Scientific Research Publishing

Energy and Power Engineering, 2024, 16, 285-292
https://www.scirp.org/journal/epe
ISSN Online: 1947-3818
ISSN Print: 1949-243X

New Insight to the Surface Temperature of the Sun

Ryszard Petela

Professor Emeritus, Calgary, Canada
Email: petelar@telus.net

How to cite this paper: Petela, R. (2024) New Insight to the Surface Temperature of the Sun. *Energy and Power Engineering*, **16**, 285-292.
https://doi.org/10.4236/epe.2024.168013

Received: June 29, 2024
Accepted: August 18, 2024
Published: August 21, 2024

Abstract

Information is given on thermal radiation from the Sun, considered in practical engineering calculations of heat exchange. It was found that although the surface temperature of the Sun is assumed to be about 5800 K, the solar spectrum data measured by Kondratyev lead to a value of at least 7134 K. Such a higher value can be obtained by interpreting the Planck formula for the black radiation spectrum for the Kondratyev data. In addition, using the Stefan-Boltzmann law, the energetic emissivity of the Sun's surface was determined to be 0.431. Furthermore, based on Petela's formulae for exergy of thermal radiation, the exergetic emissivity of the Sun's surface was also calculated at the level of 0.426.

Keywords

Thermal Radiation, Radiation Temperature, Surface Temperature, Surface Emissivity, Sun Radiation Spectrum, Plank Law, Exergy of Radiation, Photosphere

1. Introduction

The Sun is a huge mass of hot plasma [1] with a temperature of about 15 million K. However, most of the radiation energy comes from the Sun's outer layer, called the photosphere [2] [3]. It is in this layer that most of the photons leaving the Sun are produced. The photosphere is about 400 km thick, which is negligible compared to the size of the Sun. This layer is translucent, and in it, the density of the gas decreases with altitude, and the temperature drops from about 10,000 to 4400 K. The outermost part of the Sun is the corona with a temperature of about 3.5 million K, but compared to the photosphere, the radiation of the corona is negligible [4].

In practical calculations of radiative heat transfer between surfaces, their temperature and emissivity play a role [5]. From a distance, the Sun can be considered as a certain surface with a temperature associated with a specific spectrum, which represents the distribution of radiation energy as a function of wavelength [6]. Using various spectroscopic methods [7] to study the visible radiation of the Sun, an effective solar surface temperature of about 5800 K is determined, e.g. [8]. It turns out that the solar emission in the visible part of the continuous spectrum is almost identical to that of a blackbody with a temperature of 5777 K.

However, the approach in this work, based on Kondratyev's measurements [9], leads to a higher value of this temperature, which is at least 7134 K. Moreover, this surface should not be considered black, but gray. Therefore, for this gray surface of the Sun, its radiative ability, expressed in energetic and exergetic emissivity, has also been determined for the first time.

This paper proposes an obvious procedure on how Kondratyev's solar spectrum measurement data can be used to determine the Sun's surface temperature and surface emissivity. The results obtained are a kind of information that can be taken into account in various analyses of heat transfer with the Sun.

2. Basic Equations and Terms

The presented considerations concern thermal radiation, which is defined as the emission of energy of any body with a temperature higher than absolute zero.

Any real surfaces have a spectrum represented by an irregular curve that cannot be described by a mathematical formula. Therefore, to simplify practical considerations, two surface models are often used, [10]. **The first model**, a perfectly black surface, has a black spectrum and is therefore determined by Planck's law, according to which the intensity $i_{b,\lambda}$, W/(m^{3}sr), of monochromatic black radiation is determined as follows [11]:

$$i_{b,\lambda} = \frac{c_1}{\lambda^5 \left(e^{\frac{c_2}{\lambda T}} - 1 \right)}, \tag{1}$$

where:

$c_1 = hc_0^2 = 5.95416 \times 10^{-17}\ \text{W} \cdot \text{m}^2$

$c_2 = hc_0 / k = 1.4388 \times 10^{-2}\ \text{K} \cdot \text{m}$

are respectively the first and the second Planck's constants,

T—absolute temperature of black radiation, K,

λ—wavelength, m,

h—Planck's constant, $h = 6.625 \times 10^{-34}$ Js,

k—Boltzmann constant, $k = 1.3805 \times 10^{-23}$ J/K,

c_0—speed of propagation of radiation in vacuum, $c_0 = 2.9979 \times 10^8$ m/s.

