer is predominantly by convection and by the evaporation of ice or water from the surface; conduction losses to the cylinder interior and through radiation are neglected. The Ludlam limit m_c' is defined as the critical cloud water content, that is, the limiting water content for which the freezing fraction = 1. Encountered water content in excess of m_c' is not frozen and is lost from the probe by shedding. The parameter m_c' is expressed by

$$m_c' = \frac{\Pi \times 0.24 \times (Re)^{0.6} \times (K(T-T') + 600k\Delta p)}{D \times E \times V \times (80-T)}, \text{ g/m}^3 \quad (4)$$

where

m_c' = undercooled water content, g/cm^3
Re = Reynolds number
K = coefficient of conductivity of air
T' = cylinder temperature, 0°C
k = coefficient of diffusion of water vapor in air
Δp = vapor density difference between cylinder and air
D = diameter of cylinder, cm
E = collection efficiency of cylinder
V = aircraft velocity, cm/s
T = temperature of the air, °C (dynamic heating included in convection term)

Ice formation proceeds at the maximum rate when the temperature of the collecting surface is 0°C. Solving Eq. (4) on this assumption provides a method for estimating the dynamic range of the detector as a function of its diameter and the flight conditions. Figure 2 illustrates the computed Ludlam limit (m_c') vs temperature for the 0.635 cm diam detector moving at 70 m/s for two cloud conditions recently studied. The curves represent the Ludlam limit for two different cloud types and meteorological conditions. Curve a is based upon the conditions encountered during stratus flights of 1978 while curve b shows the computed limit for the thin altocumulus clouds penetrated in west Texas during 1980.

Review of Icing Measurements

In research directed toward the development of a simple instrument for measuring icing severity, Neel[5] constructed a heated-wire liquid water content instrument and flight tested it in natural icing conditions. Data obtained simultaneously with rotating multicylinders indicated that the hot-wire instrument was suitable for measurement of liquid water content (icing severity) in undercooled clouds. The tests were conducted in cumulus clouds at temperatures of −7 to −11°C. During the penetrations the presence of snow appeared to have little effect on the hot-wire measurements. It is believed that aerodynamic forces remove snowflakes striking the wire before detectable cooling of the wire takes place. This feature is desirable since the quantity of UWC is of primary concern in determining the severity of an icing condition.

The heated wire eventually found wide use in airborne meteorological research and aircraft icing certification; the instrument intended for measuring icing severity became popular as a liquid water content device for meteorological use. The design performance and limitations of the heated wire as now configured are discussed in detail by Neel.[6]

The Cloud Physics Laboratory of the University of Chicago conducted an evaluation of a hot-wire liquid water content instrument [Johnson Williams liquid water content (JWLWC)] in cumulus clouds with flights near the freezing level. This research[7] involved variable liquid water contents of up to 3-4 g/m^3 found in Midwest summer cumuli where there was no evidence of ice crystals. Four cases were studied where hot-wire measurements were compared to water contents computed from the integration of the cloud particle distribution as measured by a particle replicating device.[8] This research concluded that the hot wire has a lag of about 1 s for increasing or decreasing rates. For one case in which the JWLWC was changing slowly near 1.5 g/m^3, the comparison

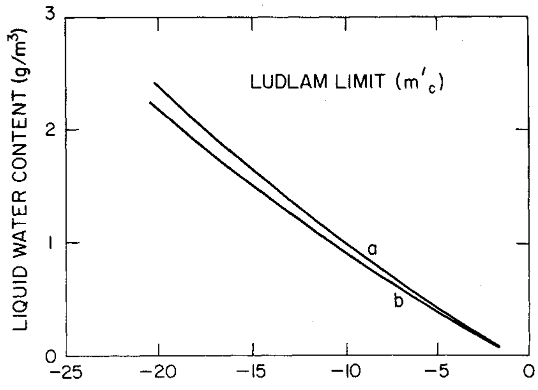

Fig. 2 Ludlam limit m_c' vs temperature for a) low-level stratus cloud with 10 μm diam droplets and b) high-altitude altocumulus with assumed droplet median diameter of 25 μm.

