The Excess Temperature of a Rigid Fast-Response Thermometer and Its Effects on Measured Heat Flux

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ABSTRACT

In outdoor experiments a temperature sensor is always subjected to a radiation load that results in a temperature excess error. Not only the mean temperature is effected by this radiation load but also, for a fast-responding sensor, the measured temperature fluctuations. In the present paper the mean excess temperature error is discussed and the fluctuation error is analyzed. A technique is presented for estimating the importance of this error in eddy correlation measurements as well as temperature variance measurements. It appears that the mean excess error as well as the fluctuation error can be considerably reduced by coating the sensor with white paint.

1. Introduction

This paper describes errors in thermometer measurements caused by radiation absorption. The thermometer can measure both mean air temperature and temperature fluctuations to high accuracy at frequencies up to 10 Hz. The thermometer is designed to measure profiles of mean temperature and temperature variance in micrometeorological studies and, in combination with a sonic anemometer, to measure sensible heat flux by the eddy correlation technique.

The temperature-sensing element of the thermometer is a manganin–constantan thermocouple. This thermocouple is made from fine wires, 0.1 mm in diameter, which have been resistance welded and then rolled out into a thin ribbon about 0.4 mm wide and 0.02 mm thick. This ensures a fast response to fluctuations in air temperature while retaining the robustness needed for studies of wind erosion in dry regions or placement within plant canopies. The joined, flattened wire is mounted across the arms of a Y-shaped support and connected to the conditioning electronics, which includes a cold reference junction, in the stem of the Y. In the absence of radiation errors, which are discussed below, the thermometer is accurate to ±0.2°C in the mean and to ±0.05°C in deviations from the mean at frequencies up to 10 Hz. The thermometer is described in more detail by Van Asselt et al. (1991).

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Though the technique of rolling the wire allows good frequency response to be obtained from a reasonably thick, strong wire, it has the disadvantage that more shortwave radiation can be intercepted by it than by round wires of similar heat capacity, particularly when the sun's beam is normal to the wide surface of the strip. As a consequence, there can be a temperature excess error that is larger than for the original round wire. The present paper reports some laboratory tests and calculations to gain insight into the excess error of this thermometer and calculations of the likely errors resulting when it is used in measurements of sensible heat flux by eddy correlation.

2. Theory

The time constant τ of a thermometer depends on the thermal properties of the material used, the shape and size of the sensor and the wind speed. The mathematical relationship is (Fritschen and Gay 1979)

$$\tau = cV(Ah)^{-1}, \tag{1}$$

where c (J m^{-3} K^{-1}) is the volumetric heat capacity of the sensor, V is volume, A is the surface area, and h (W m^{-2} K^{-1}) is the convective heat transport coefficient, which is highly dependent on wind speed. Rolling the wire into a ribbon decreases the time constant by increasing the surface area. The operation also changes h.

The convective heat transport coefficient is usually expressed in dimensionless form, as the Nusselt number, defined as

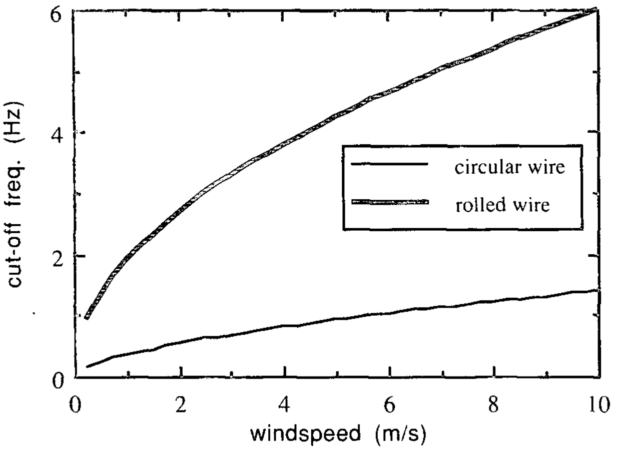

FIG. 1. The behavior of the cutoff frequency $n_c = (2\pi\tau)^{-1}$ as a function of the wind speed for the original circular wire (d = 0.1 mm) and the flattened wire (width is 0.4 mm and thickness is 0.02 mm).

