A Prototype Optical Flowmeter for the Measurement of Liquid Water Content

E. N. BROWN

September 1971
A description is given of the design and preliminary evaluation of an optical flowmeter for measurement of the liquid water content in warm clouds and rainshowers. The sensing apparatus is a subminiature silicon photodiode which functions as a reflective scanner in measuring the water flow rate from a rotating bowl or centrifuge. The device has several noteworthy features: (1) the laboratory calibration is simple and reproducible; (2) the power requirements are relatively small, unlike existing hot-wire liquid water content measurement instruments; (3) the maximum sampling capacity of 4.5 g/m$^3$ (at moderate aircraft speeds of 140-170 kt) can be increased with only minor changes to the basic instrument design; and (4) the system accuracy (exclusive of the collection efficiency) with 1-sec averaged data is about 4-5% of full scale.

ACKNOWLEDGMENTS

I am grateful to H. Paul Johnson of the NCAR Research Systems Facility who contributed to the final design of the flowmeter. Frank Brunot of the NCAR Research Aviation Facility contributed significantly to the digital counting and display electronics. I am also indebted to members of the NCAR Research Aviation Facility who assisted in the airborne testing.
CONTENTS

Foreword ........................................ iii
Acknowledgments .............................. iii
List of Figures ............................... vii

INTRODUCTION .................................. 1
INSTRUMENT DESIGN ............................ 3
    Measurement Analysis and Calibration .... 6

RESULTS OF PRELIMINARY AIRBORNE TESTS .. 13

CONCLUSIONS .................................. 23

References .................................... 25
FIGURES

1. Side view photograph of the optical flowmeter .......... 4
2. Front view cutaway in the plane of the exit hole A ........ 4
3. Vertical cross section of the optical flowmeter .......... 5
4. Strobe photograph showing the web of water on the wire of an optical flowmeter .................. 7
5. Block diagram of the optical flowmeter electronics;
pulse-shaping, counting, and display units ............... 8
6. Optical flowmeter calibration ......................... 10
7. Rainshower test of 6 February 1970 ....................... 14
8. Cumulus cloud test of 8 February 1970 ................... 15
9a-d. Rainshower and cumulus cloud tests of 2 and 3 September 1970 .................................... 17-20
Among the various meteorological instruments required for cloud physics research is a dependable device to measure liquid water content in clouds. Devices to measure cloud or rain liquid water content have been described by Barrett and Owens (1957), Vonnegut (1949), Skatskii (1963), and Nathan and Bennet (1966). The paper conductometric device of Warner and Newnham (1952) and the heated wire instrument of Neel and Steinmetz (1952) have been generally accepted by several cloud physics research groups as operational instruments for airborne application. However, Barrett (1960) asserts that there is "no single instrument which is entirely suitable for all cloud conditions. It is likely that the best liquid water data can be considered to have an accuracy of no better than 15 to 20 per cent."

The purposes of this report are to describe the design of a device for measuring liquid water content (for use on aircraft) and to evaluate its performance.
INSTRUMENT DESIGN

The instrument was designed to fulfill several basic requirements: it had to be relatively small and easy to install on the aircraft; it had to be able to quickly sense and measure small quantities of water (tenths of milliliters per second), yet also be able to measure large quantities; and the calibration procedure had to be simple and reproducible.

The optical flowmeter (Fig. 1) is a modification of a rotating bowl instrument designed to produce uniform drops from bulk water (Brown, 1961). This rotary device was chosen because of its excellent capability to quickly direct and control the flow of small quantities of water. The device was modified by inserting a fine, silvered wire in the water exit hole and by adding a photodiode reflective scanner-timing system (Fig. 2).

The design of the cup was influenced by the estimated flow rate, sampling area, the minimal time lag response, collection efficiency, and space limitation on the aircraft. The physical size of the cup is important because the measurements are not in situ; the water is removed from its natural position, coalesced, and then forced by the sensor. The radial exit path within the cup must be short to reduce the residence time of the water. All of these factors influenced the cup design of the optical flowmeter which samples a volume of $1.04 \times 10^{-3} \text{ m}^3/\text{sec/kt}$. At moderate aircraft speeds this volume is adequate to provide a minimum level of detection of about 0.20 g/m$^3$, and applying the method of Nathan and Bennet (1966) it should be sufficient to provide a statistically valid sample for rainfall rates in excess of 3-5 mm/hr.

