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Published in:
Measurement Science & Technology

DOI:
10.1088/0957-0233/2/1/004

Meas. Sci. Technol. **2** (1991) 26–31. Printed in the UK

A rigid fast-response thermometer for atmospheric research

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Received 7 December 1989, in final form 17 September 1990, accepted for publication 25 September 1990

Abstract. A fast-response temperature sensor for measuring atmospheric temperature was constructed and is described. The sensor was based on the thermocouple principle, connected to a thermocouple conditioner (AD595): the cold junction was compensated via an electrical reference and the signal amplified. This reference compensation was built into the sensor itself.

The time constant of the thermocouple was decreased by rolling out a circular wire. The advantage of this technique was that the original mechanical strength was retained. The disadvantage was that the excess temperature could increase due to a higher interception of global irradiation. It appeared that by reducing the time constant by a factor of five, the radiation error could be increased by a factor of two, depending on the orientation of the sensor head and the angle of attack of the incoming direct radiation beam.

The mean temperatures measured by the sensor were compared with those measured by an accurately calibrated Pt 100 resistance thermometer. The agreement between both sensors for outdoor measurements gave a standard error of estimate of 0.20 K.

The fast outdoor temperature excursions around the running mean, measured by the sensor, were compared with those measured by a fast-response sonic thermometer. The agreement of the temperature variances between both sensors was better than 2% (standard error of estimate 0.05 K) and was dependent on measuring height and mean windspeed. The 3 dB point of the instrument was about 2 Hz.

1. Introduction

Temperature sensors are the most common sensors used in meteorological practice and research. Here, not only the mean atmospheric temperature is important but often also the temperature variance of the flow medium. In the first application, a slow-response sensor is desired where a time constant of about 90 s (for example for a normal spirit-in-glass thermometer) is commonly used (World Meteorological Organization 1988). In the latter application, a fast-response sensor is needed where the desired time constant is dependent on the goal of the measurement program, the measuring height in the atmosphere and the mean windspeed (McBean 1972).

In many micrometeorological applications the turbulent transports of heat, mass and momentum are pursued by using the so-called eddy correlation technique (McBean 1972, Tennekes and Lumley 1983, Krovetz *et al* 1988). Here, fast measurements are taken near the earth's surface and as a rule of thumb we may say (see also later) that a time constant of the instrument is desired better than 0.1 s.

The present paper reports on a fast-response thermometer sensor that can measure the atmospheric mean temperature as well as fast excursions from the mean. *The sensor is based on the thermocouple principle* and has been designed for atmospheric use. The instrument has been designed to measure the mean air temperature to within ± 0.2 K and the temperature fluctuations to within ± 0.05 K.

2. Theory

The fast-response sensor uses a Manganine/Constantan thermocouple, the wires of which are 0.1 mm in diameter. The 'hot junction' is resistance welded under a microscope. To decrease the thermal time constant, the junction region is rolled out to a thin flat strip of about 0.02 mm thickness 0.4 mm width. The flattened wire is led via a V-shape support to the Manganine/Constantan connections of the thermocouple conditioner (see top of figure 1). The advantage of this technique is that the rigid wire keeps its mechanical strength. This

