Temperature-Induced Errors in the ML-476 Humidity Data

James F. Morrissey and Frederick J. Brousaides

Air Force Cambridge Research Laboratories, Bedford, Mass.

(Manuscript received 12 February 1970, in revised form 18 May 1970)

ABSTRACT

Temperature-induced humidity errors in the carbon humidity element ML-476 are described. The dominant error is caused by solar irradiation and results in a lowering of reported humidity values. The effect was found with both the military AN/AMT-12 and Weather Bureau radiosondes. Flight studies indicate that a significant improvement in data acquisition will result from a blackening of the sensor channel walls.

1. Introduction

Various aspects of the problem of using the carbon humidity strip (ML-476) to measure atmospheric humidity are presently being investigated at AFCRL. One important factor is that the sensor, essentially a relative humidity measuring instrument, must be in equilibrium with the atmosphere to provide accurate measurements. Bunker (1953) has previously demonstrated that the radiosonde humidity element was not in thermal equilibrium with the airstream and related the response as due solely to lag after the passage of the sonde through air temperature gradients. The present study has shown, however, that errors due to solar insolation can predominate when using the ML-476 strip with its present precipitation shield. Several laboratory and field experiments have been carried out by the authors to evaluate errors due to temperature effects and are the subject of this paper. All flight testing was performed at Bedford, Mass., during the months between May and November.

2. Description of equipment

The flight tests used in these experiments utilized two different types of radiosondes, the military non-transponder AN/AMT-12 and the Weather Bureau sonde. Both sondes use carbon humidity elements to measure atmospheric humidity and both locate the element in a channel designed to minimize solar radiation effects and the direct impingement of precipitation upon the element. Fig. 1 is a diagram of the top of the AMT-12 sonde and illustrates the airstream flow pattern through the humidity cavity. The Weather Bureau sonde has the same general shape though differences in physical dimensions exist.

The carbon element for radiosonde usage is $2\frac{1}{2}$ inches long, 11/16 inch wide, and 0.04 inch thick. The substrate material is either acrylic or polystyrene plastic and the long edges are metallized to serve as electrodes. The hygroscopic material is hydroxyethyl cellulose impregnated with a suspension of finely divided carbon particles to provide a conductive path, with the change in resistance being a function of the relative humidity. Two metal clamps extending down from the outside shield hold the sensor in the air channel. The relative humidity is computed on the assumption that the temperature of the air and of the sensor is the same. The resistance of the carbon element is related to the relative humidity in contact with the element. This relationship is not unique in that there is a temperature dependency. For small temperature differences the effect of temperature on the relative humidity vs resistance relation is a second-order effect and is not the source of errors cited in this paper. The errors evaluated are attributable to the fact that the relative humidity of the gas in contact with the carbon element is different from the ambient relative humidity by virtue of a change in gas tempera-

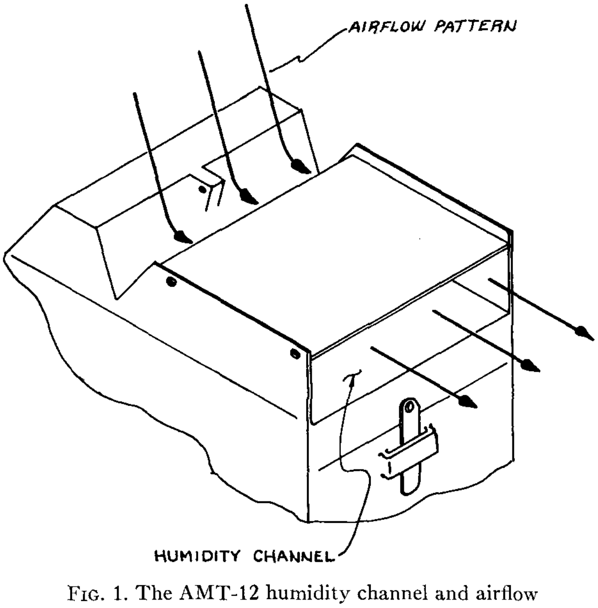

Fig. 1. The AMT-12 humidity channel and airflow pattern.

Unauthenticated | Downloaded 04/17/21 09:45 AM UTC

ture. It should be noted that the temperature of the gas in contact with the surface is the surface temperature of the carbon element since the temperature gradient at the surface must be finite.