The radiative ability of any surface can be expressed by energetic emissivity ε_λ, which is the following ratio:

$$\varepsilon_\lambda = \left(\frac{i_\lambda}{i_{b,\lambda}} \right)_\lambda, \tag{2}$$

where (i_λ) and ($i_{b,\lambda}$) are the monochromatic radiation intensities of the gray and black surface, respectively.

The second model, the perfectly gray surface, is the theoretical surface for which the energetic emissivity is the same for each wavelength (ε_λ = const).

A gray surface always emits black radiation, with a surface temperature. However, the emitting ability of such a surface does not exceed the radiation intensity of a perfectly black surface, for a given wavelength. The total ability of any surface is determined by the averaged energetic emissivity coefficient ε, and for a perfectly black surface $\varepsilon = 1$.

3. Methodology for Determining Temperature of Radiation

Measured spectrum data of any radiation from an unknow source can be used to obtain information about the temperature of that radiation or the temperature of a radiating surface. The proposed methodology is based on the rule that for each wavelength, the component i_λ of the measured spectrum cannot exceed the possible maximum, which is the corresponding theoretical value $i_{b\lambda}$ of the black spectrum component:

$$i_\lambda \le i_{b\lambda} . \quad (3)$$

Using all the measured values of i_λ, the set of the respective temperatures T_λ can be calculated from Equation (1), used as $T_\lambda = T_\lambda (i_\lambda, \lambda)$. To satisfy Condition (3) the temperature of the radiation (or a radiating surface) under consideration must be at least some minimum value $T_{\min}$ that is equal to the maximum temperature T_λ:

$$T_{\min} = \max\left(T_\lambda\right). \quad (4)$$

However, we only know about the actual temperature T of the considered radiation that it is not lower than $T_{\min}$:

$$T \ge \max\left(T_\lambda\right). \quad (5)$$

Graphically speaking, this $T_{\min}$ procedure means fitting a black spectrum curve of known temperature so that no measured component exceeds the respective value of this fitting curve, and the fitting curve must touch the measured curve at least at one point of tangency. This would mean that the temperature of radiation with a known spectrum is at least equal to the temperature $T_{\min}$ represented by the fit curve. The fitted temperature is only a certain minimum, because the actual temperature of the radiation under consideration can be even higher, but how much cannot be determined from the available spectrum.

4. Determination of the Temperature of the Sun's Surface

The proposed methodology described above has been used to consider the temperature of the Sun's surface [12]. Data on the spectral distribution of extraterrestrial solar radiation arriving at the atmosphere are given by Kondratyev [9]. This Kondratyev data is also available in [13]. Each measured component of this spectrum, for a given wavelength λ (which is the mean value of the wavelength interval, $\Delta\lambda = 10 \div 50$ nm), is taken as a black radiation component and the temperature values T_λ were calculated from Equation (1) for the first time [14], as shown in Figure 1. The T_λ values obtained for wavelengths greater than 4000 nm seem to be uncertain, because a relatively large wavelength interval ($\Delta\lambda$ = 1000 nm) was used, and the available monochromatic radiation intensities seem to be insufficiently accurate (in the range from 7×10^{-10} to 1×10^{-10} $W{\cdot}m^{-3}{\cdot}sr^{-1}$). Thus, based on Kondratyev data and according to Statement (4), the maximum value of T_λ = 7134 K, is the minimum temperature of the Sun's surface T_{min} = 7134 K.

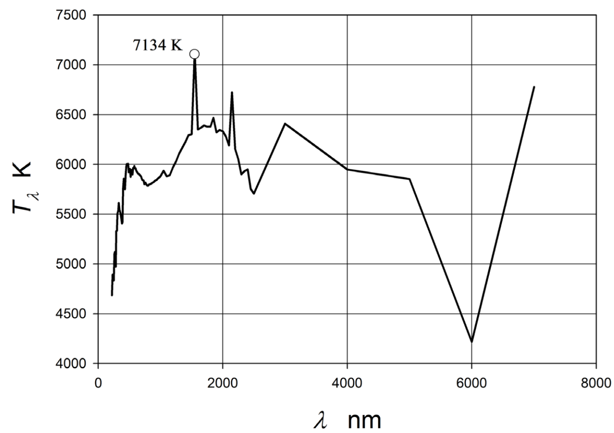

Figure 1. Temperature T_λ calculated [14] by Equation (1) as a function of wavelength λ, using solar spectrum data measured by Kondratyev [9].