$$\mathrm{Nu} = hd\lambda^{-1}, \qquad (2)$$

where, d is a length scale of the sensor (diameter for the cylinder and width for the flat strip) and λ (W m^{-1} K^{-1}) is the molecular thermal conductivity of still air. The Nusselt number of a flat strip and a cylinder are given by the expressions (Ede 1967; Jacobs and Welgraven 1988)

$$\mathrm{Nu} = 0.60\ \mathrm{Re}^{0.5}, \quad \text{for} \quad \mathrm{Re} < 2 \times 10^4 \quad \text{(flat strip)}, \qquad (3a)$$

$$\mathrm{Nu} = 0.32 + 0.51\ \mathrm{Re}^{0.52}, \quad \text{for} \quad \mathrm{Re} < 1 \times 10^3 \quad \text{(cylinder)}, \qquad (3b)$$

respectively, where Re = $ud\nu^{-1}$ is the Reynolds number, u is the wind speed, and ν (m^2 s^{-1}) is the kinematic viscosity. In the present design, Re < 2×10^3 for both cases.

Figure 1 shows the calculated cutoff frequency, $n_c = (2\pi\tau)^{-1}$, plotted against wind speed for the original round wire, with diameter d = 0.1 mm, and the flattened wire, with a width of 0.4 mm and thickness of 0.02 mm. The cutoff frequency of the rolled wire is seen to be much higher. The improvement in frequency response by rolling causes no loss of mechanical strength.

The penalty for this gain is the possibility of increased temperature excess errors caused by greater absorption of radiation. Excess temperature is expected to be largest when the ribbon is normal to the sun's beam and the wind speed is low.

Calculations have been carried out to estimate the excess temperature of the flattened wire, $\epsilon_r = T_m - T_a$, where T_m is the measured wire temperature and T_a is the ambient air temperature. For such fine wires essentially all of the energy absorbed radiatively is dissipated convectively, so the following simplified expression has been used (Fritschen and Gay 1979):

$$\epsilon_r = \frac{Ca(1+\alpha)Q}{h}, \qquad (4)$$

where Q is the global irradiation, a the absorption coefficient of the wire for shortwave radiation, α the reflection coefficient for shortwave radiation of the underlying surface (the albedo), and C the ratio of the diameter and the perimeter of the wire ($C = 1/\pi$ for a circular wire and C = 0.5 for a thin flat wire). In (4) the ribbon surface is assumed to be normal to the solar beams, so absorption of solar radiation, and therefore the excess temperature is maximal. The albedo α appears in (4) because the thermometer receives both direct and reflected radiation outdoors. For the laboratory tests discussed later there were no reflections, so the albedo α was set to zero for those calculations.

3. Experimental setup

Measurements of excess temperatures were made in the laboratory with the thermometer wire exposed to a range of radiation loads and wind speeds. Figure 2 shows the measurement setup.

The radiation load at the thermocouple wire was adjusted using a 12-V 50-W halogen lamp, with a blackbody temperature of 3400 K, focused through a lens. The focusing point was at 7 cm, and there was a provision to move the lamp to get the desired radiation levels [source system by Spindler and Hoyer (1987–88)]. In our laboratory study, the lamp's position was kept constant and the lens was used to focus the desired energy on the temperature sensor. The distance between lamp and temperature sensor was from 10 to 15 cm, depending on the radiation level selected. Radiation at the wire location was measured by interchanging the wire and a radiometer (Kipp and Zonen, type CM-11).

