A Note on Thermocouple Anemometer

By

Suekichi KAWATA

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When a hot wire is immersed in a stream of air it loses heat first due to conduction and convection of the air, secondarily due to radiation and thirdly due to conduction through supporters of the wire.

It has been shown by L. V. King[1] that the rate of heat loss Q due to the first cause from unit length of a wire passed by a fluid of temperature θ_0 and with velocity v perpendicularly to it is given by a formula

$$Q = i^2 r = (\theta - \theta_0)(A + B\sqrt{v}), \tag{1}$$

where r represents the resistance of the wire per unit length when it is heated by a current i to a temperature θ, and A and B are meant by

$$A = \kappa \tag{2}$$

$$B = \sqrt{2\pi D \rho c_p \kappa}\ ^{2)} \tag{3}$$

where κ is the thermal conductivity of the fluld, ρ its density, c_p its specific heat at constant pressure and D the diameter of the wire assumed as a circular cylinder. King[1] has shown also that formula (1) is expected to hold so far as

$$\frac{D\rho c_p v}{\kappa} > 0.08 \tag{4}$$

or down to a value of vd of 0.015 [cm^2/sec] for air near normal conditions. Heat losses due to radiation and conduction through supporters will be assumed to be proportional to $(\theta - \theta_0)$ practically, and they may be included in A. Then A is not equal to κ but something more than κ.

There are two methods of measuring wind speed by this principle, (i) by adjusting and measuring i holding the temperature or the resistance of the wire unaltered, and (ii) by observing the temperature or the resistance of the wire holding i constant. At any rate, as use is made of the variation of resistance of a wire with temperature materials of large temperature coefficient of resistance are desired. By this measurement notice should be taken of the effect of the temperature of air on the relation between the current through the wire or the resistance of the wire and the wind speed. The temperature appears in the R. H. S. of (1) explicitly as θ_0 and implicitly in A and B. According to the proposition of Langmuir [3], for air

$$\left.\begin{aligned} \kappa &= 4.6\cdot10^{-6}\sqrt{T}\,(1+0.0002\,T)\left(1+\frac{124}{T}\right)^{-1} \quad [\mathrm{cal\cdot cm^{-1}\cdot sec^{-1}\cdot deg^{-1}}], \\ c_p &= 0.2273\ (1+0.0002\ T) \quad [\mathrm{cal\cdot gr^{-1}\cdot deg^{-1}}], \\ \text{and}\quad \rho &= \frac{0.353}{T}\cdot\frac{H}{760} \quad [\mathrm{gr\cdot cm^{-3}}], \end{aligned}\right\} \qquad (5)$$

T being an absolute temperature and H an atmospheric pressure expressed in mm Hg. So, if we take these expressions as they are κ will increase with temperature, increasing about 0.3% per °C near room temperature, and B will decrease more slightly in a region of ordinary temperatures. As a first approximation the temperature affecting A and B may be taken after Davis [4] as the mean of the temperature of the hot wire and that of the cold stream i. e. $\frac{1}{2}(\theta+\theta_0)$. By King's experiments [1] A (equal to κ in the case) increases in the manner as shown, but B also increases though only slightly. Thus, strictly speaking, they are to be regarded as functions of air speed by the constant current method. To reduce the effect of θ_0 in (1) high working temperature of a wire may be used. But it is not recommended for general purposes owing to an ageing effect on a wire or even a dangerous effects upon surroundings in some cases, so other methods of compensation of the temperature effect have been considered. For example, Fay [5] has devised a skilful method of using a Wheatstone's bridge consisting of six wires, all exposed to a wind, and with an assumption that $(A+B\sqrt{v})$ is independent of temperature has arrived at a relation

$$i^2 = c(A+B\sqrt{v}), \qquad (6)$$

i being a current passing through an arm of the bridge in equilibrium, and c a constant independent of temperature.

Now it has come to the writer that an automatic compensation of temperature may be realised very simply by using a thermocouple attached to a hot wire. Such thermocouple anemometers have been constructed by Yunker [6], Hukill [7] and Asada and Nakamura [8]. An apparent advantage of the instrument over ordinary hot-wire anemometer seems to be more robust and easier to handle. These investigators measure a wind speed by observing an electromotive force of a thermocouple one junction of which is heated with a constant current through a wire and the other is placed in a cold sream, that is, by a constant current method.

When a thermocouple is attached to a hot wire distribution of temperature along the wire will be different from that along a single wire, that is, temperature will be minimum at the junction. But a formula similar to (1) may be assumed to hold in which $(\theta-\theta_0)$ is replaced by a difference of temperatures of the two junctions of the thermocouple multiplied by a constant.