On some flights a second thermistor, painted black to simulate the radiational properties of the carbon strip, was mounted in the humidity duct. This was done to obtain information on the surface temperature of the ML-476 element without the complexity of transistorizing the sonde circuitry and implanting bead thermistors in the carbon element. A number of flights were flown with this second thermistor which, being white, thereby provided a measure of the actual free stream air temperature in the duct.

Further tests involved carbon strips whose temperatures were monitored by small bead thermistors. Either transistorized circuitry was utilized to minimize Joule heating in the bead thermistor or appropriate corrections were applied to the data.

3. Induced temperature errors

The carbon strip may be considered a flat plate with a zero angle of attack to the airstream. The average heat transfer coefficient can be computed from

$$h=\frac{1}{L}\int_0^L 0.332k\mathrm{Pr}^{\frac{1}{3}}(V/\nu x)^{\frac{1}{2}}dx, \tag{1}$$

where L is the width of the carbon strip, Pr the Prandtl number, V the ventilation rate, ν kinematic viscosity, x the distance from the leading edge, and k the thermal conductivity of air. Values of h are 2.91×10^{-3} and 2.24×10^{-3} cal cm^{-2} sec^{-1}(°C)$^{-1}$ for sea level and 20,000 ft, respectively. These can be compared to a solar constant of about 33×10^{-3} cal cm^{-2} sec^{-1}(°C)$^{-1}$ to indicate that a temperature rise of several degrees Celsius is possible if an appreciable fraction of the solar energy impinges on the carbon element. The fact that an appreciable fraction does indeed reach the element is readily obvious from a visual examination of the sensing cavity in daylight; the result is largely a consequence of the fact that the internal surfaces of the sensing cavity are white allowing scattered light to reach the element.

A second factor contributing to a temperature discrepancy between the element and the ambient air is the effect of lag. An approximation of the magnitude of this effect is given by considering the element as being exposed to a ramp temperature change, dT/dZ, of 3C (1000 ft)$^{-1}$ (this assumes a standard lapse rate and a balloon rate of rise of 1000 ft min^{-1}). A close approximation to the lag effect for this semi-steady state condition is given by

$$\Delta T=\frac{dT}{dZ}\frac{CV}{hA}, \tag{2}$$

where A is the surface area exposed to the air, V the balloon rate of rise, C the strip heat capacity, and h the heat transfer coefficient. Evaluating (1) and (2) for sea level and for conditions at 20,000 ft, one obtains values of 1.5 and 2.0C, respectively, assuming the channel flow approximates the balloon ascent rate.

A third factor contributing to temperature differences between the humidity strip and ambient air is the degree to which the air in the sensing cavity has been heated by passage over the warm surfaces of the cavity walls prior to passing over the humidity element. It should be noted that this term also has a solar dependency since the wall temperature itself is influenced by solar radiation.

A fourth factor is infrared heat transfer between the element and the walls of the cavity. An estimation of the importance of this mode of energy transport is given by comparing a linearized estimate of the radiation to the convective heat transfer h, that is,

$$r=4\sigma T^3/h, \tag{3}$$

r being ~0.04 from the surface to 20,000 ft. Since the long wave equilibrium temperature for the carbon element is close to its actual temperature, this low value for r indicates that the longwave radiation heat transfer term is not significant.

Other sources of error include conduction along element clip leads and the humidity sorption processes occurring within the strip. These latter effects, however, do not contribute appreciable errors in the measurement of humidity. Summarizing the total error contributions gives us

$$\Delta T=(\text{solar effect})+(\text{time lag effect})+(\text{wall effects})$$
$$+(\text{infrared effects})+(\text{conduction, sorption, etc.}),$$

where the first three terms are the only significant contributors.

4. Flight test results

Some of the above factors can be better understood as a result of laboratory experiments, but it is quite evident that the most definitive evaluation must come from flight data. Because of this the principal thrust of the investigation has been flight data, with laboratory results used as a secondary source of information. There has been no effort to verify in the field the sampling errors in humidity caused by these biased temperatures. Only the fact that the humidity element is at a temperature other than ambient has been demonstrated. The magnitude of the temperature difference implies a certain error in humidity which is discussed.

Flight tests were divided into six main categories and are enumerated below.

1) Three day flights of both AMT-12 and Weather Bureau sondes, respectively. A white rod thermistor was used in the position normally occupied by the humidity element in addition to the rod thermistor in the standard position.