Figure 3 is a cross section through the device perpendicular to that of Fig. 2 and illustrates the relative position and scale of the cup, wire, photodiode, and cone of illumination. The diameters are: cup inlet - 5.08 cm; single exit orifice - 0.75 mm; and wire - 0.20 mm. The cup and wire are rotated at 3,600 rpm while the photodiode is stationary. During a "dry" revolution (when no water is present) the photodiode scanner is biased to conduct when the silvered wire extending
Fig. 1 Side view photograph of the optical flowmeter illustrating the drive motor in the left center of the instrument, mounting rings, isolator, flowmeter frame, and cup on the right side. The diameter of the cup opening is 5.08 cm; mounting ring diameter is 11.4 cm, length approximately 18 cm, and weight 2.2 kg.

Fig. 2 Front view cutaway in the plane of the exit hole A illustrating the wire and water web B and photodiode light source C. The diode is shown as the dark full circle while the open circle represents the cone of illumination from an internal fiber optic coupled light source.
Fig. 3 Vertical cross section of the optical flowmeter illustrating the size and relative position of components.
from the exit hole reflects from a cone of illumination back to the light-sensitive diode. The dry revolution provides a reference pulse, the length of which is arbitrarily set in terms of diode-bias for a given lamp intensity.

During a revolution when water is present, centrifugal force quickly accelerates the water ingested into the rotating cup (Fig. 3) where it is mechanically coalesced into bulk water and then forced through the exit hole and along the silvered wire. The combination of centrifugal force, wire-water surface tension, and aerodynamic drag forces produces a web of water on the wire (Fig. 4). The pulse, or diode "on time," during a wet revolution is greatly increased over the dry revolution pulse because the wire scatters and internally illuminates the web of water as the web and wire pass through the cone of illumination and reflect back to the bias-fixed diode (Fig. 2). The diode and associated optics have been positioned to scan the maximum web dimension.

A block diagram of the functional electronics is shown in Fig. 5. The photodiode-driver presents a pulse to the shaping unit which in a dry revolution is proportional to the wire diameter, and in a wet revolution is proportional to the wire diameter and to the width of the adhering web of water. This pulse is further shaped and proportionately gates a 10-MHz oscillator into the digital counting units; this binary coded decimal information is paralleled into numeric nixie displays and to a 12-bit digital-to-analog converter for recording purposes.

The rise time of the diode is about 2 μsec which corresponds to an error of 0.025 mm in the measurement of the web. At maximum web dimension of about 1.2 mm, the measurement error is 2%. This error and the diode fall times can be ignored as they represent a constant offset which acts only to delay the pulse compared to real time.

MEASUREMENT ANALYSIS AND CALIBRATION

The flowmeter is treated as a first-order system for the purpose of estimating the dynamic error. The laboratory procedure for
Fig. 4 Strobe photograph showing the web of water on the wire of an optical flowmeter.
Fig. 5 Block diagram of the optical flowmeter electronics; pulse-shaping, counting, and display units.
determining the response is to excite the flowmeter with single large drops of water to simulate a step function. The response, or "time constant," is approximately 0.10 sec, not including the time required for water to travel from the impaction site in the cup to the wire. The dynamic error for transient inputs to a first-order system is 5% of full scale at 3 τ, or 0.30 sec.

The flowmeter is basically an electro-optical micrometer and vibration or independent motion of component parts on the order of 0.025 mm introduce error. The instrument was attached to the noseboom of an aircraft which has a natural frequency of 20 Hz. To reduce this vibration to an acceptable noise level of about 1.5% of full scale (approximately 0.07 g/m³), a polyurethane collar (isolator) was installed (Fig. 3).

The photodiode on time is dependent upon the diode bias-illumination characteristics. The diode bias is arbitrarily set at 1.6 V to provide a dry, shaped pulse of 150 μsec or 0 V from the digital-to-analog converter. The on time is also influenced by variations in the diode temperature (Dimick and Trezek, 1963) and in the light sources. The combination of these influences causes the on time to increase slowly with temperature increase. This drift can be reduced to an insignificant level by insulating the diode from heat sources; the remaining thermal-induced variations are manually controlled by small adjustments to the bias. In practical application this small bias variation has no significant effect on the system error or the system calibration.

