An effect of the circumsolar sky radiation on the Ångström Pyrheliometric scale

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ABSTRACT

According to the basic equation of the Ångström pyrheliometer, the heating power of the compensation electric current is directly proportional to the incident radiation intensity. However, as Anders Ångström pointed out, this direct ratio needs two corrections; the "edge effect" correction and the correction for heat conduction in the black paint thickness. This work directs attention to the existence of a third correction arising from the non-uniform illumination of the strips. In cases of pyrheliometers having no edge effect, this inhomogeneity is due to circumsolar sky radiation. The value of this correction can be determined by applying Ångström's theory using an irradiation term depending on distance measured from the midpoint of the strip. For simplicity a linear illumination distribution was used, even though the real distribution of the energy coming from the sun's aureole is not quite linear along the strip. The incident radiation flux can be exactly determined by applying Pastiel's theory. When calculating a reliable value for the correction in question, the sensitivity distribution along the strip should be taken into consideration. This can be determined on the basis of Ångström's theory. For the pyrheliometer A_{529}, in mean Budapest circumsolar sky conditions, the correction due to non-uniform irradiation is 0.5 %. This correction is nearly compensated by the correction for heat conduction in the black paint.

Introduction

According to the basic equation of the Ångström pyrheliometer, the electric power is directly proportional to the incident radiation. That is;

$$W = \varepsilon I$$

where W denotes the heat developed by electric current per unit time per unit area of the screened strip; ε is the absorptivity of the black paint and I is the radiative power incident on 1 cm² area of receiver (circumsolar radiation included).

This direct ratio is not strictly valid and the Ångström pyrheliometric scale needs some corrections. Anders Ångström (1958) determined the value of an "edge correction" and Kyle (1967) that of a "paint correction". Including these corrections the above equation becomes:

$$W = \varepsilon I \left(1 - c_e - \frac{fd}{K}\right)$$

where c_e symbolizes the edge correction, f the thickness of black paint; K the heat conductivity of black paint; and δ the complex coefficient of heat transfer from the painted surfaces of the strips.

It was assumed when determining the above corrections that the solar radiation flux incident on the strips would be uniformly distributed along their full length. However, the energy coming from the sun's aureole and therefore the total incident flux varies along the receiver. Since the shadowed and the exposed strips have different heating-profiles, they must also have different temperature profiles. At compensation only the temperatures at the mid-points are equalized but the others are not, so even our last equation is not strictly valid. A more precise formula is thus:

$$W = \alpha I \left(1 - c_e - \frac{fd}{K} - c_c\right)$$

c_c being the correction for non-uniform illumination.

As can be seen, the aim of this paper is to investigate the result of inhomogeneous illumination. The effect of circumsolar radiation is not analyzed in connection with the pyrheliometric comparisons.

In the following considerations the edge effect will be disregarded, i.e. it will be assumed that direct solar radiation would illuminate the full length of the exposed strip.

Ångström's theory

Under normal measuring conditions the value of the correction for non-uniform illumination can be determined by using Ångström's theory (1958) together with a value for the paint effect.

In steady state conditions the heat balance as a function of the distance from the centre of strip is described by the following differential equations:

$$\lambda q T'' - \left[\gamma + \frac{K\delta}{f\delta + K}\right] T + \left[\gamma + \frac{K\delta}{f\delta + K}\right] T_0 + \frac{K\varepsilon}{f\delta + K} L_1(z) = 0$$

for the exposed strip, while for the unexposed strip:

$$\lambda q T'' = \left[\gamma + \frac{K\delta}{f\delta + K}\right] T + \left\{\left[\gamma + \frac{K\delta}{f\delta + K}\right] T_0 + W\right\} + \frac{K\varepsilon}{f\delta + K} L_2(z) = 0$$

In the above equations the following nomenclature has been used:

$$T'' = \frac{d^2 T(z)}{dz^2},$$

- z coordinate along the length of strip ($z = 0$ at centre),
- $T(z)$ function describing the temperature distribution in the manganin,
- λ heat conductivity of manganin,
- q area of cross-section of manganin,
- γ complex heat transfer coefficient at the paintless (lower) surface of the strip,
- T_0 ambient temperature (i.e. that of tube, diaphragm, etc.),
- $L_1(z)$ function describing the illumination along the exposed strip,
- $L_2(z)$ that of the shadowed strip. As is known, the unexposed strip also gains energy from the scattered sky radiation.