Unauthenticated | Downloaded 04/17/21 09:45 AM UTC

Table 1. Flight summary and analysis.

		White rod in white cavity				Black rod in white and black cavities*				ML-476 strip temperature			
Level (mb)		AMT-12		Weather Bureau		AMT-12		Weather Bureau		AMT-12		Weather Bureau	
		Day	Night	Day	Night	White cavity	Black cavity	White cavity	Black cavity	Day	Night	Day	Night
1000–701	s	0.39	0.78	0.35	0.31	0.72	0.37	0.69	0.44	0.93	0.33	0.89	1.29
	$\Delta\bar{T}$	0.50	0.51	0.93	0.37	1.46	0.44	2.35	1.15	1.84	0.72	2.54	0.87
	n	32	19	34	33	45	38	34	43	45	23	34	24
700–501	s	0.32	0.40	0.52	0.39	0.64	0.28	0.80	0.42	0.87	0.34	1.01	1.17
	$\Delta\bar{T}$	0.59	0.18	1.42	0.67	1.76	0.65	3.16	1.66	2.71	1.18	3.36	1.18
	n	28	28	28	26	42	31	30	35	46	18	32	22
500–351	s	0.50	0.39	0.36	0.20	0.54	0.45	0.76	0.42	1.04	0.36	0.76	1.48
	$\Delta\bar{T}$	0.93	0.32	1.70	0.94	1.97	1.27	4.00	2.28	3.90	1.48	5.43	2.28
	n	27	26	27	29	40	30	29	35	47	19	29	19
350–250	s	0.76	0.40	0.39	0.38	0.48	0.55	0.81	0.50	1.02	0.33	0.54	2.28
	$\Delta\bar{T}$	1.20	0.20	2.19	1.01	2.22	1.43	5.18	2.82	4.34	1.36	7.10	2.89
	n	23	22	17	21	35	22	24	29	40	10	27	12

* Day flights.

2) Four flights of the AMT-12 and three Weather Bureau flights with blackened rods in place of the carbon strip. These flights were performed during daylight.

3) Three AMT-12 sondes and four Weather Bureau sondes in daylight with blackened rods replacing the carbon strip and with the interior sensing cavity walls blackened except for the front baffle slope.

4) Three night flights of each instrument with white rods in the sensing cavity replacing the carbon strip.

5) Five day flights with AMT-12 instruments and three with Weather Bureau sondes each having carbon humidity elements with embedded small bead thermistors to sense strip temperature. Two of these flights (AMT-12's) were flown with transistorized circuitry to minimize Joule heating effects on the bead. The other flights utilized unmodified radiosondes but the data were corrected for bead heating errors.

6) Two night flights of each instrument having the same configuration as in 5). Both sondes were untransistorized.

All day flights, with one exception, were taken under clear skies. It should also be noted that in all tests where the carbon element was replaced by a temperature sensor the shunting resistor was removed from the circuitry.

The innovation mentioned in category 5) was also investigated in the laboratory. A bench study was conducted to verify the assumption that an ML-476 strip temperature differential with the air will induce a relative humidity measurement error. A small bead thermistor was implanted in a carbon element which was then placed in the throat of a small wind tunnel. The throat section was of clear plastic which allowed the strip to be irradiated with an artificial light source. The temperature of the strip and the carbon element resistance were both monitored. The air temperature downstream was checked to prove that it was not affected by the radiation. Reasonable agreement between the change in element resistance and the expected relative humidity change due to the incremental temperature rise was obtained. While a more detailed test would investigate the temperature and relative humidity gradients in the boundary layer of the strip, it was felt that the technique reported herein of measuring the temperature of the strip provides a simple measure to the required accuracy.

For purposes of analysis, the sounding data have been broken into four strata of approximately equal thickness. Data were evaluated at 1-min intervals from the chart traces. Temperature differentials between the free air temperature and the sensor in the humidity channel were compared and were then analyzed for all points in a stratum taken with similar configurations. The AMT-12 tests in category 5) which contained soundings taken with both transistorized and standard circuitry were found to be quite similar, verifying the validity of the Joule heating correction. Consequently, these runs were pooled for purposes of analysis.

