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ON THE MEASUREMENT OF AIR TEMPERATURE IN THE PRESENCE OF STRONG SOLAR RADIATION

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Abstract

The energy balance of small temperature sensors was modeled to illustrate the effects of sensor characteristics, particularly size, on the accuracy of readings in the presence of strong radiant loads, either of short or long wavelengths. For all but extremely small sensors, radiant exchange may lead to unacceptable errors. The common practice of using passively ventilated instrument screens was evaluated experimentally, indicating that differences resulting from the use of different models of shields may be an order of magnitude greater than the error resulting from sensor calibration. In the absence of technological innovation capable of reducing the error due to radiant exchange to negligible proportions, it is suggested that a standard methodology for calibrating and labeling the error resulting from the characteristics of the screens be adopted.

Key words: temperature measurement, radiant exchange, Stevenson screen

1. INTRODUCTION

The effects of radiant exchange on thermometer readings of air temperature were recognized over 150 years ago, and eventually led to the design of the Stevenson screen in 1864. This white wooden cupboard has since become the standard instrument screen, whereby indirect ventilation is provided through the bottom, double roof and louvered sides, and thermometers placed within it give a close approximation to the true air temperature, undisturbed by the effects of direct solar or terrestrial radiation. However, the Stevenson screen is unsuitable for many applications: It is too bulky to be portable; it is too large for measurements in confined spaces; it is too obtrusive to be installed in locations accessible to the public; it may be considered too expensive when a large number of screens is required for simultaneous measurements in different locations; and it does not give full protection from radiant exchange (WMO, 1971). Many other thermometer screens have been shown to introduce measurement error, too (Sparks, 1972; Andersson and Mathisson, 1992; Van der Meulen, 1998), so where electric power is available, aspirated sensors may be preferable: they can provide extremely accurate temperature readings. However, while aspirated sensors may be more accurate than non-aspirated ones, they are expensive, and their dependence on electric power is a limitation.

A variety of instrument screens are currently available. However, while temperature sensors are generally calibrated carefully and their accuracy is specified in most research papers, there is no standard procedure for assessing the effect of instrument screens on radiant exchange, and hence on the accuracy of the resulting readings. Furthermore, although changes in instrumentation (including screen) at a meteorological station are usually accompanied by a homogeneization procedure, comparison of data from non-adjacent stations using different types of screens is troublesome and prone to error.

The importance of making accurate readings of air temperature in diverse environments is highlighted in the case of urban climatology, particularly the measurement of urban heat islands. In such studies, the use of identical instrumentation does not guarantee that results are comparable, because measurements are carried out in environments that are inherently different, not least in exposure to solar radiation.

2. THEORETICAL ANALYSIS

A sensor measuring air temperature may be regarded as a node that exchanges heat with the surroundings by radiation and convection. Its temperature may be calculated from the following heat balance equation (assuming that the size and mass of the sensor are sufficiently small that internal temperature gradients can be neglected):

$$\alpha_{ir}\sigma(T_{mrt}^{4}-T_{s}^{4})+h_{c}(T_{a}-T_{s})+q_{solar}^{"}\alpha_{solar}=0 \quad (1)$$

where α_{ir} and α_{solar} are the infrared and solar absorptivity of the sensor, respectively; σ is the Stefan-Boltzmann constant (approx. $5.67 \cdot 10^{-8}$ W/m^{2}K^4); T_s, T_{mrt} and T_a [K] are the temperature of the sensor, the mean radiant temperature of the environment and the air temperature, respectively; h_c is the convective surface heat exchange

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coefficient [W/m^{2}K]; and q''_{solar} [W/m^2] is the area-averaged solar radiation flux incident over the entire surface of the sensor (which can be computed from the direct normal radiation and the diffuse radiation).

The temperature that the sensor gives us is T_s, while the temperature we would like to know is T_a.