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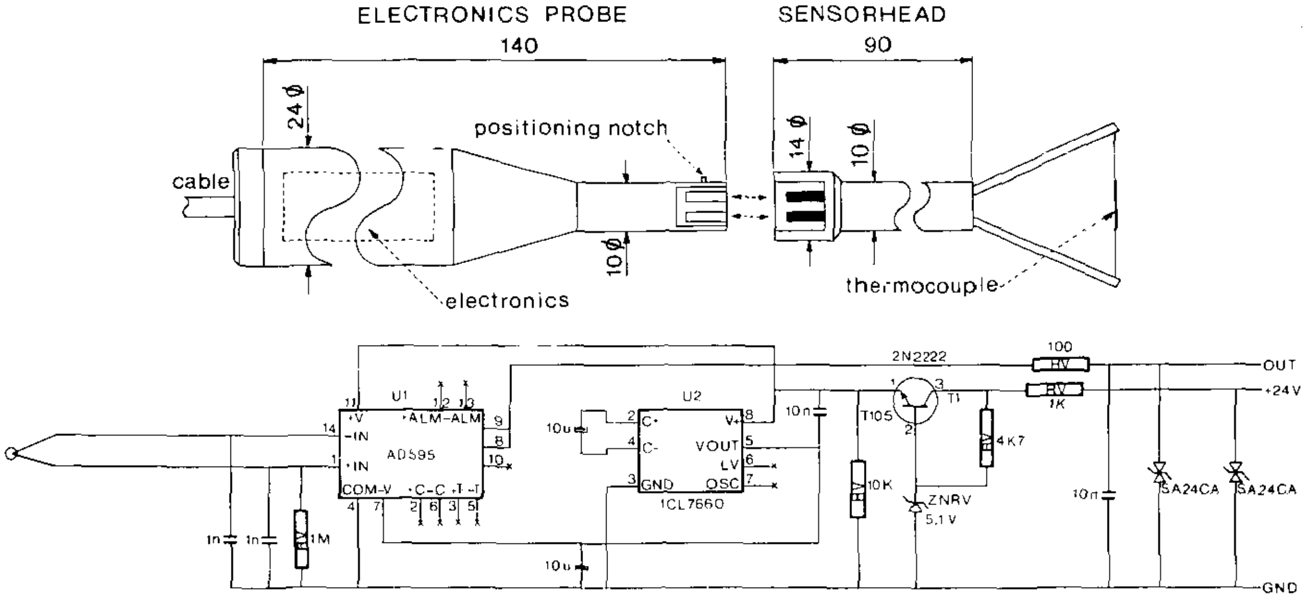

Figure 1. Top: outline of the mechanics of the fast-response thermometer design. Arrowed on the right is the sensor head and on the left is the electronic housing. The broken arrow points to the 'hot junction'. Bottom: outline of the electronic layout of the fast-response thermometer. The sensor head is connected to the electronics probe via a copper constantan two-pin connector.

can be very useful when reliable continuous measurements are desired under various atmospheric conditions. Also, it can be very useful in special atmospheric applications as in, for example, wind erosion studies in dry regions or in plant canopy studies. The disadvantage of the technique, however, can be that the radiation interception is enhanced, which increases the radiation error (see later).

In outdoor experiments the leads to the sensors can be relatively long (> 100 m) and hence can be a source of trouble for the low-level signals. To overcome this potential source of error, and to avoid having to set up a reference temperature for the thermocouple, a cold-junction electronic reference (AD595) has been built into the probe. The AD595 (Analog Devices 1988) is a complete instrumentation amplifier and cold junction compensator on a monolithic chip, and produces a high level (10 mV °C^{-1}) output directly from a thermocouple signal. The electronic layout of the design has also been presented in figure 1.

The manufacturer of the AD595 says that the so-called drift error envelope of the electronics of the AD595, i.e. the accuracy of the cold junction compensation, is better than +0.6 K, and the error caused by self heating less than +0.065 K in still air. If the thermometer is used to estimate the sensible heat using the eddy-correlation technique, in which the temperature fluctuation only is needed, no additional calibration is necessary. However, if accurate mean atmospheric temperatures are desired, the error envelope can be better replaced by an individual calibration curve per sensor, by which the error will be reduced considerably.

To avoid flow interferences between the thermometer sensor and other sensitive instruments, (for example a fast-response anemometer) the housing is aerodynamically streamlined.

The properties of the thermocouple materials used in the design are very homogeneous, and the construction process of the sensor heads well reproducible. Differences in various sensor heads are small in comparison to inaccuracies in the electronic processing of the signals. This yields the advantage that the sensor heads are easily interchangeable in the field without a time consuming recalibration.