The results of this analysis in the form of a mean ΔT, standard deviation s, and number of sample points n are shown in Table 1, where ΔT is defined as the temperature measured within the humidity channel minus the free air temperature indicated by the sonde. No attempt has been made to correct the external rod thermistor for radiation errors, since this is the temperature used in computing the relative humidity operationally and at these heights the rod thermistor errors are less than 0.4C.

In examining Table 1 note that the mean temperature difference increases with altitude and is a function of sensor emissivity. No discussion of standard deviations

Unauthenticated | Downloaded 04/17/21 09:45 AM UTC

TABLE 2. Ratio estimate of measured *RH* to actual *RH*.

Pressure (mb)	AMT-12		Weather Bureau	
	Day	Night	Day	Night
1000–701	0.89	0.95	0.85	0.94
700–501	0.82	0.92	0.78	0.92
500–351	0.73	0.88	0.62	0.83
350–250	0.64	0.87	0.49	0.74

is made other than to say that they indicate where variability was introduced.

The reason for using the blackened rod thermistor instead of carbon elements with imbedded bead thermistors was that it was easier to accomplish (no modification of the sonde was required except removal of a resistor) and consequently allowed us to gather data on various configurations. From these tests, i.e., categories 2) and 3), it is seen that 30–40% of the ΔT was removed by blackening the interior cavity walls. It is expected that an even greater reduction will be found with the carbon strip for two reasons: 1) the sensitivity of the strip to solar radiation is greater than with the rod thermistor, 2) and the carbon element is more sensitive to radiation from the interior walls—which would be blackened—than to the radiation coming from the ends of the cavity.

Interpretation of what these temperature discrepancies mean to humidity data is complex. An almost necessary assumption is that the measurement is made under static (i.e., constant) relative humidity. Making this assumption along with the knowledge that the air temperature at the humidity strip boundary is the same temperature as the strip, we can estimate the humidity measurement error from the saturation pressure–temperature relationship and the measured relative humidity. This error is given by the expression

$$RH(\text{error}) = \frac{dP_{ws}}{dT}\frac{\Delta T}{P_{ws}} RH(\text{measured}), \qquad (4)$$

where P_{ws} is the value for saturation vapor pressure at ambient temperature, dP_{ws}/dT the differential pressure increase with temperature, and ΔT the observed difference between sensor and air temperature. An estimate of the ratio of measured *RH* to the true *RH* that might have been observed on the flights that utilized the carbon humidity strip can be made from the mean temperature rise observed within each stratum and typical air temperature values. Using data from Table 1 and the expression $P_{ws}/(P_{ws}+\Delta P)$, we may generate Table 2.

Several important factors about the tables presented should be noted: 1) they are based upon mean temperature error; 2) they are from one location (Bedford, Mass.); 3) they are primarily taken during the period between May and November; and 4) they are biased toward cloud free days.

Concerning the last point, it should be noted that when sensing during overcast conditions it might be expected that a smaller error would result from minimized insolation. Also, if the cloud layer is associated with an inversion this would minimize the effect due to strip temperature lag.

Without being aware of the induced errors associated with the use of the ML-476 element one could, from a detailed examination of radiosonde flights, postulate the existence of interesting, yet unreal, diurnal humidity variations. Thus, from Table 2, for a relative humidity of of 60% between 500–351 mb, the AMT-12 will show a diurnal variation of about $60(0.88-0.73)=9\%$ *RH* and the Weather Bureau sonde a variation of $60(0.83-0.62)=13\%$ *RH*. Both errors would be entirely instrument generated.

Notwithstanding their limitations, the corrections in Table 2 can serve as a useful first approximation of the bias error to be found in data previously taken. The actual error in a given flight would necessitate intensive examination of biasing errors to be found under local conditions of cloud cover, solar zenith angle, etc.

5. Conclusions

The purpose of the study has been to demonstrate that errors in humidity measurement do exist due to non-steady-state temperature conditions between the carbon strip and the free air temperature. The magnitude of these errors has been estimated for a single location and specified meteorological conditions. The results of this study have shown that the maximum error can be markedly reduced by painting the humidity channel walls black. Further testing is underway to reduce errors introduced by the packaging. Direct measurements of the actual bias are also to be reported.

REFERENCES

Bunker, Andrew F., 1953: On the determination of moisture gradients from radiosonde records. *Bull. Amer. Meteor. Soc.*, **34**, 406–409.

Unauthenticated | Downloaded 04/17/21 09:45 AM UTC