On the Calibration of the Radiometer for Longwave Radiation(I)

—The Case of Net Radiometer—

by

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Abstract

The effects of the environmental wind and temperature fields on the measurement of net flux of radiation by conventional net radiometers are examined. The variation in output of the net radiometer due to the wind field exceeds ten percent for both FUNK's net radiometer ("wind shield-type" net radiometer) and GIER and DUNKLE's net radiometer ("ventilation-type" net radiometer) in the ranges of wind speeds, vertical temperature gradients and incident radiation fluxes concerned. And as for FUNK's net radiometer the more accurate value of net flux of radiation is expected to be obtained in the windy condition rather than in the calm condition.

The devices hitherto available for calibrating net radiometers for longwave radiation are discussed in brief and our new device is presented.

1. Introduction

Enough accuracy is not attained in the measurement of net flux of atmospheric longwave radiation by conventional net radiometers. One of the main reasons for this is the limit to the measurement accuracy proper to the instruments themselves, and another is the difficulty of precise calibration of the radiometers.

The principle of measurement of net flux of radiation by the conventional net radiometer is as follows: The radiation energy incident on each (upper or lower) sensor surface of the net radiometer is converted into heat and as a result the temperature difference between each sensor surface is created due to the difference of radiation energy incident on each sensor surface. This temperature difference is responsible for the measurable thermal electric potential which is proportional to the difference of radiation energy incident on each sensor surface (net flux of radiation). Consequently the measurement of net flux of radiation by the conventional net radiometer is probably affected by the environmental wind and temperature fields which disturb each sensor surface. Although the conventional net radiometers are constructed so as to remove the effect of environmental wind and temperature fields on measurements,

the removal does not seem to be complete. This is one of the sources that limits the measurement accuracy of the conventional net radiometers.

Another limitation to measurement accuracy is due to the difficulty of precise calibration of the net radiometer. Various types of calibration devices for net radiometers in the longwave region have been constructed (FLEISCHER and GRÄFE 1955, FUNK 1961, COLLINS 1968), none of which is free from some defects.

In the present work is discussed the effect of environmental wind and temperature fields on measurements of next flux of radiation by two kinds of conventional net radiometer and our new device for the calibration of net radiometers is presented.

2. The effect of environmental wind and temperature fields on the measurements of net flux of radiation

Consider the radiation fluxes incident on the upper and lower sensor surfaces of the net radiometer (Fig. 1). Then the energy balances of both sensor surfaces are given as follows:

Fig. 1. Schematic diagram of energy balance of the sensor surface.

$$R_1 = A\sigma T_1^4 + \alpha(T_1 - T_a) + \beta(T_1 - T_2) \quad (1)$$

$$R_2 = A\sigma T_2^4 + \alpha(T_2 - T_a) + \beta(T_2 - T_1) \quad (2)$$

$$\begin{aligned} R_N &= R_1 - R_2 \\ &\simeq 4A\sigma T_m^3(T_1 - T_2) + \alpha(T_1 - T_2) + 2\beta(T_1 - T_2) \\ &= k(T_1 - T_2) \\ &= KE \end{aligned} \quad (3)$$

where $k = 4A\sigma T_m^3 + \alpha + 2\beta$ and $T_m = (T_1 + T_2)/2$ and R is the radiation flux, T the temperature of the sensor surface, σ the Stefan-Boltzmann constant, α the heat conductivity of air, β the mean heat conductivity of the sensor base including sensor surfaces, and

the subscripts 1, 2, a and N mean the lower and upper sensor surfaces, the air and the net flux respectively. Furthermore K denotes the conversion factor from the electrical potential, E , to the radiation energy.

It is easily recognized from equation (3) that the output of the net radiometer depends on the environmental wind field because of α 's dependency on wind speed. The conventional net radiometer is, therefore, constructed so as to remove the variation of α due to the wind field either by enclosing the sensor surface in the wind-shield transparent dome ("wind-shield-type" net radiometer) or by the artificial constant ventilation to each sensor surface ("ventilation-type" net radiometer).

We shall examine whether the conventional net radiometer is completely free from the direct or indirect effects of the environmental wind field in recording net flux of radiation. Here we consider FUNK's net radiometer as an example of the "wind-shield-type" net radiometer and GIER and DUNKLE's as an example of the "ventilation-type" net radiometer.

2.1 "Wind-shield-type" net radiometer

In this type of net radiometer, wind influences exerting on the output due to the direct variation of α caused by the wind field do not take place. Instead of this, indirect influences of the wind field take place as shown below.

Fig. 2. FUNK's Net radiometer.