The wind speed past the wire was adjusted using a small fan (Micronell, type V603M.012.DA.KA) and

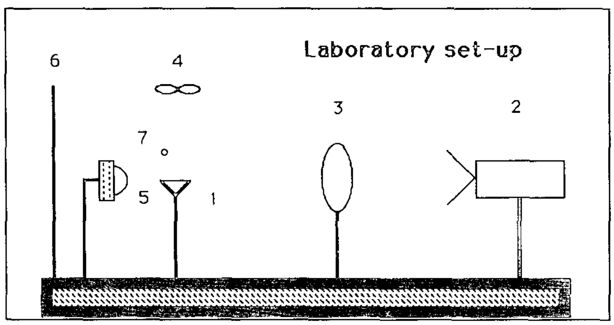

FIG. 2. Experimental setup: 1—fast-response thermocouple; 2—halogen lamp; 3—lens; 4—ventilator; 5—Kipp solarimeter; 6—black plate; and 7—thermistor anemometer.

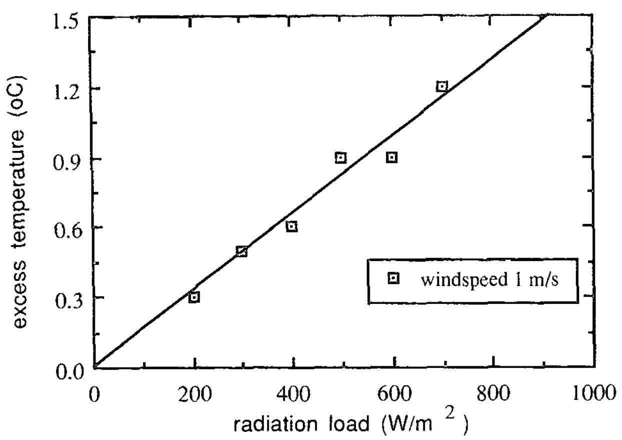

FIG. 3. The excess temperature versus the radiation load at a wind speed of 1 m s^{-1}. The unbiased linear regression line is $y = 1.65 \times 10^{-3}x$ ($r^2 = 0.96$).

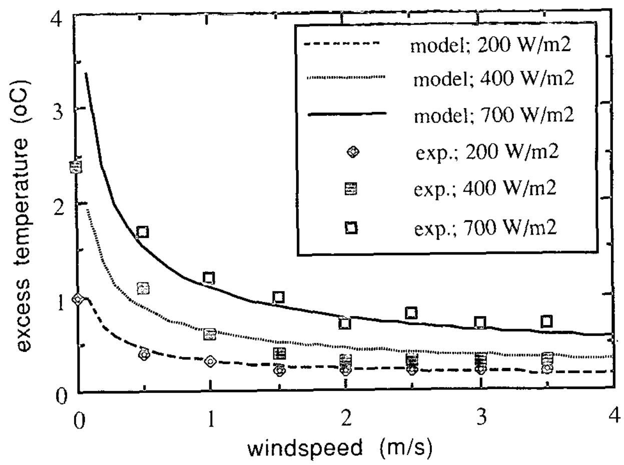

FIG. 4. The excess temperature due to radiation versus the wind speed for various maximum radiation loads. Curves represent model simulations when an absorption coefficient is used of $a = 0.60$.

measured with a thermistor anemometer (Lambrecht, type 641 N). The wind speed was adjusted by controlling power to the fan motor. The wire temperature was recorded for 15 min with a Kipp mV recorder. Before recording the temperature signal, the electrical signal was filtered by a low-pass filter (Butterworth 744 PB-1) at a frequency of 0.1 Hz.

The temperature measurements were made at six radiation levels, namely, 200, 300, 400, 500, 600, and 700 W m^{-2}, with wind velocities in the range 0–3.5 m s^{-1}. Temperature excess was calculated as the difference between the temperatures recorded with the lamp providing a radiation load and with the lamp's beam blocked with a blackened aluminium plate. Wind velocity was unchanged when the lamp's beam was blocked.

