The Eddy-Correlation Technique of Evaporation Measurement Using a Sensitized Quartz-Crystal Hygrometer

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ABSTRACT

A system is described for the measurement of the atmospheric flux of water vapor near the surface, using a quartz-crystal oscillator as humidity sensor (as described by Gjessing *et al.*) and based on the Fluxatron technique. Results from a field test give an energy balance recovery ratio $(LE+H)/(R-G)=1.00\pm0.04$.

1. Introduction

Measurement of evaporation rates from natural surfaces presents many problems. Among the methods commonly employed are the Bowen ratio approach, in which the energy available is apportioned according to gradients of temperature and specific humidity, the application of some form of water balance, the continuous weighing of sample areas of the surface, and eddy-correlation techniques. The last method is notoriously difficult due to the required speed of response of the water vapor sensor used.

A fast-response wet-bulb system was used by Dyer and Maher (1965) in the Evapotron, an instrument which measured the atmospheric flux of water vapor near the surface by applying the eddy-correlation principle to fluctuations in both dry- and wet-bulb temperature. More recently, Hicks (1970) and Linacre *et al.* (1970) report the use of identical fast-response wet bulbs with the instrument known as the Fluxatron. This latter instrument forms the average running product $w's'$, where w' and s' are deviations in vertical wind velocity and dry-bulb temperature, wet-bulb temperature, or horizontal velocity, to give the vertical turbulent fluxes of sensible heat (H), the sum of sensible and latent heats ($H+LE$), or shearing stress (τ), respectively.

To satisfy the requirements of the eddy-correlation approach, the sensors employed must have sufficiently fast response to cover the highest frequency contributing to the flux transfer. From consideration of the cospectral cut-off frequency, it is readily shown that response times of the order of 0.3 sec are necessary for adequate performance at heights of $\sim$4 m above the surface. Maintaining a fine wet bulb with this response time is difficult, particularly in field conditions. Time lost in adjusting the rate of flow of water to the element to suit prevailing conditions represents, usually, a direct loss of valuable data. Clearly, a more convenient humidity sensor is desirable.

Several alternative types of sensor are available, each posing its own problems. For example, techniques based on the variation of refractive index with humidity present one with a sometimes unacceptable electronic complexity, while sensors relying on surface changes of conductivity often exhibit undesirable hysteresis.

The system described here, based on that of Gjessing *et al.* (1968), also has some undesirable features. However, the ease of operation in the field and the quality of the results obtained make it attractive.

2. Principle of operation

Gjessing *et al.* describe a radiosonde humidity sensor, depending on the absorption of atmospheric water vapor by some suitable material deposited on the faces of a quartz crystal. The natural frequency of oscillation of the crystal depends on its temperature and the mass loading on its faces. By suitable choice of crystal cut, temperature effects can be minimized and these can be further reduced by beating the output of such a sensitized crystal against that of a similar, unsensitized one, and by careful choice of such crystal pairs. We then have a major dependency of output beat frequency on the mass loading to which one of the crystals is subjected.

In the current application, one of each selected pair of 8 MHz AT-cut[1] quartz crystals (with 1-cm diameter faces completely gold coated) is coated with a thin film of magnesium fluoride, which becomes the humidity-sensitive component. The output of an oscillator employing one of these crystals is then mixed with that of a similar oscillator, as described above and as shown in the block diagram in Fig. 1. The output mixed frequency is then converted to a fluctuating direct current by means of a simple discriminator circuit. After amplification, a signal proportional to the surface mass

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[1] Various crystalline planes of quartz are identified as AT, BT, X, etc. The physical properties of the crystals used here are determined by the particular cut used.

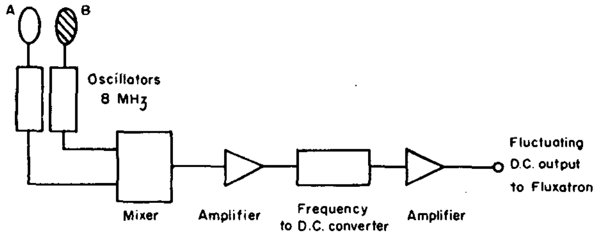

FIG. 1. Block diagram of MgF_2 hygrometer system as used for eddy-correlation work. A and B represent unsensitized and sensitized AT-cut quartz crystals, respectively.

loading of the sensitized crystal is available for injection into a standard Fluxatron eddy-correlation instrument.