The air is mostly confined inside each dome of FUNK's net radiometer (see Fig. 2). It is, therefore, possible that a temperature difference may take place between the air inside the upper dome and that inside the lower dome. The results of our experiments tend to show that this difference is mainly due to the following two sources:

- (i) the temperature difference between the upper and the lower sensor surface caused by the fact that each sensor surface faces to an object of different temperature,
- (ii) the vertical temperature gradient of the environmental atmosphere.

Taking into account the difference between the air temperature in the upper and lower domes, the energy balance equation for this type of net radiometer is reduced from equations (1) and (2).

$$R_N + \alpha(T_{a1} - T_{a2}) = KE \quad (4)$$

where T_{a1} and T_{a2} denote the air temperatures inside the lower and upper domes respectively. Comparing equation (4) with equation (3), it is recognized that

the additional term $\alpha(T_{a1}-T_{a2})$ appears in equation (4). In the following experiment, it is shown that the additional term (output) is removed or decreased by the environmental wind field. The removal or decrease of the additional output is the effect of the wind field on the output of this type of net radiometer.

2.1.1 The additional output caused by the source (i) above

In order to examine the additional output, the following experiment is carried out. The cold radiation source, a water surface with its temperature kept at 0°C , is put on a testing bench below and the warm radiation source is the ceiling of our laboratory whose temperature does not change appreciably during the experiment. Between these radiation sources a net radiometer is set (see Fig. 3). In this arrangement,

Fig. 3. Arrangement of the radiation source and radiometer.

Fig. 4a. Variation in output of FUNK'S net radiometer with wind speed. In this figure, the ordinate denote $|E| - |E_0|$ and the abscissa the wind speed. E denotes the output voltage. The subscript 0 denotes the case without wind and the symbol $|$ the absolute value.

there is observed little or no temperature gradient around the net radiometer. Then the net radiometer is exposed to the wind field with various speeds, and the absolute

Fig. 4b. Variation in output of FUNK's net radiometer with the output in the case without wind E_0 . E_0 is almost proportional to the incident net flux of radiation.

value of the output decreases with the increases of wind speed and absolute value of output (net flux of incident radiation) itself as shown by Figs. 4a and 4b. In these figures, $|E| - |E_0|$ (E_0 is the output for zero wind speed and E that for arbitrary wind speed) decreases rapidly with the increase of wind speed up to about 1.0 m/sec, and beyond this it decreases very slowly with the increase of wind speed and amounts to several percent of $|E_0|$ at about 3 m/sec of wind speed. On the other hand, $|E| - |E_0|$ decreases rather rapidly with the increase $|E_0|$ within $|E_0|$ concerned. The results are explained as follows: The difference between the air temperatures inside the upper and lower domes and consequently the absolute value of additional output is expected to increase with the increase of the absolute amount of net flux of incident radiation. The introduction of wind into the surroundings of the net radiometer causes the air temperature inside the domes to approach to the environmental air temperature and consequently the absolute value of additional output is expected to decrease with the increase of wind speed and the decrease of net flux of incident radiation as shown above.

2.1.2 The additional output caused by source (ii) above

In order to examine the additional output, the following two experiments are carried out. In the first experiment, a hot radiation source (an electric heater) is put on the testing bench below and a colder radiation source in this case is the ceiling of the laboratory. The radiometer is set about 90 cm above the hot radiation source. Between the hot source and the radiometer, an air curtain is made by a blower, by which the variable wind up to 5 m/sec is obtained. The air curtain is set so carefully that the wind of the air curtain does not hit the radiation source and the radiometer (see Fig. 5). In order to monitor the temperature of the hot radiation source, a radiation thermometer is used. The radiation thermometer watches the temperature of the hot radiation source during the experiment. No change of the temperature is observed irrespective of the existence of the air curtain; that is, the flux of radiation

Fig. 5. Arrangement of the radiation source, radiometer and air curtain.

from the source is constant during the experiment. In this arrangement, the temperature gradient around the net radiometer increases with the decrease of the wind speed of the air curtain, and the absolute value of the output of the radiometer increases slowly with the increase of temperature gradient up to about $0.25^{\circ}\text{C}/\text{cm}$, beyond which it increases rather rapidly with the increase of temperature gradient. This is shown in Fig. 6a. From the figure, the additional output caused by the temperature gradient is easily seen as the difference between the output in the case with temperature gradient and that in the case without temperature gradient. The additional output in the case with a temperature gradient of about $0.5^{\circ}\text{C}/\text{cm}$ amount to

Fig. 6a. Variation in output of FUNK'S net radiometer with environmental temperature gradient.