The convective heat exchange at the surface of the sensor cannot be exactly described analytically. However, an estimate can be obtained assuming that the sensor is a small sphere, using Whitaker's correlation for forced convection (Incropera & De Witt, 1996). The expression for forced convection is appropriate since the movement of the air is not provoked by the sphere itself.

$$Nu_D = 2 + \left(0.4\,\mathrm{Re}_D^{1/2} + 0.06\,\mathrm{Re}_D^{2/3}\right)\mathrm{Pr}^{0.4}\left(\frac{\mu}{\mu_s}\right)^{1/4} \qquad (2)$$

where Re is the Reynolds number; Pr is the Prandtl number (about 0.7 for air at ambient temperature); μ the viscosity of air; and μ_s the viscosity of air in the boundary layer near the sensor surface. Assuming that the difference in temperature between the sensor and its surroundings is relatively small (say, less than 10K), $(\mu/\mu_s)^{1/4}$ is approximately unity. The Nusselt number in this case is thus a function of the Reynolds number only. While ν is related to fluid temperature, the change is small over the normal range of ambient air temperature, so for our purposes the Reynolds number depends mainly on the velocity of the flow and on the sphere diameter. The surface heat exchange coefficient h_c is found from the Nusselt number:

$$h_c = \frac{Nuk}{L} \qquad (3)$$

where k is the thermal conductivity of the air and L is the diameter of the sphere.

The error due to solar radiation alone may be assessed assuming that the surrounding surfaces are at the same temperature as the sensor, so there is no net long wave radiant exchange. Similarly, the error due to long wave radiation can be assessed in the absence of solar radiation. In both cases, radiant energy absorbed exactly equals heat loss by convection, and the error, derived from equation 1, is the difference

$T_s - T_a = \dfrac{q''_{solar}\alpha_{solar}}{h_c}$ for solar radiation, and $T_a - T_s = \dfrac{\alpha_{ir}\sigma(T_s^4 - T_{mrt}^4)}{h_c}$ for long wave radiation.

Figure 1 shows the predicted measurement error due to solar radiation on a spherical sensor 1mm in diameter, assuming solar absorptivity α=0.5, and no net long wave exchange with the surroundings. (The values for solar radiation are the area-averaged flux over the whole area of the sensor, so a value of 500W/m^2 corresponds to a very high level of radiation, resulting from a combination of beam radiation equal to 1000W/m^2 and diffuse radiation of 250 W/m^2, for instance). The need for a radiation screen is evident: At low wind speeds (U<3m/s), the error resulting from solar radiation is 1-3K.

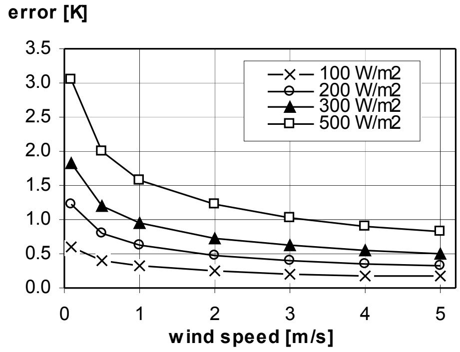

Figure 1: Effect of radiant load

Equation 3 above indicates that sensor size has a great effect on the surface heat exchange coefficient h_c, and thus on convective heat loss. Figure 2 illustrates the effect of sensor size on the error resulting from an area-averaged solar radiation flux of 300W/m^2, in the absence of net long wave exchange. The sensor is assumed to be spherical and has a solar absorptivity of α=0.5. The advantages of small sensor size are obvious: extremely small sensors, such as thermocouples constructed of very fine wire, may have an error of only 0.3-0.5K even when exposed to intense solar radiation.

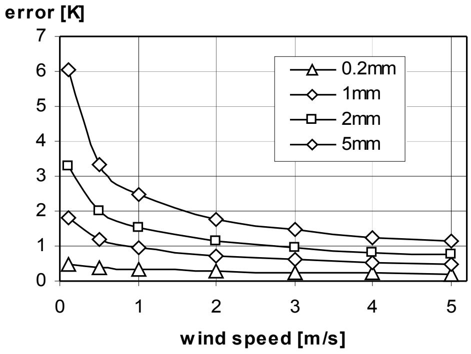

Figure 2: Effect of sensor size

Unless the sensor is exposed to an unusually hot surface in close proximity to it, the effect of long wave radiation on measurement of air temperature is likely to be largest on clear, dry nights with little or no wind, when the mean radiant temperature a sensor is exposed to may be 10-15K below air temperature. The magnitude of the error is substantially smaller than that caused by solar radiation – less than 1K for most sensor diameters if there is even a light wind. However, since wind speed at night is often quite low, the error should not be neglected unless sensor size is very small.

3. EXPERIMENTAL EVALUATION

Copper-constantan thermocouples with a wire diameter of about 0.5mm and junction diameter of about 1.2mm were used to measure air temperature in a location exposed to the sun and under an adjacent shed open on all sides, exposed to diffuse radiation only. In a period with light wind ($\bar{u}$=3m/s), global radiation of about 570W/m^2 and diffuse radiation of only 70W/m^2, the exposed sensor showed a temperature that was about 2.2K warmer, but was about 0.3K cooler at night.