In atmospheric turbulence the thermal characteristics are important, and consequently in outdoor experiments the dynamic response of the sensor. For example, to measure the RMS value of the temperature correctly, the spectral distribution must lie within the band width of the measuring system. From analysis of McBean (1972) we can conclude that for steady-state conditions and homogeneous terrain, the cut-off frequency of the instrument in dimensionless form, $f_c = n_c z u^{-1}$, must be at least 5 in order to cover completely the range of frequencies required (n_c is the cut-off frequency, z the measuring height and u the mean windspeed). If an error of 5% is accepted, f_c must be at least 1. In figure 2, the maximum frequency of the temperature fluctuation, n_{max}, has been depicted versus the mean windspeed for complete frequency cover and for acceptance of a 5% error. Here, the measuring height was 2 m, which is very common in micrometeorological practices.

The thermal time constant, τ, of the sensor is dependent on the thermal properties of the material used, the geometrical shape of the sensor and the windspeed which reads (Fritschen and Gay, 1979)

$$\tau = cV/A\,h \tag{1}$$

where c is volumetric heat capacity, V is the volume, A is the area and h is the convective heat transport coefficient, which is highly dependent on the windspeed. The convective heat transport coefficient is mostly

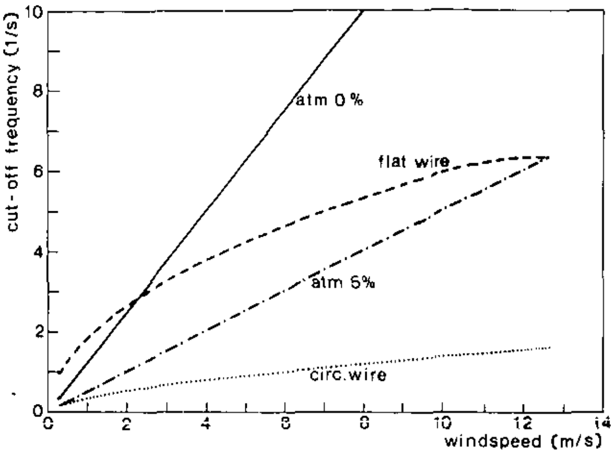

Figure 2. The maximum frequency of the atmospheric temperature fluctuations at a height of 2 m above a horizontally homogeneous terrain, if 0% error is accepted (full line) and if 5% error is accepted (broken line). Also shown are the cut-off frequencies of the circular fast-response sensor head (........ circular wire) and the improved flattened fast-response sensor head (----- flat wire).

expressed in dimensionless form, by the Nusselt number, $Nu = hd/\lambda$, where d is a length scale of the sensor and λ is the molecular thermal diffusivity of still air. For a flat strip the Nusselt number equals (Ede 1967, Jacobs and Welgraven 1988)

$$Nu = 0.60Re^{0.5} \qquad \text{for } Re < 2 \times 10^4$$
$$Nu = 0.032Re^{0.8} \qquad \text{for } Re > 2 \times 10^4 \qquad (2)$$

where Re is the Reynolds number, $Re = ud/v$, in which d is the width of the sensor and v is the kinematic viscosity. From equations (1) and (2) the cut-off frequency, $n_c = 1/2\pi\tau$ of the sensor head can be estimated and the result of this has been depicted in figure 2 together with the cut-off frequency of the original circular wire.

From the results of figure 2 it can be inferred that, if the aforementioned assumptions are reasonable, the sensor must sense the temperature fluctuations correctly up to a windspeed of circa 2.4 m s^{-1} and that in the range 2.5–13 m s^{-1} the error is less than 5%. Moreover, figure 2 clearly indicates the improvement of the cut-off frequency and the consequent time constant by flattening the original wire. Roughly speaking, it can be concluded that the time constant is reduced by about a factor of 5 over the presented windspeed range.