Fig. 6b. Variation in output of FUNK's net radiometer with wind speed in the case with or without temperature gradient. The figures on both curves denote the temperature gradients at zero wind speed.

Fig. 7. Arrangement of the radiation source, net radiometer and separation plate.

about 22% of that in the case without temperature gradient. The wind around the radiometer removes the additional output as shown in Fig. 6b. In this figure the solid curve shows the case without an air curtain (large temperature gradient) and the broken curve shows the case with one (little temperature gradient). The difference between these curves is due to the additional output caused by the temperature gradient. In the second experiment, FUNK's net radiometers is set at the middle level between the cold radiation experiment above and the warmer radiation source (a testing bench) below (Fig. 7). In this arrangement, the temperature gradient

Fig. 8. Variation in output of FUNK's net radiometer with wind speed. The ordinate and abscissa are the same as in Fig. 4a.

is small. As shown by the broken curve in Fig. 8, in which the ordinate and abscissa are the same as in Fig. 4a, the absolute value of output decreases with the increase of wind speed up to about 3 m/sec of wind speed. Beyond this the output is almost constant. The decrease of absolute value of output is considered to be due to the removal of the additional output caused mainly by the source (i) above. Next, a wooden separation plate is set on the same level as that of the sensor surface of the radiometer (Fig. 7). Then there occurs an appreciable temperature difference ($\approx 3^\circ\text{C}$) between the upper and lower parts of the separation plate. As shown by the curves in Fig. 8, the amount of decrease of output, 17 percent of $|E_0|$ in this case (solid curve), is larger than that in the case of small temperature gradient (broken curve), which is 10 percent of $|E_0|$. The difference between these two curves is considered to be due to the additional output caused by the environmental temperature gradient.

From the above discussions a more accurate net flux of radiation is expected to be measured by FUNK's net radiometer in the case with wind than in the case without wind.

2.2 "Ventilation-type" net radiometer

For this type of net radiometer, the additional output discussed above hardly takes place. Instead, it is expected that the effect of wind on the output of the radiometer takes place through the change of heat conductivity of air, α , due to the wind field (speed and direction). Our experiments were carried out for the following three cases. In the range of wind speeds concerned, the results for the cases are as follows:

(i) The first case in which the direction of wind is horizontal and perpendicular to the direction of ventilation whose speed is about 4 m/sec. The output of the radiometer in this case decreases rather rapidly with the increase of wind speed up to

Fig. 9. Variation in output of GIER and DUNKLE'S net radiometer with wind speed. The ordinate and abscissa are the same as in Fig. 4a.

about 3 m/sec, beyond which it decreases slowly as shown by the solid curve in Fig. 9,

(ii) The second case in which direction of wind is opposite to that of ventilation. The output in this case decreases rather slowly with the increase of wind speed up to about 4 m/sec of wind speed, beyond which it decreases rapidly as shown by the broken curve in Fig. 9.

(iii) The third case in which the direction of wind is the same as that of ventilation. No appreciable variation of output with wind speed is observed, up to about 6.5 m/sec unlike the situation in the other two cases.

3. A device calibrating net radiometers for longwave radiation

Several kinds of devices calibrating net radiometers for longwave radiation have been presented (FLEISCHER and GRÄFE 1955, FUNK 1961, COLLINS 1968).

The device proposed by FLEISCHER and GRÄFE (1955) is shown in Fig. 10a. In calibrating by this device, the net radiometer is set between two cavities whose temperatures are kept at T_1 and T_2 respectively. Then, from the values of output of the net radiometer, E , and the temperatures of both cavities T_1 and T_2 , the sensitivity of the net radiometers is given as follows,

$$s = E / \sigma (T_1^4 - T_2^4) \quad (5)$$

However, the sensitivity obtained with such a device is higher by about 30% than the expected sensitivity as discussed by FUNK (1961). FUNK suggests that this higher value is mainly due to an additional output caused by the environmental temperature difference between both cavities. This can also be expected by our experiments described in the previous section. Therefore this type of calibrating device needs improvement.

FUNK proposed a different type of calibrating device which overcomes this defect. The device is shown in Fig. 10b. In this device a net radiometer is set in a blackened copper enclosure at temperature T_1 and is exposed to the blackbody radiation originating in a black cavity at temperature T_2 through an opening of effective aperture ψ . The sensitivity s in this case is given by the equation (6),

Fig. 10a. Device for calibration of the net radiometer designed by FLEISCHER and GRÄFE.

Fig. 10b. Device for calibration of the net radiometer designed by FUNK.

$$s = E / \psi \sigma (T_1^4 - T_2^4) \quad (6)$$

In this case an additional output due to the environmental temperature gradient around the net radiometer discussed above is not created as shown by the experiment made by FUNK (1961).