4. Experimental results

Figure 3 shows the observed excess error plotted against the maximum possible radiation load for a wind speed of 1 m s^{-1}. The maximum possible radiation load is the situation where the direct beam is perpendicular to the ribbon and is, consequently, where the maximum possible interception occurs. As expected from (4) the relationship displayed is linear.

Equation (4) also shows that the absorption coefficient a of the wire can be calculated from the slope of the line in Fig. 3. This value must be calculated for our particular wire rather than using published values for polished metals (e.g., Weast 1970), because welding and rolling probably increase the absorption coefficient. From the unbiased linear regression line, displayed in Fig. 3, we found the value $a = 0.60$. This value has been used in all further calculations.

Figure 4 shows a comparison between the measured excess temperatures and those calculated from the model for a range of wind speeds and radiation loads. The model calculations agree well with the experimental results. These results show that the excess temperature error is always larger than 0.2°C when the radiation exceeds 200 W m^{-2}. Unfortunately, this does not meet our original design requirement of an accuracy of 0.2°C for mean temperature measurements, which is the standard of the World Meteorological Organization (WMO 1988).

To reduce the excess temperature, the wire can be provided with a white thin reflective coating (Thakur 1989). This was done for our thermometers using an optical white paint with an averaged absorption coefficient of $a = 0.05$ (lithopone paint, Weast 1970). The excess error was reduced, and it appeared also that the coating was so thin that it did not affect the time constant. Results for a radiation load of 700 W m^{-2} have

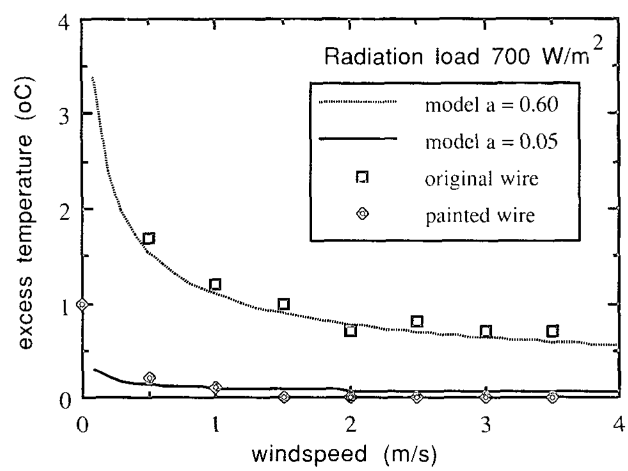

FIG. 5. The excess temperature due to radiation absorption for the unconditioned rolled wire as well as for the same but white-coated wire.

been depicted in Fig. 5 for the coated wire as well as for the original, uncoated wire. We conclude that coating the wire is effective and necessary if an absolute accuracy of 0.2°C is to be achieved.

5. Effect of excess temperature errors on measurements of the heat flux

In the eddy correlation method for measuring the sensible heat flux H (W m^{-2}), measurements are made of both vertical wind speed w and temperature at frequencies of about 10 Hz, and the heat flux is calculated using the equation

$$H = \rho c_p \overline{w'T'_a}, \tag{5}$$

where ρ is density, c_p is specific heat capacity, w is vertical wind speed, T_a is ambient air temperature, and the primes indicate deviations from the mean values. In practice, measured T_m is used in place of the true air temperature T_a. This temperature introduces error into the calculation because the excess error depends on the ventilation rate and so is correlated with w'. This is investigated in this section.

The previous section shows that, at each instant, the measured temperature of the wire is the sum of the true air temperature and an excess error, with $T_m = T_a + \epsilon_r$. Only the fluctuating part of these temperatures enters into the calculation of the sensible heat flux using (5), so we write an equation for the fluctuating part as

$$T'_m = T'_a + \epsilon'_r. \tag{6}$$

Using this, $\overline{w'T'_m}$ can be expressed as

$$\overline{w'T'_m} = \overline{w'T'_a} + \overline{w'\epsilon'_r}, \tag{7}$$

so the flux calculated using (5) and the measured wire temperature has an error that is related to the fluctuations in the excess temperature.