The performance of a variety of instrument screens was then evaluated by comparison of concurrent temperature readings from sensors in these screens and in a standard Stevenson screen. Two commercial screens were included in the sample: This selection is of course by no means exhaustive - it was merely intended to illustrate the differences in temperature readings even in screens produced by the same manufacturer. The thermistors used in this case, though small, were substantially larger than the TC used previously: they are disc-shaped, with a diameter of 3mm and thickness of about 1.5mm. The sensors have a dark maroon color, with an estimated solar absorptivity of 0.7.

Designs for jury-rigged thermometer screens

The makeshift screens tested may be classified into three general categories (below), according to the means of providing the sensor with ventilation. Additional variations included the type of exterior finish (glossy white or aluminum foil), and modifications to the basic form to improve protection from direct radiation:

- *Vertical pipes* (cases 1-9): 50mm or 75mm PVC (or cardboard) pipes, with T-section at top. Some variants had a second external 110mmm pipe, creating a double-barreled screen. Exterior finish - aluminum foil or glossy white paint. This type of screen was expected to allow efficient convective air flow, but less exposure to horizontal flow (wind).
- *Horizontal pipes* (cases 10-12): 75mm PVC pipes 50cm long; External finish – aluminum foil or glossy white paint. One variant had lightweight cardboard louvers added to both ends. This type of screen was expected to allow efficient exposure to wind, but relatively poorer exposure to vertical flows.
- *Multi-plate gill-type* (cases 13-14): Inverted plastic bowls with the center cut out to create a cavity for the sensor (except in the top and bottom bowls), attached by means of threaded metal rods, with thin plastic pipes serving as spacers to maintain a 30mm gap for ventilation. Exterior finish: glossy white. Interior: matt black. This type of screen, which is also used in most commercial designs, allows multi-directional horizontal air flow, but restricts vertical flow to a certain extent.

Table 1 summarizes the performance of the various instrument screen in comparison with the Stevenson screen:

Table 1

#	Description of shield	Difference in temp. vs. Stevenson screen [^{o}C]			
		mean	max	min	stdev
1	Vertical pipe: 50mm, T top, white	0.44	2.85	-1.78	1.77
2	Vertical pipe: 50mm, T top, alum foil	0.78	6.76	-1.92	2.15
3	Vertical pipe: 75mm, T top, white	0.80	5.19	-1.69	1.83
4	Vertical pipe: 50mm, T top, insulation + alum foil	0.44	3.77	-1.79	1.52
5	Vertical pipe: 50mm, white, T top & bottom	0.52	3.71	-1.15	1.17
6	Double vertical pipe: internal 50mm, external 110mm, alum foil	0.65	3.76	-1.25	1.32
7	Double vertical pipe: internal perforated 50mm, external 110mm, alum foil	0.45	2.98	-1.63	1.11
8	Double vertical pipe: internal 50mm, external 110mm, alum foil, bottom cone	0.37	2.78	-1.51	1.06
9	Inverted styrofoam cup + alum foil	2.59	10.56	-1.25	3.54
10	Horizontal pipe: 75mm diameter, 500mm long, white	0.33	4.47	-2.06	1.63
11	Horizontal pipe: 75mm diameter, 500mm long, alum foil	0.22	2.25	-1.40	0.77
12	Horizontal pipe: 75mm diameter, 500mm long, alum foil, louvers at both ends	0.87	4.78	-1.10	1.61
13	Gill type: 150mm dia. Inverted bowls, 30mm spacing	0.00	1.76	-1.40	0.65
14	Gill type: 122mm dia. Inverted bowls, 30mm spacing	0.08	2.04	-1.28	0.79
15	Commercial gill - “Type A”: 170mm anodized aluminum	0.40	2.81	-1.30	1.08
16	Commercial gill – “Type B”: 120mm white plastic	0.36	2.38	-1.03	0.87

The mean temperature recorded in the Stevenson screen over a 4-day period in June, 2002 was lower than that recorded in all of the screens tested, with differences of up to 0.80K, except for the inverted Styrofoam cup, which was warmer by an average of 2.59K. While the discrepancy in the average temperature was relatively small, differences in the maximum temperature were substantial, ranging from 1.76K to 6.76K, with the Styrofoam cup again displaying an extreme maximum of 10.56K above the Stevenson screen (Figure 3). Minimum temperatures for all of the screens were, however, 1.10-2.06K lower than that of the Stevenson screen during the test period.

