Tests on Ventilation Rates and Other Factors in Radiosonde Performance

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ABSTRACT

Concern for the performance of temperature sensitive elements on radiosondes led to these tests on ventilation rates in a special wind tunnel. Results with sondes in current use show large reductions in flow through the housings. Variations of flow with angle of attack indicate that 2:1 changes in convective heat dissipation of sensors in the air duct are possible.

1. Introduction

Because of the necessity for matching the temperature reported by a rocketsonde at the end of its mission with that of a radiosonde at the top of its flight, much attention has been given their comparative readings. Several test programs for comparing rockets and radiosondes have been reported (Thiele and Beyers, 1966; von Gohren, 1968; Caplan and Camp, 1969; Salmela and Sissenwine, 1968). In the region of overlap around 30 km, the effect of solar radiation is of particular concern. While simple corrections can be applied, it is recognized that each is a variable which cannot be predicted in some designs of sensors, and close agreement is not easily assured.

A program of evaluation of temperature errors found in different thermistor configurations has been in progress for several years at the AFCRL Aerospace Instrumentation Laboratory (Thompson, 1968; Morrissey, 1970). The simulation of results in ground facilities of radiation and ventilation effects has been matched with rocket and balloon flights using specially instrumented sondes (Morrissey and Carten, 1967). More recently, the effect in radiosondes of these errors on humidity sensors was found to be significant, and definitive measurements have been reported by Morrissey and Brousaides (1970). At the same time, the problem of ventilation inside radiosondes has been reviewed even though the temperature elements are mounted outside. Some of the more interesting results are reported here together with earlier work not generally known.

Radiosonde development is a long and complex undertaking in engineering and manufacture, and the present highly successful designs became practical after breakthroughs in such diverse fields as radio and plastics, to name but two. It is surprising to find so little in the literature about the subject, probably due

to the fact that the changes were made gradually and recorded only in contractor and using-agency files. In this country, the original Diamond-Hinman system, designed at the National Bureau of Standards in 1935 under Navy contract (Middleton and Knowles, 1941) is still the standard in use today, although notable improvements have been made in the sensors and the recorders. The housings have also been changed with different but not always improved exposures of the thermistor and hygistor.

Before proceeding with the details of recent tests, it is useful to review some obscure reports which are valuable in this test work. Among these were the ground tests of Rosen (1946) who studied the radiation errors in the U. S. Weather Bureau's AN/AMQ-1 housing, using brown colored semi-conductor rods, which had replaced the original liquid temperature tubes. A 3-5C effect, due to solar radiation, was predicted on the basis of the ground measurements. A thin foil coating on the rod was found to cancel the sun's effect at sea level. Another important contribution was a wind tunnel measurement of the flow rate in the housing. He reported 2% or less attenuation in the air flow through the open-type shield of the AN/AMQ-1 [Fig. (1)]. The next year Weiss continued the work and determined the lag of the rod thermistors. The 1.6-mm diameter rods, about 5 cm long, had a lag of ~7 sec while that of the foil-coated rod was 8 sec. He experienced difficulty with the repeatability of the thermistors available to him and concluded, with the quality control of production items at that time, that the errors due to sensor variability would be greater than those due to radiation.

Hull and Thayer (1948) carefully selected the thermistors in the AN/AMQ-1 at the MIT Meteorology Laboratory which had a regular sounding program at that time. After calibrating the test thermistors, they could check their predicted errors. They compared untreated elements exposed in the two positions

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FIG. 1. Drawing of AN/AMQ-1 radiosonde, showing location of thermistor in the radiation shield.

available in the duct of the AN/AMQ-1. A maximum temperature difference of 15C at 75 mb was observed, as compared to a predicted maximum of 11C. However, results showed the average differences amounted to ~ 3 C as in Rosen's tests. A nighttime test showed a negligible difference. Since Weiss had already cited the pendulum action of the sonde as a contributing factor, measurements were made of the variations with angle of incidence of the sun. On the ground, this effect produced changes from 0–1.7C. After considering other variables (to be discussed below), they concluded from their sample that they could not derive absolute values of radiation corrections to apply generally to all soundings made with an instrument which houses the thermistor in a duct. They did find that the foil-coated and the lead-carbonate-painted thermistors performed equally well in reducing the effect of radiation.