Graphically, to achieve Condition (3) the fit curve values must exceed all measured component values, as shown in Figure 2 by means of a fitted curve (solid line) and a measured spectrum line (dashed). Both curves meet at λ = 15,500 nm. The right part of Figure 2 shows the magnification of the wavelength segment where the fitted curve meets the spectrum curve. However, the actual surface temperature of the Sun's surface can be even higher than the determined minimum value and represented by some other spectrum curve.

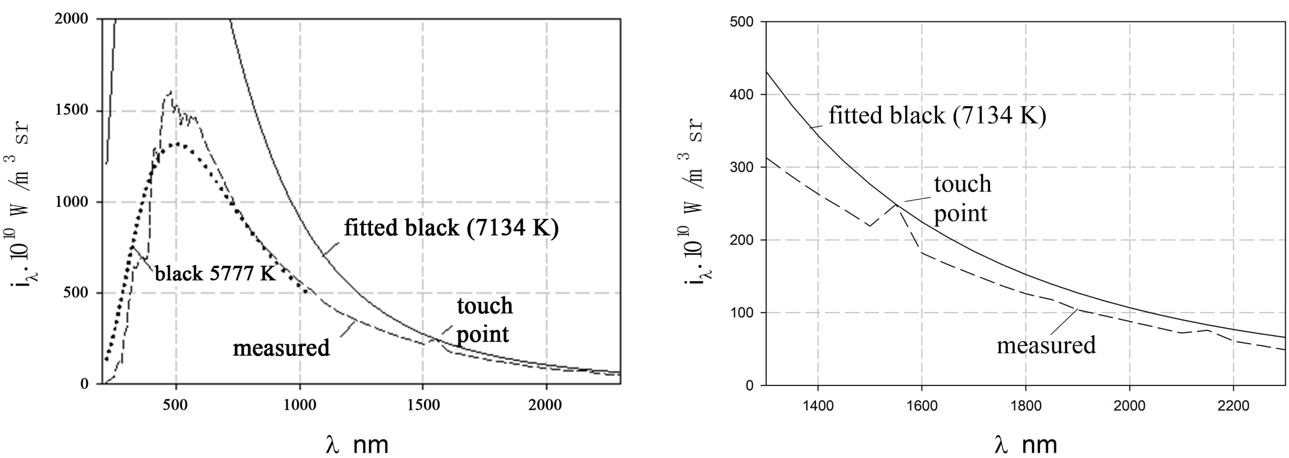

Figure 2. Measured spectrum (dashed line) with fitted curve (solid line) of the black radiation spectrum at 7134 K.

As mentioned, the general belief is that the surface temperature of the Sun is about 5777 K. This is because solar radiation is usually considered in the wavelength range (380 - 750 nm) of the visible radiation, and this temperature value is suggested by the "fitted" curve (dotted line in **Figure 2**), which does not fulfill Condition (3). However, a glance at the $\lambda > 750$ nm range of the solar spectrum (**Figure 2**), reveals relatively higher spectral values (higher ε_λ vales), which justifies such a high radiation temperature of 7134 K.

The temperature of 7134.7 K was calculated for an intensity value of 249 W/(m^{3}sr). The effect of the accuracy of the intensity measurement on the temperature calculated from Equation (1) can be roughly estimated by calculating this temperature for two intensity values around the measured value. Therefore, when the intensity changes about 1%, e.g. from 246.5 to 251.5 W/(m^{3}sr), the calculated temperature changes from 7094.6 to 7174.7 K, respectively.