The disadvantage of the present design is the enhanced radiation interception that increases the radiation error. To obtain an estimate of the excess temperature, $\varepsilon_r = T_w - T_a$, where T_w is the wire temperature, and T_a the ambient air temperature, model calculations have been carried out for the circular wire as well as for the flattened one. Here, the following simplified expression has been used (Fritschen and Gay 1979):

$$\varepsilon_r = \frac{CaQ_g(1+\alpha)}{4\varepsilon\sigma T_a^3 + h} \qquad (3)$$

where Q_g is the global irradiation, a the absorption coefficient of the wire, α the albedo – the mean reflection coefficient for short wave radiation of the underlying surface – ε the emissivity of the wire, C the ratio between the diameter and the outline of the wire ($C = 1/\pi$ for the circular wire and $C = 1/2$ for the flat wire), and σ the Stefan–Boltzmann constant. In this formula it has been assumed that the orientation of the strip is perpendicular to the incoming direct short wave irradiation, hence the interception of the short wave radiation is maximal and consequently also the excess temperature. The radiation error has been plotted for the circular and flat wire in figure 3 for $Q_g = 500$ W m^{-2}, $a = 0.25$ (polished copper (Weast 1970)), $\alpha = 0.20$ (mean value for most vegetated surfaces (Jacobs and Welgraven 1988)) and $T_a = 290$ K. From this result it can be inferred that, on average, the radiation error is increased by a factor of 2. In laboratory tests, it appeared that by welding the junctions the actual absorption coefficient was increased by about a factor of 4. To overcome this negative effect on the excess temperature, the wire was provided with a white, thin reflective coating (Thakur 1989). It should be noted that the estimated radiation error is a maximal value, since in the assessment it is assumed that the maximum radiation interception and the consequent maximum excess error occurred. The radiation error can be considerably reduced if the wire is installed vertically, and in addition if the smallest side of the wire faces the direct sun beam.

In the laboratory, the model to assess the excess temperature has been checked. Under perpendicular irradiation, the model results agreed with the experimental results within 15%. The excess temperature reduced by a factor of 10 when the incoming direct beam was parallel to the widest side of the wire.

Generally, it can be concluded that by flattening the wire, the time constant has been decreased by about a factor of 5 while the maximal possible radiation error will be increased by only a factor of 2.

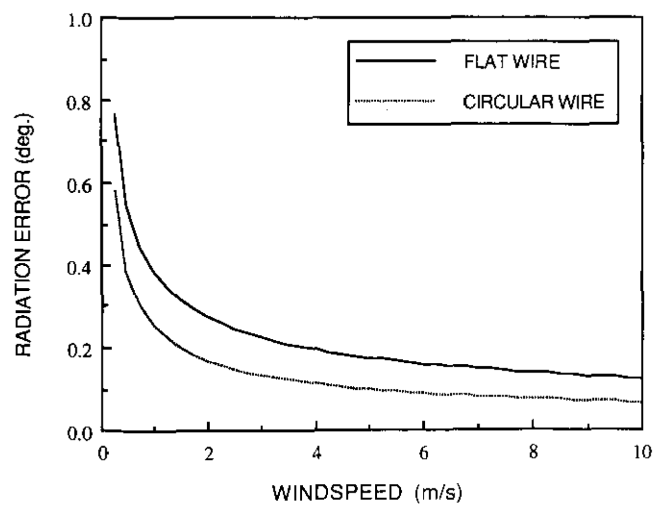

Figure 3. The radiation error versus the windspeed for a circular wire and a flat wire if $Q_g = 500$ W m^{-2}, $a = 0.25$, $\alpha = 0.20$ and $T_a = 290$ K.

3. Laboratory calibrations

For mean atmospheric temperature measurements an individual calibration is necessary due to the absolute error of the AD595, the thermocouple conditioner used in the present design. A simple gain and offset calibration over the temperature range used must be executed in order to obtain an absolute accuracy of at least 0.1 K under laboratory conditions.

Under laboratory conditions, calibrations have been carried out for 11 sensors. Here, the sensors were placed in a cryostat and were compared with an accurately calibrated standard Pt 100 thermometer. The calibration was carried out ranging from 0 to 30 °C. Between the standard thermometer and the individual sensor a linear regression line was fitted, with the result for all sensors that the correlation coefficient was better than $r > 0.9999$ and the standard error of estimate was of the order of 0.06 K.