The laboratory procedure for calibration is to precisely meter bulk water into the device at various flow rates. Figure 6 illustrates the calibration results of the prototype instrument which was eventually flight tested. The points represent the average of data from a 10-20 sec period for precise flow rates. Averages were used because the output deviates by ± 15%. This deviation results from the sensitive photodiode which detects variations in the width of the web due to extremely small flow irregularities on the wire between successive revolutions of the cup. The calibration is valid for water flow rates of less than 0.7 cm³/sec. A flow rate of 0.7 cm³/sec yields an output
Fig. 6 Optical flowmeter calibration.
of 750 MV which corresponds to a liquid water content of approximately 4.5 g/m\(^3\) at a true airspeed of 150 kt. (No adjustment is made for the 4% decrease in surface tension between 0 and 20°C, the operating temperature range of the instrument.)

The accuracy of the calibration is difficult to determine because there is no true standard and because of the small irregularities in the flow of the water. To measure the precision of the instrument itself, a reflective metal model was used to simulate the web of water. The percentage error using this method was less than 1%; this measurement, however, is related more to the instrument's repeatability than to its accuracy.

The collection efficiency of the instrument remains to be empirically determined. For a given drop size, the ratio of the number of drops ingested into the model per unit time per unit area to the average density of drops in the free stream test conditions defines the efficiency. In general, apparatus for generating large quantities of uniform drops smaller than 50 \(\mu\)m radius are not available. The collection efficiency considered to be valid for this instrument (Table 1) is computed by the method of Langmuir and Blodgett (1944). The calculated efficiencies beyond 50 \(\mu\)m radius asymptotically approach unity. Calculations indicate that the greatest differences in collection efficiencies should occur when sampling the smaller drops. However, observations show that the greatest differences occur in rainshowers which indicates other quantities of influence which might involve sampling probability and the drop impaction-retention characteristics of each probe.
<table>
<thead>
<tr>
<th>Drop Radius (μm)</th>
<th>Optical Flowmeter</th>
<th>Johnson-Williams Hot Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.20</td>
<td>0.76</td>
</tr>
<tr>
<td>10</td>
<td>0.53</td>
<td>0.91</td>
</tr>
<tr>
<td>15</td>
<td>0.69</td>
<td>0.95</td>
</tr>
<tr>
<td>20</td>
<td>0.78</td>
<td>0.98</td>
</tr>
<tr>
<td>25</td>
<td>0.84</td>
<td>0.99</td>
</tr>
<tr>
<td>30</td>
<td>0.87</td>
<td>0.99</td>
</tr>
<tr>
<td>35</td>
<td>0.89</td>
<td>0.99</td>
</tr>
<tr>
<td>40</td>
<td>0.92</td>
<td>0.99</td>
</tr>
<tr>
<td>45</td>
<td>0.93</td>
<td>0.99</td>
</tr>
<tr>
<td>50</td>
<td>0.94</td>
<td>0.99</td>
</tr>
</tbody>
</table>

\(^1\)Assumes the hot wire to be a cylinder 0.6 mm in diameter and the flowmeter a cylinder 5.08 cm in diameter.
RESULTS OF PRELIMINARY AIRBORNE TESTS

Preliminary comparative tests between the Johnson-Williams Liquid-Water Content Indicator and the optical flowmeter were conducted aboard the NCAR Queen Air over southern Florida on 6 and 8 February, and on 2 and 3 September 1970. Concurrent measurements were made of air temperature, indicated airspeed, and absolute pressure. Many clouds and rainshowers were sampled in each area; data representing the widest variety of cloud conditions are presented.

The flight tests in February included penetration into light rainshowers from low stratiform clouds and into warm cumulus clouds in various stages of vertical development; the data are illustrated in Figs. 7 and 8. (In these as well as the following illustrations, the data are represented by 1-sec means based on eight discrete measurements per second.)

The rainshowers (Fig. 7) fell from stratiform clouds with base heights of 1,200-1,800 m; the vertical cloud depth was not determined nor was the origin of the showers, although a scattered middle layer was present along with a high overcast. The showers were not widespread and in general produced only trace amounts of rain.

The cloud data for 8 February (Fig. 8) were obtained from several different cumuli whose base heights were 750 m and whose top heights varied between 2,400 and 3,600 m. The measurements were usually made in the lower half of the cloud at 1,650 m (820 mb). Considering the meteorological conditions at the condensation level (6 to 7°C 900 mb) and at the measurement level (2 to 3°C 820 mb), the calculated condensed free water content available at the flight level would be 1.2-1.3 g/m³.

