SONIC THERMOMETRY TODAY

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Sonic anemometer-thermometers began appearing in field studies over 50 years ago. They have since been used extensively in field experiments by atmospheric scientists in their studies of turbulent flow in the surface layer—the first 100 feet or so above the ground. The sonic approach promised better high-frequency response and far less flow distortion than what past sensors could offer. The idea of measuring vertical wind and temperature fluctuations along the same vertical acoustic path held great appeal.

The 1968 Kansas Experiment saw the first deployment of sonic anemometer-thermometers in a major field program. Conducted by scientists at the Air Force Cambridge Research Laboratories with three newly delivered Kaijo Denki, Inc. sonic anemometer-thermometers mounted at three levels on a 100-ft tower, the experiment was a success. The large amounts of sonic wind fluctuation data collected over several weeks helped redefine the nature of turbulent transport near the ground. But the sonic thermometer data was disappointing. They departed significantly from fast-response temperature data provided by back-up platinum fine-wire thermometers mounted within the frame of the sonic probes, behind the vertical axis. There was no reason to doubt the accuracy of the platinum sensors. The sonic temperature data were never used.

Sonic thermometry fell out of favor in the United States for the next 20 years until the arrival of a new generation of non-orthogonal sonic anemometers. Their three axes were tilted 60 deg from the horizontal with the three paths intersecting in the middle. They offered a common sampling volume and an open aspect to horizontal winds but the vertical wind component had to be derived from measurements along tilted axes. Several versions of this design came on the market with each manufacturer offering sonic temperature measurements as well. Soon large numbers of users in the forestry and agricultural research communities were opting for the new non-orthogonal sonic anemometer-thermometers. But no serious efforts were made to check the accuracy of the temperature measurements. Several intercomparison experiments have been conducted to resolve issues with their vertical wind measurements, but sonic temperature takes more than side-by-side comparisons to sort out sensitivity to factors other than temperature. This prompted us at ATI to study the problem and come up with ways to make the sonic temperatures more accurate.

We started with tests on our own K-Probe. Its three axes are orthogonal; it has a vertical axis that can be tapped for temperature measurement. It measures horizontal winds we would need for real-time corrections. And the array is open enough to allow insertion of a padded box around the vertical probe for calibration. The aim of the calibration is to ensure that the sonic thermometer reading matches exactly the temperature of air in the calibration chamber. This temperature is measured by an accurate thermistor (Omega Model HH41) inserted through a hole on the side of the chamber. The thermometer reading is entered manually into the sonic software before the start of each calibration run.

We invoke two well-known relationships, expressed in terms of the speed of sound, *C*,

$$C^2 = \gamma \frac{RT}{M_d}$$
$$= 401.878 \ \mathrm{T} \,, \qquad (1)$$

Where, *T* is the absolute temperature of dry air, γ is the ratio of the specific heats at constant pressure and constant volume, *R* is the universal gas constant and M_d the molecular weight of dry air. The latest estimates of these terms yield the coefficient above that differs only slightly from 403 used in earlier studies.

$$C^2 = \left(\frac{d^2}{4}\right)\left(\frac{1}{t_1} + \frac{1}{t_2}\right)^2 + V_n^{\ 2} \quad , \qquad (2)$$

where d is the path length (nominally 15 cm) and V_n is the horizontal cross-wind, zero in the calibration chamber, but finite outside it. The transit times t_1 and t_2 can be measured very accurately, but d not so well. (The critical importance of d is highlighted by the fact that a 1% error in d can result in a 6° C offset in T.)

We resolve this by substituting for C^2 from (1) and solving for d, with T set at the thermometer reading in the calibration chamber. The derived d is stored in the software for all temperature calculations until the next calibration cycle. The derived d should be very close to the nominal 15 cm. For our K-Probe it is 14.828 cm, and this will vary for each probe.