During this time, work was going on at the Signal Corps Engineering Laboratories (Brasefield, 1948) to move the air temperature sensor from within a shield to an exposed position on the sonde. Thermistors were used with a lead carbonate coating developed under contract by Pfund, Fastie and Peters of Johns Hopkins University which had a reflectivity of $\sim 94\%$. These white rods were mounted on wires protruding several inches from the body of a sonde which was flown on the same balloon that carried a standard radiosonde. Comparative temperature readings were then made with the sensor in the air duct of the AN/AMQ-1 sonde. Untreated brown thermistors in the duct were stated

to have radiational errors of 3–6C at 50,000 ft, 5–10C at 75,000 ft, and as much as 20C at 100,000 ft. A similar comparison of outboard treated rods on a Weather Bureau radiosonde with an "S duct" showed that untreated rods in the duct had temperatures 1–2C warmer in the troposphere, and an error of more than 5C in the stratosphere. He added that radiation corrections should be made to the data for treated rods above 80,000 ft. Following the above findings, the thermistor literally became a free air thermometer as it has since been located on struts or outriggers on the upper part of the sonde package. The details of radiation corrections and of the influence of the mount must be left for another publication.

As mentioned above, a housing has a secondary effect on the temperature observation. Lugeon and Ackerman (1944), reporting on early radiosonde developments up to 1944, described the error in a duct as being the result of "thermal drag", the difference in temperature between the sonde and the thermal element being due to the difference in their response times or lag coefficients. With ascent into a colder atmosphere, they obtained differences from 0.8C at 8 km to 16.0C at 15.5 km. This cumulative effect lasts ~ 15 min after entering an isothermal layer. [The same time required to reach equilibrium after having been exposed to a temperature change of a few degrees is also shown on records presented by Brasefield (1948)]. It is to be expected that the thermal lags of the duct will vary greatly, being dependent upon construction, and quite obviously on ventilation rate. Much attention has been given in earlier designs to avoid having a heat sink closely coupled to the thermistor but the emphasis on the design of the humidity channel is to protect it from liquid water, as indicated by the name rainshield given the present radiosonde top. Since there was a question as to the suitability of such a shield in promoting the ventilation of the humidity element, a short measurement program was carried out.

Two types were tested: the military AN/AMT-12, and a Weather Bureau 1969 model, first as is and then with modifications. The latter were simple, no attempt being made to change the whole package. Actually, parts of current sondes were used in the modification in some tests.

2. Test setup

The tests reported here were made in the AFCRL Meteorology Laboratory wind tunnel. The Micro-meteorology Instrument Calibration System, as it is called, is a 1 m tunnel normally used for calibrating anemometers. The sonde, mounted in the center so that it could be rotated, did not change the tunnel flow sufficiently to complicate the comparative tests described here. The speed inside the duct or channel in which the humidity element was located was measured by a hot film anemometer mounted *transverse* to the

FIG. 2a. Top view of AN/AMT-12 radiosonde showing locations of anemometer probe (1, 4, 10) with respect to the position of the humidity strip.

FIG. 2b. Side view of AN/AMT-12 radiosonde showing locations of anemometer probe (1, 4, 10), the air flow channel (wavy lines), the inlet flow angle for the pitching angle test, and a design modification (dashed lines) not used in the data shown in Fig. 2c.

flow (Basic Devices Inc., 1968). The sensor is a platinum cylinder (0.16 cm diameter by 1 cm long) plated on a ceramic rod with a stem support (0.25 cm diameter by 2 cm long), connected for constant current operation with voltage output. Calibrations were made at beginning and end of a series of runs with the probe mounted in the free stream in the center of the tunnel ~ 1 ft ahead of the sonde, with the values being compared with a precision pitot static air speed indicator on the same axis upstream. For a given rod-bridge combination, these calibrations appeared consistent when a temperature dependence was introduced which was thereafter applied to all readings. The output voltage was linear with the log of the speed above ~ 1.5 m sec $^{-1}$. A change in the slope in the curve at lower speeds was noted. Since the pitot head used for tunnel speed can give an erroneous response at these Reynolds numbers (Ower and Johnson, 1931), computations were made for such a correction; it was not sufficient, however, to explain the changes in slope in the hot film response curve. As a result of this anomalous calibration curve and the difficulty in making low-speed measurements, the accuracy of the readings is limited to $\pm 10\%$ at the lowest speeds. The same accuracy would apply at the top speed above 5 m sec $^{-1}$ when the local turbulence in the tunnel gave unsteady readings. However, repeat readings at intermediate speeds on the same configurations indicated an accuracy of a few percent.