Fig. 11. The present device for calibration of the net radiometer.

Recently COLLINS (1968) presented a calibrating device for which the heating is performed by an electrical heater in order to obtain the uniform temperature of the inner surface of the device, and which is set rather vertically than in horizontally as in the other devices.

As discussed in the previous section, the output of the net radiometer depends on the velocity of wind which usually exists in the field where the measurement of atmospheric radiation is carried out. It is very rare to have a complete calm condition in the field. Therefore it is desirable for a calibrating device to be able to estimate the influence, inevitable for the conventional net radiometer, of the environmental wind field on the sensitivity (output) of the net radiometer. Unfortunately this can not be estimated by the devices described above. So we have constructed a calibrating device by which this can also be estimated. The present device is shown in Fig. 11. The device consists of two similar blackbody cavities. Each cavity is contained in a cylinder and joined to it in an opening end and consists of a cone-shaped blackened brass of about 100 cm long and 15 cm of opening diameter. Each cavity is kept at a temperature different from each other by controlling the temperature of the steam which is contained in the cylinder. The control of the steam temperature is done by a microswitch which switches on or off the electric heater in the cylinder. The temperature of the black cavity wall is uniform except the vicinity of the opening end where the temperature of the wall differs from the uniform temperature by about 1.0°C . Furthermore a polished aluminum plate is attached to each blackbody cavity about 5 cm apart from its frontal surface outside (see Fig. 11). The aluminum plate serves as a shield to protect each blackbody cavity from the longwave radiation emitted by the other blackbody cavity. The distance between the two cavities is variable. And the net radiometer to be calibrated is set at the middle of the center line of the two blackbody cavities.

In such a configuration, each side of the net radiometer receives the radiation emitted from a blackbody cavity and from an aluminum plate. Because of the very low emissivity of the aluminum plate and the very small temperature difference of the aluminum plates in both sides, the radiations coming from the two aluminum plates almost cancel out each other and consequently the contribution to the output of a net radiometer due to these radiations are negligible. Furthermore, the radia-

Fig. 12. Dependence of sensitivity of a net radiometer on wind speed.

tion coming from each cavity and reflected by the aluminum plate keeps outside of the device and exerts no influence on the output of the net radiometer because of the geometry of the configuration of the device. The radiation coming from each side of the environment is also cancelled out by keeping uniform the temperature of laboratory, in which the device is set. Thus, in our device the radiation contributing to the output of the radiometer in calibration is only originated in the blackbody cavities. Because of the space between the two blackbody cavities, the dependence of sensitivity (output) of the radiometer on the wind speed is also estimated without disturbing the temperature of the blackbody cavities. Denoting by ψ the effective aperture of the opening of the blackbody cavity for the sensor surface of a net radiometer, we can obtain the sensitivity by the equation (6). The effect of wind on the output (sensitivity) can be estimated by our device. We give in Fig. 12 a result of calibration of the sensitivity of FUNK's net radiometer by the present device.

4. Discussion

In the previous sections were discussed the effect of environmental wind and temperature fields on the output of a net radiometer and the capabilities of several devices for calibrating the net radiometer.

The conventional net radiometers have the defect mentioned above, and FUNK's net radiometer gives a more accurate net flux of radiation in the case with wind rather than in the case without wind as described in section 2. It is, therefore, necessary to make a device able to calibrate the net radiometer in the case with wind as well as in the case without wind. In our device, it is possible to do this as shown in the previous section. After obtaining the sensitivity of the radiometer as a function of wind speed by the calibration device, the value of the net flux of radiation is obtained with more accuracy by the conventional net radiometers.

The effective aperture of the opening of the blackbody cavity for a net radiometer, ψ , is smaller than 2π in most devices. In this case it is important not to have

a too small ψ , because the estimation error of ψ is serious in the case of a too small ψ .

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長波長放射計の検定について(I)

—放射収支計の場合—

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長波長放射の測定精度が悪いことはよく知られている。これは、現用放射計固有の測定精度の限界およびその検定の困難さにある。

この論文では、本邦などで広く用いられている FUNK 型放射収支計（風防型放射収支計）および GIER-DUNKLE 型放射収支計（通風型放射収支計）について、その測定精度につき種々実験をおこなった。その結果両放射収支計とも、放射収支計の周りの風、温度の垂直勾配および入射放射の大きさの条件によって、放射収支計の出力に10パーセント以上の誤差が生じうることがわかった。

従来の検定装置の性能を吟味し、その欠点の主要な部分を改良した検定装置を試作した。その概要およびそれによって FUNK 型放射収支計を検定した結果を示す。