4. DISCUSSION

The magnitude of error resulting from radiant exchange at the surface of temperature sensors is too large to be neglected in most environmental conditions. Regardless, temperature measurements are being carried out in field studies all over the world, using a variety of instrument screens in diverse conditions where the guidelines of the WMO for maintaining meteorological stations (WMO, 1996) cannot be followed systematically. The problem becomes acute when comparative measurements are carried out at non-standard locations, as is often the case in urban climate studies. The use of identical instrumentation at all sites is not sufficient to ensure comparable data, since differences in measured temperature may be the result of varying exposure to radiant exchange the screens are incapable of preventing.

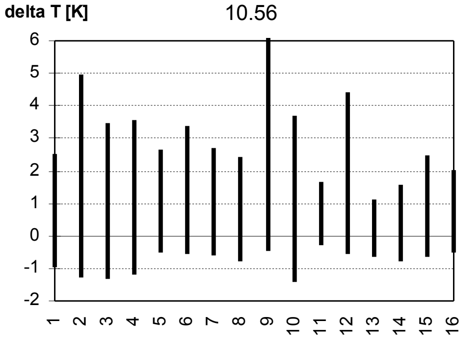

Figure 3: Accuracy of screens

The results of the tests conducted to assess cheap, low-cost thermometer screens indicate that some of the simple designs can provide protection that is the equivalent of that provided by the Stevenson screen or by expensive commercial screens. The following generalizations may be made concerning the designs tested:

- Exposure to horizontal airflow may be more efficient than exposure to vertical flow: The best designs were those that comprised horizontal pipes or gill-plates, rather than vertical pipes.
- The use of shiny aluminum foil at the external surface resulted in lower daytime temperatures than white paint, as illustrated by comparing the two horizontal pipes (#10 and #11), which were otherwise identical. Concurrently, the lower infra red emissivity of the aluminum foil also resulted in higher night-time temperatures, as radiant loss from this shield was less efficient than in the white-painted version.
- Temperature readings in two makeshift gill-type shields were very close to those of commercial screens of simlar construction. However, a simple PVC pipe 50cm long and 75mm in diameter, covered with aluminum foil and suspended horizontally, gave similar readings – and is much easier to construct.

Passively ventilated instrument shields are apparently incapable of providing protection from radiant exchange that is sufficient to ensure highly accurate temperature measurement in all conditions. In the absence of calibration procedures for instrument screens – and sufficiently detailed meteorological information on-site to assess the likely measurement error – the best approach to achieving accurate temperature measurement in the presence of high levels of radiation would appear to be the use of very small sensors. As the analysis in the first part of this article shows, the surface convective heat exchange coefficient depends on the size of the sensor. If the sensor diameter is less than about 0.2mm, the error from full exposure to bright sunshine is estimated to be less than 0.3K, even at very low ambient wind speed. Such small sensors may be suitable for use in restricted spaces where a radiation shield is too bulky, or where the presence of the shield would alter conditions, especially air flow, to an extent that is unacceptable.

5. CONCLUSIONS

Accurate measurement of air temperature in the presence of strong radiation presents difficulties that are not easily resolved. The factors affecting error due to radiant exchange were analyzed, and the importance of sensor size was shown to be critical in this context. A number of alternative designs for instrument screens were evaluated: though none was found to give full protection from radiant exchange, several jury-rigged screens were found to give similar results to some commercial products. Until thermometer screens are developed that eliminate error due to radiant exchange, a universal method of calibration and labelling should be adopted, so that errors in measurement resulting from the response of the specific screen to combinations of environmental factors may be assessed.

References

Andersson T. and Mathisson, I., 1992, A field test of thermometer screens, *WMO No. 462*, p. 436, 1992.

Incropera F. and DeWitt, 1996, *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, Inc.

Sparks, W., 1972, The effect of thermometer screen design on the observed temperature, *WMO No. 315*.

Van der Meulen, J., 1998, A thermometer screen intercomparison, *WMO/TD – No. 877*, p.319.

WMO, 1971, Guide to Meteorological Instruments and Observing Practices, 4th edition, WMO-No.8, Geneva.

WMO, 1996, Guide to Meteorological Instruments and Methods of Observation, 6th edition, WMO-No.8, Geneva.