Now the excess temperature depends on air wind speed and radiation, so its fluctuations are related to the fluctuations in wind speed and radiation by

$$\epsilon'_r = \frac{\partial \epsilon_r}{\partial u} u' + \frac{\partial \epsilon_r}{\partial Q} Q', \tag{8}$$

which gives the error term in the heat flux calculation as

$$\overline{w'\epsilon'_r} = \frac{\partial \varepsilon_r}{\partial u} \overline{w'u'} \tag{9}$$

when $\overline{w'Q'}$ is neglected because radiation fluctuations are unlikely to be correlated to fluctuations in vertical wind speed. We see that $\partial\epsilon_r/\partial u$ can be calculated using (4) for any wire size and radiation level.

Using (4) and (3a) we obtain

$$\frac{\partial \epsilon_r}{\partial u} = -\frac{Ca(1+\alpha)Q}{2hu}, \tag{10}$$

and so

$$\overline{w'\epsilon'_r} = -\frac{Ca(1+\alpha)Q}{2hu} \overline{w'u'}. \tag{11}$$

Evidently we can estimate the error term in the calculated sensible heat flux from this equation if we know the various parameter values and $\overline{w'u'}$.

The term $\overline{w'u'}$ in (11) is similar to the eddy covariance expression for the momentum flux, though u is here the magnitude of the wind speed over the sensor, not the streamwise component of the wind speed. The magnitude of u can be written in terms of the Cartesian components of the wind vectors, u_i, u_j, and u_k; thus,

$$|u| = [(\overline{u_i} + u'_i)^2 + (\overline{u_j} + u'_j)^2 + (\overline{u_k} + u'_k)^2]^{1/2},$$

so

$$|u| = (\overline{u_i}^2 + 2\overline{u_i}u'_i + u'^2_i + u'^2_j + u'^2_k)^{1/2}, \tag{12}$$

because $\overline{u_j}$ and $\overline{u_k}$ are zero. For most situations above vegetated canopies (but not within them), $\overline{u_i}$ is several times larger than any of the fluctuating components, so the u_j and u_k fluctuations contribute only a minor fraction to the fluctuations in u. For a magnitude estimate of the error flux, albeit a slight underestimate, it is sufficient to identify $\overline{w'u'}$ with the momentum flux, which is to say with $-u_*^2$, where u_* is the friction velocity.

In neutral conditions u_* is related to the mean wind speed by

$$u_*^2 = \frac{k^2 u_z^2}{[\ln(z/z_0)]^2}, \tag{13}$$

where u_z is mean wind speed measured at the level of the thermometer, k is von Kármán's constant, and z_0 is the roughness length of the underlying surface. This equation will underestimate u_* in unstable conditions and overestimate it in stable ones. A formula to estimate the error in the sensible heat flux arising from temperature excess is then obtained from (11), with h coming from (2) and (3), and is given by

$$\rho c_p \overline{w'\epsilon'_r} = \rho c_p \frac{k^2 \nu^{0.5} d^{0.5} \overline{u}^{0.5} Ca(1+\alpha)Q}{1.2\lambda[\ln(z/z_0)]^2}, \tag{14}$$

from which the error flux can be estimated. A curious feature of this equation is that though the size of the excess temperature decreases with wind speed, its effect on calculated sensible heat flux increases.