In practice, both crystals are exposed directly to the air, but protected from insects by a coarse plastic gauze. The crystals and oscillators are constructed as a single unit, measuring 12×3×3 cm, with the crystals protruding from one end. The mixer-converter unit is separated from the sensor by a distance of ~2 m to reduce the bulk of the instrument near the sensor. Connection is made via a multi-core, shielded cable. Fluctuating dc signals are then fed to the instrument consoles some 100 m away.

In the context in which we desire to operate the system, voltages proportional to fluctuations in specific humidity are required. As reported by Gjessing *et al.* (and as confirmed here), the system responds to relative humidity h.

The calibration curve shown in Fig. 2 is expressed in terms of the sensitivity of the instrument (dV/dh), so that the effect of instrument drift with time and its inherent sensitivity to airborne dust (both of which cause shifts in the output voltage but not in the sensitivity) are not evident. These aspects may be critical in other applications, but in the present work it is sufficient that the output sensitivity be independent of them. This beneficial feature results from the need to correlate fluctuations in humidity with those in vertical velocity to obtain the evaporative flux E; clearly, step-function changes in output from either sensor will not interfere with the answer obtained if these are not correlated with changes in the other channel.

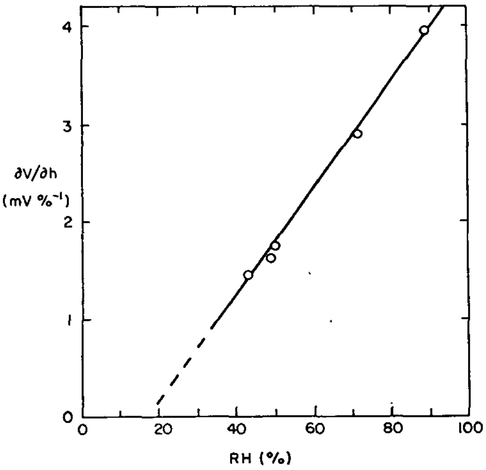

FIG. 2. Calibration curve of MgF_2 quartz-crystal hygrometer system.

The data plotted in Fig. 2 (obtained using the sensor employed in the field tests described below) indicate a linear relationship between dV/dh and h, leading to a quadratic dependence of V on h. A similar, but not identical, result is found for each of the sensing systems we have tested. This result is different from that of Gjessing *et al.*, who found a small linear dependence for MgF_2 but a result similar to ours for a glass surface. This difference may result from the choice of a different cut of crystal in the present case since Gjessing *et al.* employed BT-cut quartz crystals. Any difference in sensitizing techniques might also be critical.

There is reason to suspect that it is not valid to extrapolate the calibration curve of Fig. 2 to low humidities, where some fluorides are known to exhibit changes in their water absorptivity. No thorough investigation of this aspect has been attempted, but a recent calibration gave consistent data to 20% relative humidity. Further tests are necessary, however, before the sensor can be used with confidence in low humidity situations.

Temperature sensitivity of the system is minimized by suitable choice of crystals. With those used here, no temperature sensitivity, independent of relative humidity, is detectable.

An accurate figure for the response time is not available due to the difficulty in producing sufficiently rapid changes in humidity. However, experience indicates a response time $\lesssim 0.1$ sec.

3. The application of a relative humidity sensor to the measurement of evaporation

The usual eddy-correlation technique as applied to evaporation (E) involves the computation of the time average $\overline{w'q'}$, where q is specific humidity, from which E is calculated as $\rho\overline{w'q'}$. Variations in air density are usually neglected.