4. Field experiments

During an outdoor experiment, the sensor was compared with a radiation shielded slow-response aspirated Pt 100 resistance thermometer. Both instruments were installed at a height of 2 m above a corn crop canopy. The results of five days and two nights of the mean temperature of the sensor and the Pt 100 thermometer, averaged over 30 minutes, have been plotted in figure 4. The unbiased linear regression line is found to be $y = 1.001x$ with a linear correlation coefficient $r = 0.999$ and a standard error of estimate of 0.20 K.

To obtain results about the dynamics of the instrument, the standard deviations of the temperature measured by the sensor and a sonic thermometer were compared also, and the result is plotted in figure 5. A Kaijo Denki sonic anemometer/thermometer (type DAT 310 with sensor type Tr-61C) was used, which was

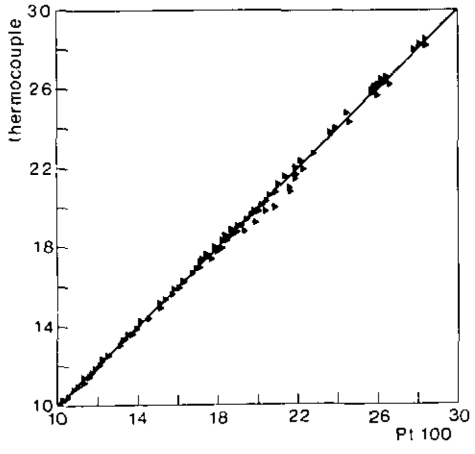

Figure 4. The mean outdoor temperature measured by the sensor compared with an aspirated Pt 100 thermometer. The unbiased regression line has been indicated and equals $y = 1.001x$ ($r = 0.999$, with a standard error of estimate of 0.02 K).

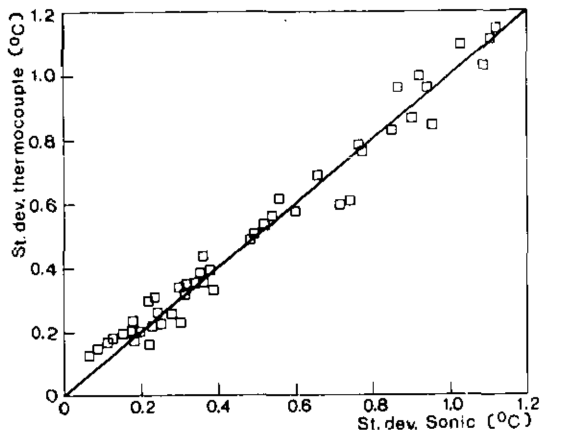

Figure 5. The standard deviation of the outdoor temperature measured by the sensor and compared with the results from the sonic thermometer. The unbiased regression line is $y = 0.986x$ ($r = 0.99$, with a standard error of estimate of 0.05 K).

installed at a height of 2 m above the canopy. In figure 5, data from only two days could be used, since due to instrumental trouble with the sonic system only two days were available. The unbiased linear regression of the scattergram is found to be $y = 0.986x$ with a linear correlation coefficient $r = 0.99$ and a standard error of estimate of 0.05 K.

The sonic thermometer has a path length 0.20 m. By measuring the travelling time for a sound pulse in both directions of this path, the mean speed of sound can be estimated. This speed is a function of the so-called virtual sound temperature, T_{vs}, (Kaimal and Businger 1963, Schotanus *et al* 1983) according to

$$c^2 = \gamma R T_{vs} \qquad T_{vs} = T(1 + 0.51q) \tag{4}$$

where, γ is Poisson's constant, R is the specific gas constant for dry air and q is the mean specific humidity. Corrections to the results were made by measuring the mean dry and wet bulb temperatures with an aspirated psychrometer.

Also, the temperature fluctuation measured by a sonic anemometer/thermometer is affected by the humidity of the ambient air (Kaimal and Businger 1963, Schotanus *et al* 1983) according to

$$T'_{vs} = T' + 0.51 T q' \tag{5}$$

where T' is the actual temperature excursion from the mean, T'_{vs} is the temperature excursion from the mean as measured by the sonic system and q' is the actual humidity excursion from the mean. Corrections to results were made by measuring the humidity using a Ly-α absorption hygrometer.