5. Emissivity of the Sun's Surface

Solar radiation can practically be classified as coming from a perfect gray surface with a certain averaged value of energetic emissivity ε, which can be calculated as the following ratio:

$$\varepsilon = \frac{e_\omega}{e_{b,\omega}}, \tag{6}$$

where e_ω and $e_{b,\omega}$ are the emission density of the gray and black surface, respectively, propagating within solid angle ω at which the Sun is seen from the Earth. The black emission density e_b, W/m^2, is determined by the Stefan-Boltzmann law [15]:

$$e_b = \sigma T^4, \tag{7}$$

where $\sigma = 5.6693 \times 10^{-8}$, W/(m^{2}K^4), is the Boltzmann constant for black radiation. The value of e_b expresses the energy emitted from an area of 1 m^2 in a solid angle 2π. However, only a part $e_{b,\omega}$ of this energy reaches the Earth within the solid angle ω. Approximately the radius of the Sun is 695,500 km, and assuming an average distance from the Sun to the Earth of 145,500,000 km, the solid angle is:

$$\omega = \frac{\pi \times 695500^2}{145500000^2} = 2.16 \times 10^{-5} \times \pi \text{ sr}. \tag{8}$$

Using Equation (7) and the calculated value of ω, from Equation (8), the black emission from the surface of the Sun would be:

$$\begin{aligned} e_{b,\omega} &= \frac{e_b}{\pi}\omega = \frac{\sigma T^4}{\pi}\omega \\ &= \frac{5.6693 \times 10^{-8} \times 7134^4}{\pi} \times 2.16 \times 10^{-5} \times \pi \\ &= 3170 \text{ W/m}^2 \end{aligned} \tag{9}$$

However, according to Kondratyev's measurement data [9], only $e_\omega = 1367.9$ W/m^2 reaches the atmosphere. Thus, the energetic emissivity $\varepsilon_{e,S}$ of the Sun's surface is equal to the following ratio:

$$\varepsilon_{e,S} = \frac{1367.9}{3170} = 0.431. \tag{10}$$

In addition to considering energetic emissivity, exergetic or entropic emissivity can also be analyzed [16]. For example, only the exergetic emissivity of the Sun's surface is discussed here.

The exergy of the black emission b_b, W/m^2, is as follows [17]:

$$b_b = \frac{\sigma}{3}\left(3T^4 + T_0^4 - 4T_0T^3\right), \tag{11}$$

where T_0 is the absolute ambient temperature, (assuming T_0 = 300 K). Analogous to (9), the exergy $b_{b,\omega}$ of black emission from the surface of the Sun reaching the Earth would be:

$$\begin{aligned} b_{b,\omega} &= \frac{b_b}{\pi}\omega = \frac{\sigma}{3}\left(3T^4 + T_0^4 - 4T_0T^3\right)\frac{\omega}{\pi} \\ &= \frac{5.6693\times10^{-8}}{3}\left(3\times7134^4 + 300^4 - 4\times300\times7134^3\right)\times2.16\times10^{-5} \\ &= 2990\ \mathrm{W/m^2} \end{aligned} \tag{12}$$

Based on Kondratyev's measurements [9], it was determined that the exergy of solar radiation is b_b = 1275.8 W/m^2 [18]. Thus, the exergetic emissivity ratio $\varepsilon_{b,S}$ of the Sun's surface, analogous to Equation (6), is equal to:

$$\varepsilon_{b,S} = \frac{1275.8}{2990} = 0.426. \tag{13}$$

The exergy-to-energy ratio for solar radiation is 1275.8/1367.9 = 0.9327, and the respective ratio of exergetic and energetic emissivity is 0.426/0.431 = 0.988. These values can be used in various considerations of the exergy of thermal radiation [19].

6. Conclusions

Overall, the findings of this article are cognitive and can be inspiring.

It turns out that the temperature of the Sun's surface, which is generally assumed to be around 5800 K, has a different value, and according to the Kondratyev's measurement of the solar spectrum, this temperature is at least 7134 K. It has also been shown that the surface of the Sun is gray, and the maximum energy emissivity is about 0.431. For the first time, the maximum exergetic emissivity of this surface was set at 0.426.

The ratio of exergetic and energetic emissivity determined here has a meaning corresponding to Carnot's efficiency. This ratio determines the maximum ability to change the radiant energy of a gray surface into work, just as the Carnot efficiency determines the maximum ability to convert heat into work [20].

The above information can be used in various practical calculations of radiative heat transfer associated with the Sun and can be a kind of specific contribution to various exergetic analyses of processes occurring with the participation of solar radiation. An example of such processes can be the concentration of solar radiation [21]. When producing sources with extremely high temperatures, the temperature of the Sun's surface sets the theoretical limit of the temperature of concentrated radiation, which, according to the second law of thermodynamics, cannot be exceeded.

The procedure proposed is of general importance because it is convenient to use in any case where a known spectrum of radiation is used to determine the unknown temperature of that radiation.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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