In the present case, we employ a sensor which detects deviations (h') in relative humidity, where $h=100(e/e_s)$ in the usual notation. Assuming that e_s' is much less than $\bar{e}_s$, we have

$$h'=100(e'/\bar{e}_s)-100\bar{e}(e_s'/\bar{e}_s^2), \tag{1}$$

or converting to specific humidity and neglecting variations in atmospheric pressure,

$$h'=100\bar{p}(q'/0.622\bar{e}_s)-\bar{h}(\partial e_s/\partial T)(T'/\bar{e}_s). \tag{2}$$

Thus, fluctuations in q and T result in associated deviations h' determined by the ambient pressure $\bar{p}$, relative humidity $\bar{h}$, saturated vapor pressure $\bar{e}_s$ at dry-bulb temperature $\bar{T}$, and by the slope of the satu-

Table 1. Values of the coefficients A and B in Eq. (3) for temperatures in the range 0–40C. Flux units are assumed to be mW cm^{-2}.

	Temperature				
	0C	10C	20C	30C	40C
A	9.16	4.56	2.39	1.32	0.76
B	0.063	0.059	0.054	0.050	0.046

rated vapor pressure curve. In the eddy-correlation application, the average product $\overline{w'h'}$ is

$$\overline{w'h'}=A(LE)-B\bar{h}H, \qquad (3)$$

which is obtained from (2) where A and B are functions of ambient parameters; the values are given in Table 1.

The above equations are valid only if $e_s' \ll \bar{e}_s$. In normal operating conditions over uniform terrain this requirement is probably met to sufficient accuracy, since we would then expect $(e_s'/\bar{e}_s)$ to be of the order 0.06 (corresponding to a 1C change in temperature). It can be shown that the error involved in neglecting higher order terms in Eqs. (1) and (2) should not exceed 5%.

4. Experimental results

Values of $\overline{w'h'}$ using the Gjessing system were obtained at Gurley, N.S.W., during March 1970. These data form part of a larger body of micrometeorological results, which will be reported elsewhere.

The surface was uniform bare soil, recently saturated by heavy rainfall. Fluxatrons measuring sensible heat flux and $\overline{w'h'}$ were erected at a height of ~4.5 m. Ancillary measurements included those of air temperature and humidity, net radiation R, and ground heat flux G.

During the period of the experiment, the relative humidity was about 45%, allowing the humidity sensor to operate at the lower end of its calibrated range. The sensors were shielded from solar radiation to prevent radiative heating of the exposed quartz crystals.

In Table 2 are listed estimates of LE obtained at Gurley using Eq. (3) and the coefficients of Table 1. Corresponding half-hourly averages of H, R and G are also presented. From these, a measure of the degree to which a heat energy balance at the surface is satisfied can be obtained as the recovery ratio, $(LE+H)/(R-G)$. It is seen that the values obtained range from 0.87 to 1.27, averaging at 1.00±0.04. Thus, the energy balance achieved does not differ significantly from unity.

Table 2. Heat energy budget components measured at Gurley, N.S.W., on 19 March 1970. Data refer to half-hour runs, centered at the time stated. Flux units are mW cm^{-2}.

Time	R	G	H	LE	$\frac{(H+LE)}{(R-G)}$
1030	54	10	13.7	25.5	0.89
1100	58	11	14.2	28.7	0.91
1130	56	12	13.9	25.4	1.12
1200	60	13	16.4	27.2	0.93
1230	58	12.5	16.3	41.5	1.27
1300	54	12.5	15.2	26.2	1.00
1330	57	13	13.0	25.4	0.87
1400	52	12	13.6	31.8	1.14
1430	48	9	10.3	27.9	0.98
1500	44	9	11.3	20.7	0.91
Average	54.1	11.4	13.8	29.0	1.00 ± 0.04

5. Conclusions

The system for measurement of evaporation described here has the benefits of electronic simplicity and ease of operation in the field. It has some drawbacks. First, it is subject to contamination by airborne particles (in common with many other types of sensor), and obviously it must be protected from rain. Second, the interpretation of the results obtained when it is operated as an eddy-correlation sensor depends on the availability of a sufficiently accurate measure of the sensible heat flux.

For use with equipment such as the Fluxatron, where values of H are normally obtained, its ease of operation certainly exceeds that of a conventional fast-response wet bulb, and the results obtained are probably more accurate.

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