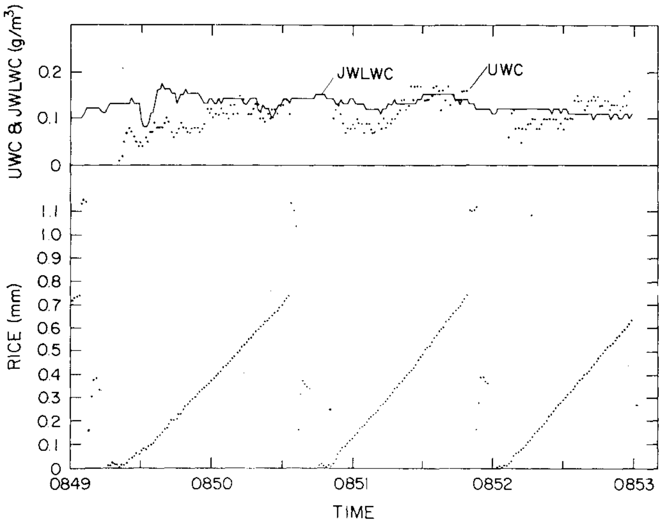

Fig. 3 Stratus cloud penetration, 0849:00-0853:00: top, JWLWC liquid water content (solid line) and UWC (dots) calculated from ice detector data; bottom, RICE-Rosemount ice accumulation in mm vs time (conversion 1 mm = 5.0 VDC, temperature was − 10°C, altitude 2743 m).

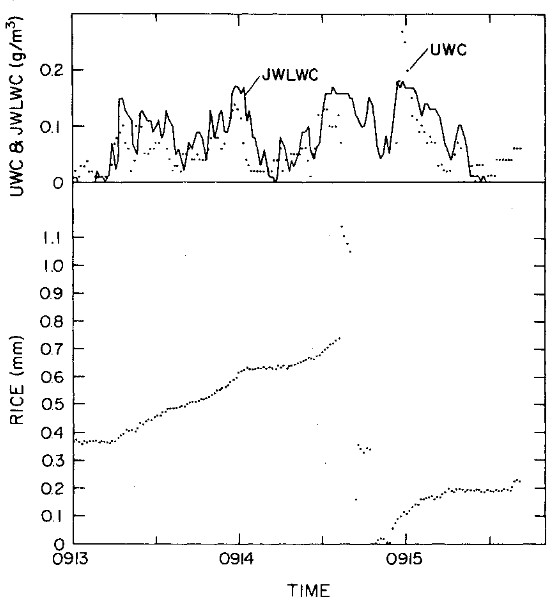

Fig. 4 Stratus cloud penetration, 0913:00-0915:45: top, JWLWC liquid water content (solid line) and UWC (dots) calculated from ice detector data; bottom, RICE-Rosemount ice accumulation in mm vs time (conversion 1 mm = 5.0 VDC, temperature was − 11°C, altitude 2743 m).

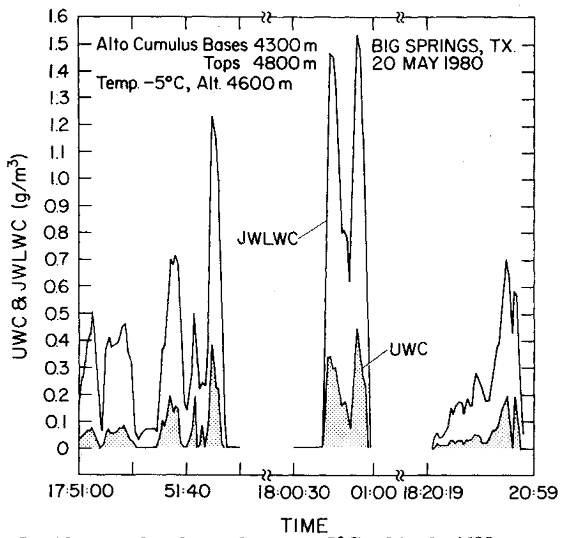

Fig. 5 Altocumulus data taken at − 5°C, altitude 4600 m, near Big Spring, Tex., May 20, 1980 (solid curve, JWLWC; stippled area, computed UWC).

of the two measurements was ∓10%. The cloud particles in this case were about 20-25 μm in diameter.

Measurements made more recently[9] with a compensated heated-wire instrument and an optical array spectrometer show striking similarities in water content values and structure in small cumulus clouds.

The comparative evidence available suggests that the hot-wire probe is accurate for liquid water content measurements in clouds having drop diameters of <30 μm and is insensitive to snow crystals. The JWLWC, therefore, can be applied as a UWC detector in cloud systems having distributions of small droplets.