The flow pattern in the duct was measured at several positions to the side of, ahead of, or behind the humidity strip. The probe was held in a plastic tube mounted externally in the body of the sonde and tests were made at different speeds with the rod fixed in a predetermined position. Continuous horizontal or vertical traverses were not attempted. Since it was evident from the tests that the velocity profile in the duct changes with distance from the walls, repeatability for a given position in similar sondes was a matter of adjustment of the position of the probe. (Note that the flow is averaged over the 1-cm length of the probe.) In the time available, the comparisons were best made by taking observations of the speed in the duct for various tunnel speeds from ~ 0.5 –5 m sec $^{-1}$ within a 10-min period. During a run, the air temperature would usually change a few degrees, requiring a correction in both the pitotstatic and hot film data reduction. The complete tunnel

facility has a computer available for repetitious calibration, but the data reported here were reduced by slide rule using nomograms devised for the purpose.

The mounting shaft in the tunnel could be rotated by remote control so that "angle of attack" tests were made for many configurations. Since the center of rotation for the box was near the top of the sonde, the speed of the flow in the tunnel was relatively constant at the front. With the shaft and the hot film sensor support both being downstream, they were assumed to have the same small effect for each configuration tested. Pitch tests were made with the box rotated about the short transverse axis, an alignment which would be preferred by a swinging sonde. Roll tests were made with the box rotated about the longer transverse axis. These angle-of-attack data can then be correlated if desired, with solar radiation data taken under identical axis rotations.

3. Measurements

While instruments in current production were used, only the results for the military version AN/AMT-12 are presented here. To compare with the older sonde design Figs. 2a and 2b show sectional views of the sonde with different test positions (1, 4, 10) of the anemometer probe in relation to the humidity strip. The dashed lines in Fig. 2b give the outline of one simple modification cited below, while the wavy lines indicate the air-flow through the horizontal duct. The top part of

FIG. 2c. Variation (relative) of flow rate in AN/AMT-12 channel with anemometer probe in position 4 as a function of inlet flow angle for two wind tunnel speeds, 1.4 and 3.3 m sec $^{-1}$.

FIG. 3. Results of ventilation tests with AN/AMT-12 radiosonde using a 1-cm hot film anemometer probe.

Fig. 2b shows the vectors for the air approaching the top of the sonde at different pitch angles.

For normal orientation with flow at zero pitch angle the fractions of the free stream velocity recovered at different airspeeds at positions 1, 4 and 10 are shown on Fig. 3. Curves marked modified refer to the non-standard configuration indicated by the dashed lines in Fig. 2b. The intention of the modification was to promote higher velocities and was generally effective at the lower velocities. Anomalies were observed which may have been due to the variations in test models or to a Reynolds number (Re) effect discussed later. The curve at the bottom of Fig. 3 indicates near stagnation in the flow; this might have been expected since the probe was adjacent to the brackets mounting the relative humidity element.

Fig. 2c shows the pitch angle test data with the recovery ratio plotted for the various angles shown in Fig. 2b. The two curves were obtained at constant tunnel speeds of 1.4 and 3.3 $m\ sec^{-1}$, the points indicating the values of recovery ratio. The spread of points at the lower speeds indicate a variability to be expected. Data taken for roll tests are not presented here

FIG. 4. Thermal factor, or cooling power, variations resulting from a pendulum type motion of an AN/AMT-12 radiosonde. Computations have been made for a swing of $\pm 30^\circ$ with an 8-sec period.

FIG. 5. Air speed V for transition from laminar to turbulent flow in channels of various sizes for a critical Reynolds number Re of 2300. The computations were based on the expression $Re = d_h V / \nu$, where d_h is the equivalent hydraulic diameter (equal to 4π times the area divided by the perimeter) and ν the kinematic viscosity.

because they are somewhat similar to pitch data. The same may be said for the Weather Bureau sonde tests which generally showed lower internal speeds.