The L_1 and L_2 functions are determined on the basis of the following assumptions:

(i) direct solar radiation reaches all points of the exposed strip,

(ii) the energy received from scattered radiation is symmetrically distributed around the centre and can be described by a linear function.

According to these assumptions:

$$L_1(z) = I + i_1|z| + j_1$$

$$L_2(z) = i_2|z| + j_2$$

where I denotes direct radiation, $|z|$ is the distance measured from the centre of strip and i_1, i_2, j_1, j_2 are parameters describing the linear distribution of energy coming from the aureole.

Solving the equations at compensation we obtain:

$$W = \frac{K\varepsilon}{f\delta + K}\left\{\left[J + j_1 - j_2 + \frac{a}{2}[i_1 - i_2)\right] - \left[\frac{a}{2}\frac{ch\,(Ea) - 3}{ch\,(Ea) - 1}(i_1 - i_2)\right]\right\}$$

where a denotes the lamella half length, and

$$E^2 = \frac{f\gamma\delta + K\gamma + K\delta}{\lambda q (f\delta + K)}$$

In the first brackets we find the resultant of the fluxes, with the flux belonging to the shadowed strip taken with a negative sign. The term in the second brackets describes the effect of differential illumination. If i_1 would be equal to i_2, then this term would vanish.

To estimate the significance of these terms, the mean values for the A_{529} pyrheliometer were determined. The mean resultant flux, that is the average of "direct" radiation values measured by pyrheliometers, is approximately 1 cal cm^{-2} min^{-1}. The incident circumsolar flux was determined for the mid-points and the end-points of the lamellae, to obtain four parameters of the linear energy distribution. The aureole was characterized by taking into consideration its mean Budapest value. During 1968 more than 70 aureole functions were determined using an instrument similar to that of Linke-Ulmitz (Major, 1970). This function ($E/\vartheta/$) describes the energetic radiance variation with the angular distance measured from the sun's centre; in other words: the angular distribution of the scattered radiation within the aureole. These functions cannot be properly approximated with the well-known analytic expressions and therefore numerical description was used.

The four parameters i_1, i_2, j_1 and j_2 have the values:

$j_1 = 0.0777$ cal cm^{-2} min^{-1} $i_1 = -0.0372$ cal cm^{-1} min^{-1}

$j_2 = 0.0117$ cal cm^{-2} min^{-1} $i_2 = -0.0040$ cal cm^{-1} min^{-1}

From these values, it follows that the circumsolar flux in the "direct" radiation,

$$j_1 - j_2 + \frac{a}{2}(i_1 - i_2) = 0.0496 \text{ cal cm}^{-2} \text{ min}^{-1}$$

and the effect of non-uniformity, taking $E = 2.4$ cm^{-1} (Ångström, 1958),

$$\frac{a}{2}\frac{ch\,(Ea) - 3}{ch\,(Ea) - 1}(i_1 - i_2) = -0.0093 \text{ cal cm}^{-2} \text{min}^{-1}$$

Pastiel's theory

The linear distribution of incident circumsolar radiation along the strip is a rough approximation. The most precise description can be achieved by using Pastiels' theory (Bossy & Pastiels, 1948; Pastiels, 1959). According to this theory, the resultant radiation flux has the form:

$$\bar{I} = \pi \int_0^{\vartheta} E(\vartheta)\, G(\vartheta) \sin 2\vartheta \, d\vartheta$$

where

- ϑ the angle-distance measured from the sun's centre,
- ϑ_e the limit angle of the pyrheliometer: the maximum angle in which radiation can fall on the receiver,
- $E(\vartheta)$ a function, describing the circular distribution of radiation intensity along the sun's disc ($0 \leq \vartheta \leq 16'$) and in the aureole ($\vartheta > 16'$),
- $G(\vartheta)$ the geometrical penumbra function of the pyrheliometer. This expresses the fraction of receiver surface reached by the radiation inclining at an angle ϑ to the optical axis.