Once set, the sonic thermometer should track precisely the temperature along the acoustic path. The cross-wind effect outdoors is small: a 0.25° C increase for 10 m/s wind. Not so small is the offset from moisture in the air (Kaimal and Gaynor, 1991). The effect of moisture on the speed of sound takes the form

$$C^2 = 401.878\,T\left(1+\frac{0.32e}{p}\right), \tag{3}$$

where e is the vapor pressure of water and p is the atmospheric pressure. We can frame this in terms of the measured sonic temperature, T_s , and the air temperature T as

$$T_s = T\left(1+\frac{0.32e}{p}\right). \tag{4}$$

The effect of moisture is to always raise the value of the sonic temperature. The temperature offset can be as high as 2.4° C in fully saturated air. We have refined the coefficient 0.32 to 0.328 to allow for a slightly different value of M_d. Our software requires entry of expected values of relative humidity and atmospheric pressure for any planned observation period in both the calibration and operational modes.

Our field tests were conducted in the back yard of ATI. It soon became apparent that comparing the rapidly fluctuating sonic temperature with the much slower readings from a manual thermometer was no easy task. It was complicated by sensitivity to solar radiation and condensation of moisture. We finally resorted to comparing 15-sec averaged sonic readings to periodic measurements of air temperature near the sonic probe with our Omega calibration thermometer, in a Climatronix motor-aspirated solar shield.

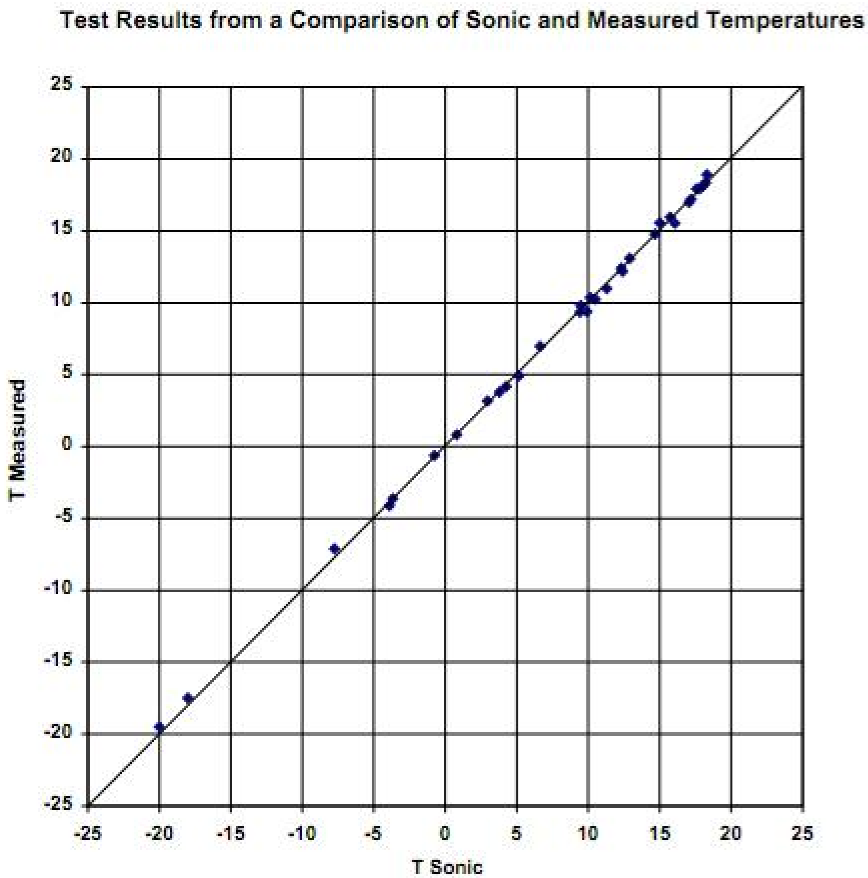

Fig. 1: ATI test results presented as a scatter plot of sonic temperature vs. air temperature measured by an aspirated platinum thermometer in ºC.

The results of our tests made during the month of December (2013) show remarkable agreement between the two (see Fig. 1). The observations cover a range of outdoor temperatures, from -20º C to +20º C. The tracking of temperature over that wide range inspires confidence in the relative accuracy of sonic temperature fluctuations that go into calculation of the vertical heat flux. We hope to duplicate this success in our own non-orthogonal A-Probe. We will continue our K-Probe tests into the spring and summer months to see if the results are as good above 20º C.

REFERENCE

Kaimal, J. C., and J.E. Gaynor: 1991, 'Another look at Sonic Thermometry,' Boundary-Layer Meteorol. 56, 401-410.