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AN IMPROVED SIMPLE RADIATION THERMOMETER

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SUMMARY

A simple home-made radiation thermometer and directional radiometer is described, which operates in the full range of the long-wave spectrum. Sensitivity to short-wave radiation is made small by using a white thermocouple as a radiation sensor and a glass shutter as a reference temperature.

Some sources of error in radiation thermometry with the present and other instruments are discussed.

1. INTRODUCTION

In an earlier publication (STOUTJESDIJK 1965) a radiation thermometer was described which performs satisfactorily in the field but has the disadvantage that its field of view is about 40° with a minimum target size of 2.5 cm. Furthermore the instrument is rather slow. The time for full response is 15–20 sec.

In the meantime several radiation thermometers have appeared on the market, some of which are not too heavy for field use.

For ease of operation these direct-reading instruments have considerable advantages over the device described here. However, the direct-reading radiation thermometer has the disadvantage that it is unsuitable as a directional radiometer, e.g. for measuring the heat radiation from the sky (STOUTJESDIJK 1974), as this comes mainly from wavelength bands outside the range transmitted by the filter.

Furthermore, as will be discussed later, measurements of surface temperatures in a narrow wavelength band may have a higher emissivity error than when an instrument is used that senses the full spectrum.

Finally the instrument described here can be used in combination with a general purpose microvoltmeter which may save weight, an important consideration when field work is done in rough terrain.

Therefore, we thought it worthwhile to improve the home-made instrument as regards opening angle and time of response.

2. CONSTRUCTION

The construction of the improved instrument is shown in *fig. 1.* A block of dimensions 6 × 6 × 3 cm consists of an upper part, made of copper containing a glass shutter and a small mercury thermometer. The lower part contains a

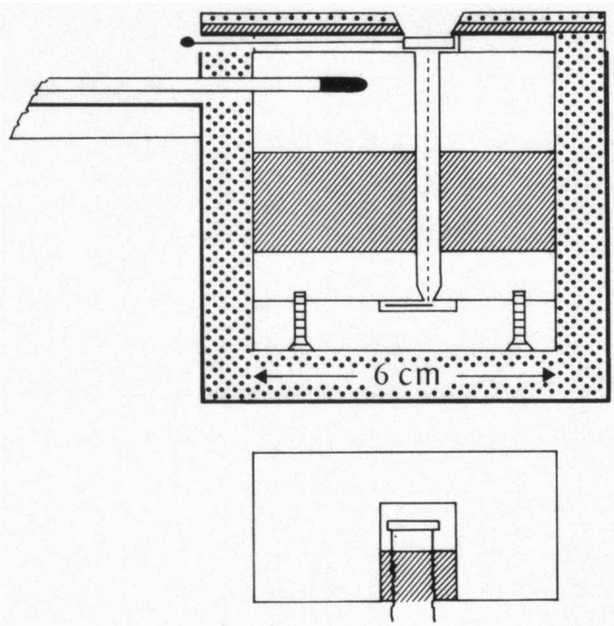

Fig. 1. Longitudinal section of radiation thermometer.
Hatched: perspex, stippled: styrofoam.
The lower part of the figure shows how the thermocouple is mounted, seen from above.

thermocouple as a radiation sensor. For improved thermal stability an isolating layer of perspex is sandwiched between the upper and the lower part. The radiation admitted is defined by a cylindrical bore which is closed by a polythene window 0.02 mm thick. The block is isolated by a layer of styrofoam. The whole is surrounded by an aluminium mantle to which a handle is attached which also protects the thermometer.

As a detector a manganine-tellurium-manganine thermocouple is used. The thermocouple, a thin strip measuring $0.1 \times 2 \times 10$ mm, receives the radiation at one end through a diaphragm with a diameter of 2 mm. With a bore of 5 mm ⌀ and a depth of 5 cm the radiometer has an angle of acceptance of 8 degrees and a minimum target size of about 1 cm. An instrument with opening angle 13 degrees was made as well.

The thermocouple is painted white. With the shutter open resp. closed it absorbs via the upper aperture the following radiation fluxes:
shutter open: $K(\sigma T_1^4 + CR)$
shutter closed: $K\{\sigma T_2^4 + (1\text{–}A)\ CR\}$
σT_1^4, resp. $\sigma\ T_2^4$ are the heat radiation emitted by the surface viewed and by the shutter, R is the diffusely reflected solar radiation, C, resp. A are the absorptivities of the thermocouple and the glass shutter for this radiation. K is a view factor depending on the size and distance of the aperture.