With the hot-wire instrument used as a reference, the calculations of UWC from the Rosemount icing detector are compared for two stratus cloud cases of Nov. 21, 1978. Period 0849:00-0853:00 (Fig. 3) was obtained in thin undercooled altostratus at an altitude of 2743 m where the temperature was − 10°C; three ice-deice cycles of the detector are shown with a smooth, constant rate of ice accumulation. Period 0913:00-0915:45 (Fig. 4) was selected because the RICE (Rosemount ice accumulation) trace is more irregular, the water content is generally less than in Fig. 3, and the temperature is − 11°C. Overall, the comparisons are quite good. The 0913:00-0915:45 period is particularly impressive since the spatial structure of the water content is almost identical from the two instruments. Looking at the details, we note that—particularly during the 0913:00-0915:45 period—in every case when water content was increasing the two data sets were together; however, when decreases occurred the UWC decreased before the JWLWC, perhaps reflecting on the inability of the hot wire to respond to rapid decreases in water content. These computed UWC values are well within the Ludlam limit shown in Fig. 2.

Analytical results from the use of the Rosemount probe are very scarce. Musil and Sand[10] present very limited data from flights through thunderstorms. However, they conclude that accurate quantitative results are applicable for water content of 1 g/m³ or less; "this limits its use in thunderstorm penetrations where water contents are apt to be much higher." A Rosemount study by Knowles[11] illustrates differences of icing tunnel calibrations at − 10°C for two similar icing detector units; the departures observed were attributed to erratic performance near Ludlam limit conditions.

Figure 5 shows ice detector and JWLWC measurements taken in three separate altocumulus towers at − 5°C. The general shape of the JWLWC and UWC plots are quite similar, although the magnitude differs by a factor about 3.5 for the maximum values. The ratio of JWLWC to UWC is more variable than orderly, but the three UWC peak values are approximately equal to the Ludlam limit and are located near the maximum values of the JWLWC. Size measurements of precipitation particles, made simultaneously, indicate that droplets ranging 250-1000 μm in size were present in these clouds, in concentrations of 10^2-$10^3/m^3$. However, the contribution to icing from these larger size distributions is uncertain since the phase of the particles is unknown. The Rosemount evidence cited and the dichotomy of these measurements at $-5°C$ are indicative of the lower limit for UWC calculations using the detector method, but demonstrate the usefulness of the detector as an icing severity indicator for purposes of flight safety.

Conclusions

1) The Rosemount 871 ice detector is an extremely sensitive instrument with reasonable dynamic range. As such it is a safety-of-flight instrument which will provide icing severity and valid UWC values for conditions of small water content and/or low temperatures. The altocumulus test results present a case where the Ludlam limit is 0.45 g/m^3 at $-5°C$ and the maximum values of JWLWC are considerably larger than UWC by a factor of 3.5. Under these conditions the detector provides only a relative measure of icing severity and low UWC values result.

The obvious temperature dependence clearly limits the dynamic range of the system in icing conditions warmer than $-10°C$ for meteorological application. The range of this measurement technique for stratus cloud studies, where water contents are frequently less than 0.5 g/m^3, is probably adequate; the use at temperatures of -5 to $-10°C$ in cumulus studies, where water contents often exceed 2-3 g/m^3, will provide large underestimates of UWC.

The restrictions occurring because of the temperature limitation of the Rosemount icing detector perhaps could be alleviated most easily by either reducing the cylinder diameter or installing it in such a way as to significantly reduce the collection efficiency.

2) Figures 3-5 indicate that the heated wire tends to lag 1-2 s when the water concentrations change rapidly. The internal cloud structure appears to be more clearly depicted by the ice detector, particularly when the rate of change is large.

3) During the deice cycle, the output exceeds the full-scale value due to the temperature sensitivity of the oscillator. The exact mechanics of the ice removal process in such a cyclic thermal system are not fully understood and thus during the cycle the detector output is not used. The restoration time of the sensor to an equilibrium temperature is calculated for average operating conditions of $-10°C$ air temperature and a sensor deicing maximum temperature of $+15°C$; if forced convection were the only heat loss mechanism, the sensor would reach equilibrium in 2.6 s for clear-air flight. As illustrated in Figs. 3 and 4 (RICE curve) the data typically show a sharp signal decrease for 1-2 s after the peak occurs, followed by a characteristic "knee"; since most of the deice cycles occur during in-cloud conditions, this "knee" is thought to signify conditions of partial freezing and runback from the sensor. The "knee" is typically 5 s in length; thus the instrument is inoperative as an ice detector for 7-8 s after the heat cycle maximum is found.

4) The in situ icing measurements considered here present a clear illustration of the need for an expanded systematic effort to determine the accuracy and limitation of these instruments. The research and operational limitations cannot be appreciated unless the systems are evaluated under controlled and natural conditions.

Acknowledgments

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