In Fig. 6 the excess temperature, for the original as well as for the painted wire, has been depicted as a function of the wind speed for two ratios of z/z_0. From this result we conclude that the error is relatively small and increases with increasing surface roughness. It must

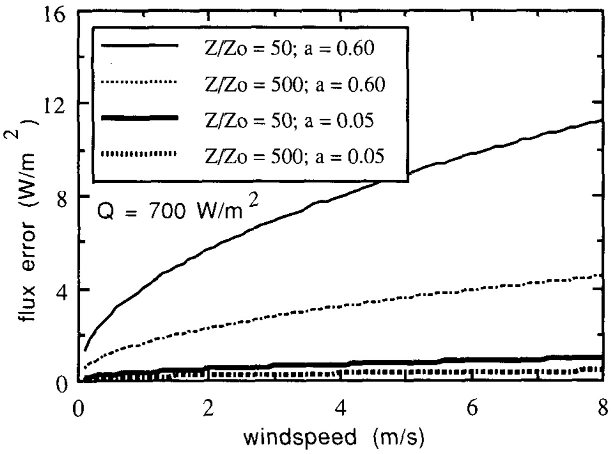

FIG. 6. The flux error under outdoor circumstances when the incoming global radiation is $Q = 700$ W m^{-2} and the terrain parameters are $z/z_0 = 500$ (smooth terrain) and $z/z_0 = 50$ (rough terrain). Data are plotted for the unconditioned wire ($a = 0.60$) and for the painted wire ($a = 0.05$).

be noted that the present results are for neutral conditions, which means that this result is an underestimate in unstable conditions because unstable conditions will modify the equation for mean u, (13), in such a way as to increase u_* for a given wind speed.

It is recognized that (14) is an underestimate of the error flux in unstable conditions because of the approximations involved in the derivation. To provide some check that (14) is able to provide good estimates of the error flux, calculations have been made using (11) directly and measurements of fluctuations in all the wind components for very unstable conditions. Though these investigations were not systematic, they confirm that (14) is an underestimate of the error flux, by 50% or more on some occasions. However, we believe that (14) remains valid as a simple guideline for evaluating the significance of excess temperature errors in heat flux measurements.

6. Effect of excess temperature errors on temperature variance measurements

Measurements of temperature variance can be used to calculate the sensible heat in a relatively simple way (Tillman 1972; De Bruin 1982; Lloyd et al. 1994; De Bruin et al. 1993). Therefore we investigate the effect of the excess error on the temperature variance and so on the calculated sensible heat flux.

Tillman (1972) suggested that there exists a relation between the sensible heat flux H and the temperature variance σ_T^2. From this relationship it is easy to show that the relative errors in both terms are related by

$$\frac{\Delta H}{H} = \frac{3}{2}\frac{\Delta\sigma_T}{\sigma_T}. \qquad (15)$$

where ΔH and $\Delta\sigma_T$ are errors in sensible heat and temperature variance, respectively.

As before, we can derive an equation plus error term for the measured temperature variance in terms of the real variance by squaring (6) substituting for ϵ_r' using (8) and then averaging over time. The result is

$$\sigma_{T_m}^2 = \sigma_T^2 + 2\overline{T_a'\left(\frac{\partial\epsilon_r}{\partial u}u' + \frac{\partial\epsilon_r}{\partial Q}Q'\right)} + \overline{\left(\frac{\partial\epsilon_r}{\partial u}u' + \frac{\partial\epsilon_r}{\partial Q}Q'\right)^2}, \qquad (16)$$

from which we obtain an expression for the error in the measurement of the temperature variance:

$$E_{\text{tot}}^2 = \left(\frac{\partial\epsilon_r}{\partial u_r}\right)^2\sigma_u^2 + 2\frac{\partial\epsilon_r}{\partial u_r}\overline{u'T_a'} + \left(\frac{\partial\epsilon_r}{\partial Q}\right)^2\sigma_Q^2 + 2\frac{\partial\epsilon_r}{\partial Q}\overline{Q'T_a'} + 2\frac{\partial\epsilon_r}{\partial u}\frac{\partial\epsilon_r}{\partial Q}\overline{u'Q'}$$

$$= \underset{\text{(error 1)}}{(E_1^2)} + \underset{\text{(error 2)}}{(E_2^2)} + \underset{\text{(error 3)}}{(E_3^2)} + \underset{\text{(error 4)}}{(E_4^2)} + \underset{\text{(error 5)}}{(E_5^2)}. \qquad (17)$$

It is interesting to find out which terms in this equation are most important. However, under steady irradiation conditions the radiation variance, σ_Q^2, and radiation covariance terms $\overline{Q'T_a'}$ and $\overline{u'Q'}$ can be neglected and we may restrict ourselves to the first two terms. Moreover, concerning error 5, we may suspect that this term can be neglected due to poor correlation between u' and Q'. To compare the remaining two terms we express the latter equation in dimensionless form by dividing (17) by σ_T^2.