When D_1 and D_2 are the readings of the microvoltmeter we have the relation:
$K\{\sigma(T_1^4 - T_2^4) + ACR\} = P(D_1 - D_2)$. (1)
ACR is the error due to short wave radiation. When R is, e.g., 0.3 cal/cm².min, a common case, A = 0.1 and C = 0.03, ACR = 0.0009 cal/cm².min. As $\sigma(T_1^4 - T_2^4)$ is about 0.008 cal/cm².min for a temperature difference of 1 °C, the error is in this case about 0.1 °C and a correction can be made for it. The shutter was cut from a spectacle glass with antireflection coating.

3. CONSTRUCTION OF THERMOCOUPLE

Pure tellurium has a high specific resistance and rather poor thermo-electric properties (SMITH et al. 1968) and therefore tellurium containing c. 1 % silver + 1 % sulphur was used. Powdered tellurium mixed with 1 % Ag_2S + 1 % S was molten in a quantity of c. 500 mg in a test tube. When the drop of molten material is poured out of the test tube, a thin strip is formed which can be cut to the desired size. The thermo-electric properties of tellurium are improved both by small amounts of silver and sulphur; we found a thermo-electric force of the material used by us of 475 μV/°C.

The connection between the manganine strips and the tellurium was made by means of silver paint. The thermocouple obtained has a resistance of about 60 Ohms.

As mentioned above, the thermocouple is painted white for reducing its sensitivity for short-wave (0.3–2.5 μm) radiation. A good paint is made by a suspension of TiO_2 in amylacetate with a small amount of cellulose cement as a binder. The reflectivity on tellurium was measured by means of a Zeiss spectrophotometer with photometric sphere. Results are shown below.

Wavelength μm	Reflectivity %
0.4	86
0.5	93
0.6	93
0.7	90
0.8	90
0.9	89
1.1	84
1.6	80

4. CALIBRATIONS AND PERFORMANCE

The instrument was calibrated using relation (1), ACR being reduced to zero.

As a black radiator an internally blackened aluminium cylinder was used, surrounded by a water bath with a thermostate. Fifty measurements of the calibration factor over a longer period showed a standard deviation of 1.1 % from

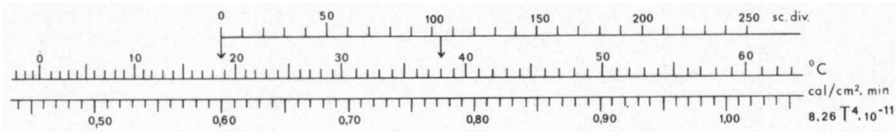

Fig. 2. The lower linear scale shows the heat radiation emitted at the corresponding temperatures of the centigrade scale. When instrument readings with shutter open and closed show a difference of e.g. 104 scale divisions with instrument temperature 18.8 °C we find by means of the upper (moving) scale that surface temperature is 38 °C. The spacing of the upper scale is found by calibration.

the mean. The temperature difference ($T_1 - T_2$) was about 20 °C. Using the mean value of the calibration factor the error of temperature measurements did not exceed 0.5 °C for the instrument with 8 degrees opening angle. With the instrument of opening angle 13 degrees the error did not exceed 0.2 °C. In the field practically the same results were obtained using melting ice as a test target. *Fig. 2* shows how a nomogram can be made for converting measurements rapidly into surface temperatures.

The influence of wind was found to be small. Only with a strong gusty wind readings showed fluctuations round the mean, equivalent to 1 °C for the 8 degree instrument, or 0.3 °C for the wide angle instrument. The low sensitivity to air movement was obtained by inserting a window of polythene foil below the shutter. The absorption data given by FUNK (1959), SCHULZE (1962), and WARTENA et al. (1966) show considerable differences but anyway it may be concluded that polythene of 0.02 mm thickness absorbs only a few per cent of the longwave radiation and that temperature changes of the window can have only a very small effect on the measurement.

The sensitivity of the 8 degree instrument is c. 0.16 μ V/°C for the measurement of surface temperatures, for the 13 degree instrument it is 0.5 μ V/°C. The output of the detector expressed per unit of radiation received is 2.2 μV/μW. The time of response for full deflection is 10 seconds.

To read outputs in the field the best compromise between size, weight, ruggedness, sensitivity and reliability was found to be a micro-voltmeter made from a Knick (Berlin) A3 amplifier in connection with a 600 Ω, 25 microampère taut suspension meter from Gossen (Erlangen). The instrument has a maximum sensitivity of 6.25 microvolt full scale. Including batteries, switches for range and circuit selection and connectors for several sensors including e.g. thermocouples, it can be built in an aluminium box of 18 × 15 × 12 cm with a weight of 1.8 kg.