The tests in September 1970 were in large cumuli and some 50 cloud and rainshower penetrations were made. Data from two flights in representative clouds are illustrated in Fig. 9. The lower levels of the atmosphere were stable and the temperature at the flight level varied
Fig. 7 Rainshower test of 6 February 1970. (Light rainshower from stratus cloud observed between 11:10:15 and 11:11:27.)
Fig. 8 Cumulus cloud test of 8 February 1970.
only 1°C over the two days of sampling. The average calculated free water content for the cloud base at 20°C and 900 mb and flight level at 9 to 10°C and 710 mb was about 4.7 to 4.9 g/m$^3$.

On 2 and 3 September, cumulus cloud conditions were excellent for testing because individual cells were large, they produced precipitation, and they were isolated to provide ease of observation. The average height of the cumuli studied was generally 6,000 m. Data from low level penetrations into rainshowers below the cloud base are shown in Fig. 9a. The data shown in Figs. 9b-d were obtained at 710 mb.

The data illustrate several distinct differences between the two instruments. The water content signature (Fig. 7) indicated that the hot-wire instrument shows no systematic response to large drops. The rain samples in Fig. 9 indicate practically no response from the hot-wire device. The instruments responded differently to showers even though the computed collection efficiencies (Table 1) were similar for large drops.

Owens (1957) reports that wind tunnel test data show that the hot-wire device greatly undersamples the large particles; it does not collect droplets greater than 15 μm in radius. Possibly the effective collection efficiency of the hot-wire device may be less than the computed efficiency. Or, the difference may be caused by collision efficiency effects or by the larger drops shearing or breaking up on contact with the wire or not completely evaporating while on the wire. The hot wire is 0.58 mm in diameter and 2.54 cm long which is a cross-sectional area only 1/170 of the sampling aperture area of the optical flowmeter.

The data in Figs. 8 and 9 compare the efficiency of the operation of the two instruments in cumulus clouds of various sizes. The readings below zero and the irregular, small amplitude variations are common to the Johnson-Williams signal. In some cloud penetrations, such as the 1-min mark on 8 February (Fig. 8), where the height and diameter of the cloud were extremely small, the cloud probably contained only small droplets (less than 50 μm in radius) as precipitation was not observed.
Fig. 9a Test of 2 September 1970. Data shown at 14, 16, and 18 min are from clear air showers. (L = light, M = moderate, H = heavy; estimates of shower intensity are subjective.)
Fig. 9b Test of 2 September 1970. Data shown at 46 and 51 min are from cumulus clouds with tops at 6,000 m with rain on the exit side.
Fig. 9c Test of 2 September 1970. Data shown are: 55 min from cumulus cloud with top at 6,000 m with rain on the exit side; 59 min from cumulus cloud with top at 6,000 m with no rain; 1 min from cumulus cloud with top at 3,600 m.
Fig. 9d  Test of 3 September 1970. Data shown at 7½-9 min are from cumulus cloud with top at 4,500-5,400 m with varying intensity of rain; data shown at 15 min are from cumulus cloud with top at 4,500-5,400 m with rain on exit side.
If this were true, and since there were great differences between the calculated collection efficiency of the two instruments, the water content measured by the optical flowmeter should have been far less than that measured by the hot-wire device. The data, however, do not support this assumption.

In the two large clouds (e.g., Fig. 9d, 3 September, 15-16 min) the measurements are similar with respect to time; these two clouds were in the early stages of precipitation and probably contained a broad droplet spectrum.

The data from the large precipitating cumuli (Figs. 9a,b) show the largest disagreement between the two instruments. The hot-wire instrument, as shown earlier, is ineffective in precipitation. It undersampled by as much as 3 g/m³ in rain on 2 September.
CONCLUSIONS

The flowmeter has two main limitations: the apparent low collection efficiency for small drops and the lack of a deicing device which limits its use to warm clouds and showers. Despite these limitations preliminary tests are encouraging. The data indicate that water contents as great as 2.5 g/m$^3$ can be measured in cumulus clouds and water contents ranging from 0.5 to 3.4 g/m$^3$ can be measured in rainshowers. The data also suggest that the instrument would be useful in the study of the water budget of precipitating warm clouds or below the cloud base. Increasing the number of exit holes in the present instrument may expand its use to the larger tropical cloud systems where water contents may be in excess of 4-5 g/m$^3$. The instrument's sensitivity to large drops indicates its possible use in laboratory or wind tunnel measurements for engine test purposes.
REFERENCES