In the free convection state, σ_T is related to the sensible heat H according to (Tillman 1972)

$$\sigma_T = c_1\left(\frac{H}{\rho c_p}\right)^{2/3}\left(\frac{T_a}{gz}\right)^{1/3}, \qquad (18)$$

where g is gravity, z is height, and c_1 is a constant. If we assume that $\sigma_w \approx \sigma_u$, (Tennekes and Lumley 1983), a good estimate for σ_u is

$$\sigma_u = u_* c_2\left(\frac{z}{L}\right)^{1/3} = u_* c_2\left(\frac{gzH}{\rho c_p T_a u_*^3}\right)^{1/3} = c_2\left(\frac{gz}{T_a}\right)^{1/3}\left(\frac{H}{\rho c_p}\right)^{1/3}; \qquad (19)$$

where c_2 is a constant, L is Obukhov's stability parameter, and we arrive at the variance ratio in error 1:

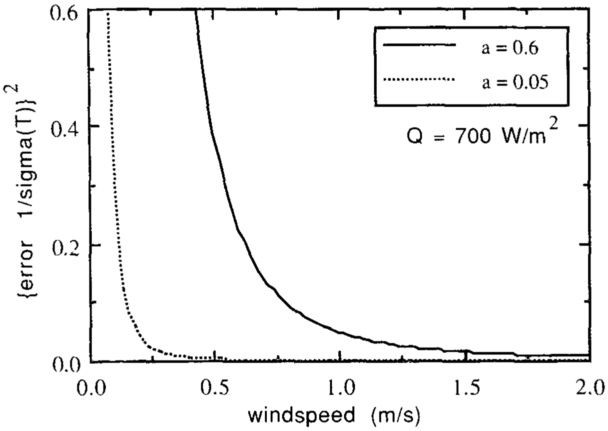

FIG. 7. The contribution of error 1 (E_1^2/σ_T^2) to the total variance error (E_{tot}^2/σ_T^2) for the unconditioned wire (a = 0.60) and for the painted wire under a radiation load of Q = 700 W m^{-2} and for a measurement height of 3 m.

$$\frac{\sigma_u^2}{\sigma_T^2} = \left(\frac{c_2}{c_1}\right)^2 \left(\frac{gz}{T_a}\right)^{4/3} \left(\frac{\rho c_p}{H}\right)^{2/3}. \qquad (20)$$

Error 1 can be estimated by using (20), (16), and (10). In Fig. 7, this error has been depicted for the unpainted (a = 0.60) and painted ribbon (a = 0.05) under a radiation load of 700 W m^{-2} and for a measurement height of 3 m. Moreover, in order to get an estimate for the sensible heat H, it has been assumed that 50% of the irradiation is transformed into sensible heat that is high and probably will lead to an overestimated error. From this result we conclude that error 1 under low wind speed conditions (u < 1 m s^{-1}) can be extremely high for the unpainted wire and that it is then necessary to take additional measures to reduce this error. Such a reduction can be attained by painting the ribbon as can be inferred from the same Fig. 7.