Now we will assume following conditions:

(i) To select a thermocouple so that the electromotive force E holds a linear relation with $(\theta-\theta_0)$ irrespective of θ or θ_0 (now θ being a temperature of the hot junction). In practice, such a couple as of alumel and chromel will be used.

(ii) To use a hot wire the electric resistance of which is practically constant with temperature, contrary to the case of an ordinary hot-wire anemometer, for example a constantan wire being used.

By this scheme we will have

$$i^2 = kE(A+B\sqrt{v}), \tag{7}$$

where k is a constant independent of θ and θ_0.

(iii) To keep the electromotive force of the couple constant, that is, to keep $(\theta-\theta_0)$ constant. By this procedure E will be put to be constant, and moreover losses of heat due to conduction and radiation will be taken as constant independently of wind speed.

Thus we will have a relation

$$i^2 = k_1(A+B\sqrt{v}), \tag{8}$$

where k_1 is a constant independent of θ or θ_0. The result will be equivalent formally to that attained by Fay[5], and the compensation will be satisfactory for most purposes as A and B may be assumed sensibly constant for temperatures of an ordinary region. But, it may seem to be able to go further. If i_0 is a current necessary to maintain a wire at constant E in still air (i. e. $v=0$), (8) may be written in the form

$$i^2 = i_0^2+k_1B\sqrt{v}, \tag{9}$$

which may be more useful as B seems to vary very slightly. Again, if, instead of assuming the condition (ii), we adopt a wire of which resistance varies with regard to temperature in the same manner as B (if a variation of B with temperature be known) — the process will be possible as $(\theta-\theta_0)$ is kept constant in this case — we arrive at

$$i^2-i_0^2 = k_2\sqrt{v}, \tag{10}$$

k_2 being a constant independent of θ and θ_0. In reality, however, we will meet a difficulty as explained below.

The writer has made a tentative experiment with a thermocouple anemometer consisting of alumel and chromel wires both 0.1 mm thick attached to a constantan wire 0.1 mm thick, the latter being held vertically to minimise a free convection current, once by means of a glass tube and a wet gas-meter, and once by means of a wind tunnel, a static tube and a Chattock manometer. When points are plotted against $\sqrt{v}$ and i^2 with constant E of 3, 4 and 5 mV these points lie on a straight line respectively for speed of air flow of from 3 ms per sec down to 10 cms per sec as to be expected from (8). But downwards from there the line alters its direction and approaches parallel to $\sqrt{v}$ axis, and the point obtained by cutting air flow which will correspond to i_0^2, if natural convection currents be negligible, is deviated markedly from the point extrapolated from the straight part. This character of the curve may be explained chiefly by the effect of free convection currents due to the hot wire. Evidently the effect of free convection currents is large when a hot wire is held horizontally and is small when it is vertical, and affects (8) in different manners corresponding to different orientations of the hot wire as it may be remarked that the eq. (1) should hold true only for the flow of a fluid prependicular to a hot wire. Again it ought to be remembered that eq. (1) is restricted by the condition (4). So, measurement of a wind of low speed of magnitude comparable with natural convection currents should be performed by a special calibration. So far as elimination of A is difficult the merit of condition (iii) for compensation of the variation of an atmospheric temperature may be somewhat reduced.

It may not be useless to add here comparison of advantages of the two methods, the constant E method and the constant i method. The relations will be similar to the case of ordinary hot-wire anemometers. By the constant current method the instrument is highly sensitive in the region of very low speed, but the sensitivity will soon become very poor for higher speed, while by the constant E method fairly good sensitivity will continue for region of higher speed. The relation may be seen from eq. (7). By the constant current method temperature of the wire should be made higher for lower speed, so it may be likely to make the disturbing effect of free convection currents greater, thus decreasing the advantage of high sensitivity in the region of very low speed. Care should be taken that in this method A and B are dependent on wind speed as noticed above. A defect of constant E method which is more standard will manifect itself markedly when it is used for wind of rapidly varying speed. As it may be expected, especially by the use of condition (ii), i remains constant for different speeds while E is variant, and efforts should be made to alter the standing i to bring

E to a designated value. For universal use it may be advisable to construct an instrument to be used in two ways, both an ammeter and a millivoltmeter being calibrated in scale of wind speed, and to put it in use adequately for different purposes, and especially for widely variable atmospheric temperatures multiple calibrations for several different temperatures will be recommended. It is very regretful that the writer could not perform experiments to ascertain the temperature effect owing to want of an appropriate thermostat.

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