4. Discussion—ventilation speeds

While only a fraction of the test data taken are presented here, the curves shown indicate what is happening. It can be stated that it is difficult to obtain free stream velocity in any duct which changes the direction of flow of the air relative to the motion of the sonde. The air motion past the relative humidity strip is at a reduced rate and is affected by the mountings. Even the original duct had this problem. The change in speed with "angle of attack" of the sonde entrance to the wind is significant in that it affects both the speed of response of the sensing element and the accuracy of the relative humidity reading. The assumption that the air in the duct is at the same temperature as that measured by the outrigger thermistor can lead to errors in the determination of relative humidity by the hygistor as pointed out by Morrissey and Brousides (1970).

The effect of the cooling power of the air as the flushing velocity changes due to swinging of the sonde is graphically shown in Fig. 4. This cooling power, here called a thermal factor, is a function of the square root of the air speed. The angle of swing is converted to an approximate time by using the formula for a simple pendulum corrected for large displacements. Assuming a period of 8 sec and using the data given in Fig. 2c for 1.4 $m\ sec^{-1}$, the curve shown is essentially a step function which has been smoothed by the time response of the structure. This "swinging" response is a result both of the lag of the sensor and the rate at which the heat in the warmer duct air is removed by conduction.

5. Discussion—Reynolds number effects

The next problem is that of extrapolating the data taken at ground level to the altitudes penetrated by the sonde where measurements are more important and behavior more critical. As is common in wind tunnel work, the assumption is made, for a given value of Re , that the variation in velocity can be used to simulate density changes. The data taken at lower tunnel speeds then represent conditions at higher elevations in the range for which boundary layer performance is predictable. Such is expected here for the moderate changes of speed and density used.

Another critical factor must be taken into account in duct flow, i.e., the possible development of a critical Re at which the motion changes from laminar to turbulent since, when this happens, the flow rate can change abruptly. Examining the data taken on these and other tests, there was evidence of a change in the flow ratio at some low velocity. Low-speed tunnel experience suggests that the critical Re changes with tunnel turbulence on a given day. The measurements made here showed that some days were "noisy" with undulations of the order of 10% in duct speed. In other cases, duct configurations gave variations at a rapid rate indicating turbulence which could be associated with the design. For example, the strap used on the Weather Bureau sonde, located a few centimeters from the air entrance, proved to be an obstacle to laminar flow. The string used on the AN/AMT-12 sonde did not introduce this turbulence.

Other evidence of a Reynolds number dependency is sought in the shape of the curves of response ratio vs speed. Before too much emphasis is placed on the change in the curve of the velocity recovery ratio below 2 m sec⁻¹ (Fig. 3), it should be stressed that data at low velocities are less accurate. If one assumes that the transition from steady (laminar) flow to turbulent flow occurs at a given Re , one can compute the velocity of this transition at different altitudes. While there is some difficulty in determining an effective dimension for a rectangular duct, an equivalent hydraulic diameter for the sonde can be computed from an empirical formula (see Fig. 5 legend). Using the duct cross section for either of the sondes, a characteristic dimension of about 5 cm is found. Given a critical Re of 2300 for the transition from laminar to turbulent flow, the value of a critical velocity for each pressure is easily determined. On Fig. 5 curves for a pipe 3.4 cm in diameter (which would have the same cross-sectional area as the duct) and for a pipe having the previously mentioned characteristic diameter of 5.1 cm are shown. This chart serves another purpose since it can be used to pick a speed at sea level which will be equivalent to another at a higher altitude for a given dimension. For the 5.1-cm channel and a velocity of 5 m sec⁻¹ in the duct, it is evident that the flow therein would remain turbulent to about 80 mb. Considering that the velocities in the

duct are already much lower than the balloons' rate of rise (~ 5 m sec⁻¹), it is possible that the flow could become laminar at higher levels, and thus improve the performance. It could also introduce some unsteadiness in the effect of the duct on the performance, if the sonde were swinging enough to change its ventilation speed markedly. This transition could also explain some of the variability in test data, since the sea level data taken here at ~ 1.5 cm sec⁻¹ are in turbulent flow while at lower speeds there may have been a transition to laminar flow.

The above observations have several implications. As applied to current sondes, severe fluctuations in ventilation may possibly be identified on the humidity trace. In new designs, the angle of attack variation must be considered in calculating the flow. Further, in the use of shields for any sensor, the heat lag must be considered as another variable. These factors become important in designing shields which provide radiation effectiveness with no ambiguity at high altitudes, and at the same time give uniform, adequate ventilation.

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