5. EVALUATION OF MEASUREMENTS

The instrument described has the disadvantage that, for measurement of temperatures, there is an appreciable effect of the air through which the target is viewed. A layer of air of 1 m depth and a vapour pressure of 10 mm absorbs about 8 % of the black-body radiation (MCADAMS 1951). When the air is 10 °C cooler than the surface viewed its temperature is measured roughly 0.8 °C too low. At 25 cm distance the error is about 0.3 °C. Absorption is mainly by water vapour, CO_2 is of less importance at short distances. Fortunately when a high accuracy is needed (leaf temperature), the distance sensor-target can usually be kept small and the difference target temperature – air temperature is often not very high.

With a suitably filtered instrument the absorption bands of H_2O and CO_2 can be avoided but here 'emissivity errors' can be considerable as will be shown.

Natural surfaces often have emissivities below that of a black body. GATES & TANTRAPORN (1962) give data for leaves showing that emissivity is usually close to 1, but especially for leaves with a hard cuticle it may be as low as 0.83 (*Citrus limonia*). BÜTTNER & KERN (1965) give emissivities for several types of rock, sand, and water and discuss some cases of remotely sensed surface temperatures which are obviously too low.

When the emissivity of a surface is less than unity, an error is introduced when its temperature is measured by a radiation thermometer. This error depends upon the spectral characteristics of: the emissivity of the target, the heat radiation from the surroundings, and the sensing instrument. We can illustrate this point by an extreme though not unrealistic example.

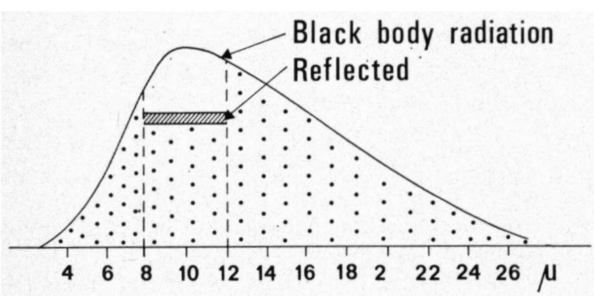

Fig. 3. The area under the "black body" curve shows the heat radiation emitted by a black radiator at about 300 °K. The stippled area gives, schematically, the radiation emitted by a quartz surface at the same temperature. The hatched area represents the sky radiation reflected by the quartz.

In *fig. 3* the emission spectrum is drawn for a black surface and, simplified, for a quartz surface of the same temperature. The heat radiation emitted by the quartz is proportional to the dotted surface, the heat radiation from the black body is proportional to the surface under the black body curve. The heat radiation received by a radiation thermometer is proportional to the black body radiation (R) for the black surface. For quartz it is proportional to the quartz radiation plus the reflected radiation. Under a clear sky this is very small in the wavelength band 8–12 μm as sky radiation is mainly outside this wavelength band. For quartz with a mean emissivity (after BÜTTNER & KERN 1965) of 0.7 in the wavelength band 8–12 μm we calculated that an instrument operating in the same wavelength band receives: $\{0.7 + (1\text{–}0.7)\ 0.2\}$ R. The factor 0.2 arises from the assumption that the sky radiation received in this wavelength range region is about 20 % of the radiation emitted by the quartz surface. To fix thoughts this seems to be a reasonable assumption considering the data given by SLOAN et al. (1955). We find thus that a radiation thermometer in the wavelength band

8–12 μm receives about 76 % of the black body radiation, an instrument operating over the full range shown in the figure would receive 93 %.

The errors introduced in the temperature estimate would be −19 °C and −5 °C, respectively. For quartz sand we calculated 92 % and 98.5 %, respectively and errors of −7 °C and −1.2 °C respectively.

It will be understood that emissivity deficits in ranges where the sky is "warmer" will have a smaller influence on the temperature measurement because of the higher amount of sky radiation reflected.

Furthermore, owing to the shift with temperature of the radiation curve, the percentage of the black body radiation transmitted by the filter must depend on the temperature of the target. A lower emission is erroneously interpreted by the instruments electronic system as a lower temperature and consequently an error will be made in the filter factor used.

We had the opportunity to compare a Heimann KT24 radiation thermometer with the instrument described in this paper. The Heimann instrument has a cutoff filter transmitting wavelengths >8 μm. As a test object window glass was used. The overall emissivity of glass is 0.94 (McAdams 1951). With the Heimann instrument a temperature of −6.0 °C was measured, with our instrument −3.5 °C. When the sky which had an effective radiation temperature of −18 °C was replaced by a large screen, both instruments gave the same reading: −1.5 °C.

The error obtained with the Heimann instrument is higher than can be accounted for by both the effects mentioned, but matters may be further complicated by filters with uneven transmission characteristics.

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