In figure 6 the smoothed atmospheric spectral variance, S_{TT}, of the temperature as measured by the sensor and the sonic thermometer are given on a normalized log–log plot. Moreover, in this graph the atmospheric high-frequency $-\frac{2}{3}$ power law (corresponding to the Kolgomoroff $-\frac{5}{3}$ law (Tennekes and Lumley 1983)) has been depicted. From this result it is suggested that the

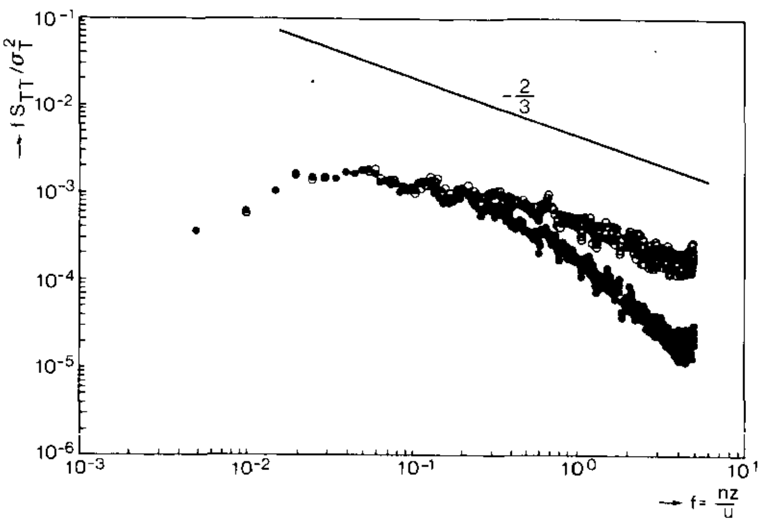

Figure 6. The atmospheric spectral variance of the temperature as measured by the sensor (full circles) and the sonic thermometer (open circles). The $-\frac{2}{3}$ high frequency behaviour, corresponding to the $-\frac{5}{3}$ Kolgomoroff law, has also been indicated. The spectra were observed at a height of 2 m above a corn crop canopy, with a mean windspeed of 2.25 m s^{-1}.

sonic instrument follows the $-\frac{5}{3}$ law rather closely; hence it approximates the true atmospheric high frequency fluctuations correctly, whereas the thermocouple sensor shows a steeper slope and starts to drop at about 0.5 Hz.

The difference in area between both graphs is a measure of the relative error, ε_w, made in estimating the variances and equals (McBean 1972):

$$\varepsilon_w = \int_{n_L}^{n_H} \frac{(nS_{TT}^{s} - nS_{TT}^{th})}{\sigma_T^2} \, d(\ln n) \qquad (6)$$

where σ indicates the true variance, subscripts L, H and T stand for low, high and temperature, respectively, and superscripts s and th stand for sonic and thermocouple, respectively. From the particular example of figure 6, the error, ε_w, can be easily estimated and yields $\varepsilon_w = 0.1\%$, which is small, as must be expected from figure 2. Moreover, from figure 6 it can be inferred that the 3 dB point of the sensor is about 2 Hz.

5. Conclusions

From the foregoing, we can draw the following conclusions:

- In a relatively simple way, by flattening a wire, a relative, strong fast-response thermometer, based on the thermocouple principle can be constructed.

- The excess temperature due to short wave irradiation interception can be increased by flattening the wire. Relatively speaking, the rate of decrease in response time is much higher than the possible rate of increase of the excess temperature.

- In order to reduce the so-called drift error envelope of the electronics of about 0.6 K, an indoor calibration for each sensor has to be executed.

- With the sensor, the mean air temperature can be estimated accurately with a standard error of 0.2 K. This result meets the standard of 0.2 K required by the World Meteorological Organization (WMO-no 8, TP 3).

- With the sensor, the temperature variance of the outdoor turbulence can be estimated within a standard error of 0.05 K. For most daytime temperature variances, this result is acceptable.

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