For the A_{529} pyrheliometer, applying the mean Budapest $E(\vartheta)$ function, the circumsolar flux

$$\int_{16'}^{\vartheta_e} E(\vartheta)\, G(\vartheta) \sin 2\vartheta \, d\vartheta = 0.0626 \text{ cal cm}^{-2} \text{ min}^{-1}$$

which is somewhat higher than in the previous case. The difference is caused by the error of linear approximation: i.e. the incoming circumsolar radiation is higher than the values given by the straight line connecting the mid-point and end-point values.

In this theory the output of the pyrheliometer is written:

$$W = u\pi \int_0^{\vartheta_e} E(\vartheta)\, F(\vartheta) \sin 2\vartheta \, d\vartheta$$

Here u is the mean surface sensitivity of receiver, and $F(\vartheta)$ is the effective penumbra function. The latter differs from the geometrical one in that that the apparent fraction is weighted with its sensitivity. The sensitivity distribution has been calculated using Ångström's theory (Major, 1968).

Pastiels' theory requires a sensitity distribution and Ångström's theory gives a possibility of determining such a distribution. These two theories together therefore would not only give the best value for the correction of non-uniform illumination but also quite complete description of the pyrheliometer. From the above equations we get:

$$W = u\bar{I} + u\pi \int_0^{\vartheta_e} E(\vartheta)\,[F(\vartheta) - G(\vartheta)] \sin 2\vartheta \, d\vartheta$$

As in our case

$$u = \frac{K\varepsilon}{f\delta + K}$$

we can write

$$W = \varepsilon \bar{I}\left(1 - \frac{f\delta}{K} + c_c'\right)$$

c_c' symbolizes the ratio of the second term to I. Thus, c_c' vanishes when $F(\vartheta) = G(\vartheta)$, i.e. when the sensitivity is uniform along the receiver. Under the mean Budapest conditions for the A_{529} $c_c' = 0.0045$, only half of the value received previously.

One could ask if these two corrections denote the same effect? The answer is yes, as both follow from the circumsolar radiation. In the first case the role of the inhomogeneous energy distribution is emphasized, while in the second the inhomogeneous sensivity distribution is considered. The presented figures refer to the average conditions. Of course, this correction varies with the aureole intensity. According to the Budapest measurements the circumsolar flux varies between 50% and 200% of its mean value.

Results

1. In the Ångström pyrheliometer (and in others too) the output (W) is not directly proportional to the input (I), because of both non-uniformed illumination and the non-uniformed sensivity distribution.

2. Using the direct ratio a correction must be applied because of the above effect, the value of which lies between 0.2–1.0% as the aureole intensity varies. This correction almost compensates the paint correction.

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ВЛИЯНИЕ ИЗЛУЧЕНИЯ НЕБА ВОКРУГ СОЛНЦА НА ПИРГЕЛИОМЕТРИЧЕСКУЮ ШКАЛУ АНГСТРЕМА

Согласно основному уравлению пиргелиометра Ангстрема мощность нагрева компенсирующего электрического тока прямо пропорциональная интенсивности падающей радиации. Однако, как отметил Андерс Ангстрем, эта прямая пропорциональность нуждается в двух поправках: в поправке на «эффект края» и в поправке на теплопроводность в слое черной краски. В данной статье привлекается внимание к необходимости третьей поправки, возникающей из-за неоднородной освещенности полос. В случае пиргелиометров, не имеющих краевого эффекта, эта неоднородность возникает благодаря излучению неба вокруг солнца. Величина этой поправки может быть определена с помощью теории Ангстрема с использованием члена иррадиации, зависящего от расстояния, измеренного от средней точки полосы. Для простоты использовалось линейное распределение освещенности, хотя реальное распределение энергии, поступающей от солнечного ореола совсем не линейно вдоль полосы. Поток падающей радиации может быть определен точно с помощью теории Пастьелса. При вычислении надежной величины данной поправки надо учесть распределение чувствительности вдоль полосы. Это может быть сделано на основе теории Ангстрема. Для пиргелиометра A_{529} при средних условиях в Будапеште для неба вокруг солнца величина поправки благодаря неоднородности иррадиации составляет 0,5 %. Эта поправка приблизительно компенсируется поправкой на теплопроводность в слое черной краски.