The second term can be worked out in the same way. However, a difficulty arises to find an estimate for the covariance term $\overline{u'T'_a}$. On average, this correlation has, roughly speaking, the same magnitude as the correlation term $\overline{w'T'_a}$ as can be inferred from Fig. 8. With this assumption we find the estimate for the ratio $\overline{u'T'_a}/\sigma_T^2$:

$$\frac{\overline{u'T'_a}}{\sigma_T^2} = \frac{1}{c_1^2}\left(\frac{gz}{T_a}\right)^{2/3}\left(\frac{\rho c_p}{H}\right)^{1/3}. \qquad (21)$$

Error 2 can be estimated by using (21), (16), and (10). In Fig. 9 this error has been depicted under the same conditions as error 1. We conclude that error 2 dominates error 1 and that this error is very serious even under moderate wind speed conditions (u < 3 m s^{-1}). It also can be concluded from this figure that this error also can be reduced considerably by painting the ribbon. Only under extremely low wind conditions

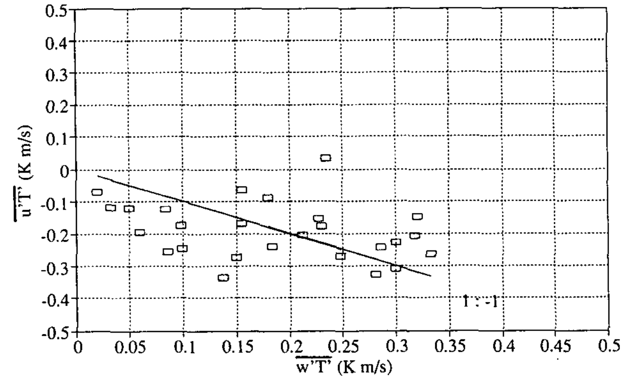

FIG. 8. The relation between the covariances $\overline{w'T'_a}$ and $\overline{u'T'_a}$ as measured during the EFEDA experiment in Spain 11 June 1991.

(u < 0.25 m s^{-1}) does this error become unacceptably high.

7. Conclusions

From the foregoing, we can draw the following conclusions:

(a) A mechanically strong, fast-response thermocouple thermometer can be constructed simply by flattening a wire.

(b) The excess temperature due to shortwave irradiation interception is considerably increased by flattening the wire. This excess can be reduced by coating the wire with white paint. Outdoor experiments showed that cleaning and recoating the wire every second week is sufficient.

(c) In normal field conditions this excess temperature error can be reduced considerably depending on the orientation of the wire with respect to the direct

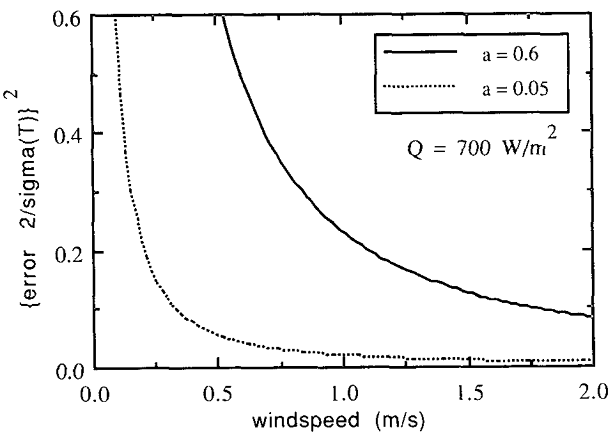

FIG. 9. The contribution of term error 2 (E_2^2/σ_T^2) to the total variance error (E_{tot}^2/σ_T^2) for the unconditioned wire (a = 0.60) and for the painted wire under a radiation load of Q = 700 W m^{-2} and for a measurement height of 3 m.

radiation beam. In our field studies we installed the wire vertically in such a way that at noon the smallest side of the wire faced the direct sunbeams so that the error did not exceed 15% of the possible maximum error.

(d) Excess temperature errors in a thermometer used in eddy correlation measurements can cause errors in the calculated sensible heat flux. These errors should not exceed 5 W m^{-2} for our thermometer design if care is taken to maintain the reflective white paint on the thermometer.

(e) If the present unconditioned sensor is used in temperature variance measurements, large errors can occur especially under very low wind conditions. Additional precautions have to be executed in order to reduce this error. By using a coating of very efficient reflected paint, this error can be considerably reduced.

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