Assessment of the intensity and flow of straight solar radiation falling onto the horizontal surface of a room

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Abstract. The paper presents the results of experimental studies of straight solar radiation in the Central Chernozem region of Russia. The intensity and flow of straight solar radiation falling onto a horizontal surface of a room were evaluated. Measurements were made of the flow of straight solar radiation on a horizontal surface through a translucent structure. Experimental data were obtained using a high-class measuring device in the period from July 1 to August 1. The measurement results showed an intense wave-like change in the solar radiation flux over 8 hours. The paper describes a method for estimating the intensity and flow of straight solar radiation falling onto a horizontal surface of a room. This method of evaluating daytime radiation allows one to determine the density of the total and straight radiation flux. Using this estimate to calculate solar installations used in the Central Chernozem region, their efficiency will increase by 10%.

1. Introduction

Renewable energy sources are of interest at all levels of the world community. Renewable energy sources have gained significance in energetics and politics. This is due to the increased interest in the environmentally safe and sustainable energy supply of mankind in the future [1, 2].

Accurate prediction and calculation of solar radiation flows falling onto a horizontal surface at a specific geographical point are not possible in practice, since meteorological information is not always available and reliable [3, 4]. To calculate the characteristics of solar installations, it is necessary to use the data from experimental measurements of solar radiation parameters in the considered location. The most reliable information is the amount of straight solar radiation falling onto a horizontal surface.

The characteristics of solar radiation are often presented in different ways, but the following information is important for understanding and using solar radiation data:

1) the results of a momentary measurement or for a certain period;
2) the measurement time interval;
3) the measured radiation (straight, diffuse, or total);
4) the orientation of the receiving surface to the cardinal directions;
5) the averaging period (month or day).

Most of the measurements of the incident solar radiation flux include direct and scattered ones and relate to the horizontal receiving surface. Such measurements can be made using thermoelectric pyrometers. They are used to measure the most popular characteristics of solar radiation. The sensitivity of the sensors of such devices does not depend on the wavelength in the spectrum of solar radiation, and they are protected from external influences. In addition, these devices must not be sensitive to the angle of incidence of radiation. Most of these devices allow one to get instantaneous
data series that are not average or integral values. Therefore, data is stored in the device's memory or on a personal computer and integrated graphically.

2. Problem statement
To estimate the flow of incident solar radiation, you can also use the results of measuring the time during which the solar disk in the sky is visible when the sky is clear. The average sum of total monthly day solar radiation is the most available data on the flows of incident solar radiation falling onto a horizontal surface. Similarly, hourly amount of the total radiation received by the horizontal surface is available. Data from ground-based measurements of solar radiation fluxes made under the auspices of the world meteorological organization are presented in the archives of the World Radiation Data Center. However, it should be noted that the accuracy of the data obtained differs from the corresponding modern requirements, the error of which is from 5% to 20%.

Measurement of solar radiation flows falling onto inclined or horizontal surfaces is important in determining the energy input of solar collectors. For a long time, the traditional unit for measuring the flux density of incident solar radiation was the calorie/cm$^2$. Currently, the more familiar unit of measurement is MJ/m$^2$ or W/m$^2$.

3. Conducting experiments
Detailed data on solar radiation is necessary for calculating the dynamic behavior of solar installations. They are also used to model the long-term operation of installations. In this regard, we measured the flow of direct solar radiation onto a horizontal surface through a translucent structure. The measurements were made using a high-end device from July 1 to August 1, 2019.

![Solar radiation measurement device](image)

Figure 1. Solar radiation measurement device.

Measurements were made on the horizontal surface of the experimental model of the room with a size of 1×1×1 m. The model of the room was made of light structures with one of the vertical walls
completely made of glass. The model fully meets the requirements for thermal protection for the climatic parameters of the Voronezh region and is shown in figure 2.

![Experimental model](image1)

**Figure 2.** Experimental model.

The measurement results showed an intense wave-like change in the solar radiation flux over 10 hours. Figure 3 shows the measurement graphs.

![Changing the flow of solar radiation](image2)

**Figure 3.** Changing the flow of solar radiation.
These measurements are the best source of information for estimating the average values of incident solar radiation. Using the obtained values helps avoid large errors in the engineering method of calculating the performance of solar installations [5, 6].

4. Calculations

The state of the atmosphere and its mass changes during the day. The scattering and absorption of incident solar radiation also depend on time. When calculating the flows of solar radiation falling onto a horizontal surface, it is necessary to use the concept of a standard (clean) sky. In [7], Professor of the Massachusetts Institute of Technology Hoyt Clark Hottel proposed a method for assessing the flow of direct solar radiation propagating through a transparent atmosphere, which considers the Zenith angle and height of the measurement site. However, the method allows calculations for standard atmospheric conditions and four types of climate. In this case, the atmospheric transparency coefficient for direct solar radiation \( \tau_b \) is equal to the ratio of the scattered radiation flux to the flow of the transatmospheric radiation falling on to a horizontal surface and is determined by the formula:

\[
\tau_b = a_0 + a_1 \exp \left( \frac{-k}{\cos \theta} \right),
\]

where \( \cos \theta \) - the cosine of the sun's Zenith angle [8, 9], and is determined by the following formula:

\[
\cos \theta = \cos \phi \cos \delta \cos \omega + \sin \phi \sin \delta,
\]

\( a_0, a_1, k \) - the constant coefficients for a standard atmosphere with a visibility of 23 km are calculated from the coefficient values \( a_0', a_1', k' \), which are defined for altitudes in the atmosphere less than 2.5 km by the following expressions:

\[
a_0' = 0.4273 - 0.0821(6 - A)^2, \quad a_1' = 0.5055 + 0.0595(6.5 - A)^2, \quad k' = 0.2711 + 0.01858(2.5 - A)^2,
\]

where \( A \) – the height of the observation in kilometers.

The transparency of the standard atmosphere for direct radiation can be determined for any Zenith angle and any height. As a result, the flow of direct radiation to the normal surface of the beam in a clear sky is determined as follows:

\[
G_{cab} = G_{ao} \tau_b, \ W/m^2,
\]

where, \( G_{ao} \) - the solar radiation flux density, \( W/m^2 \).

But to get the total radiation flux falling onto a horizontal surface, it is necessary to estimate the intensity and flow of direct solar radiation in clear sky conditions. In [10], the following empirical relationship was proposed between the transparency coefficient for direct and scattered radiation in a clear sky:

\[
\tau_d = \frac{G_d}{G_o} = 0.271 - 0.294 \tau_b,
\]

where \( \tau_d = G_d / G_o \) - the ratio of the scattered radiation flux to the transatmospheric flux falling onto a horizontal surface. The above equation can be used to estimate the flow of direct solar radiation and its intensity.

Thus, the flow of radiation falling onto a horizontal surface can be found as follows:

\[
G_{d} = G_{ao} \cos \theta \tau_d, \ W/m^2,
\]

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Based on the measurements, we estimate the transparency of the atmosphere for the direct flow of solar radiation for each hour (the middle of an hour) and calculate the flow of radiation falling onto the horizontal surface. We calculated $\tau_d$ for the time interval from 10 to 11 hours (i.e. for 10:30). Using the height of the standard atmosphere equal to 0.27 km we get the following coefficient values:

$$a_0^* = 0.4273 - 0.0821(6 - 0.27)^2 = 0.154,$$

$$a_1^* = 0.5055 + 0.0595(6.5 - 0.27)^2 = 0.736,$$

$$k^* = 0.2711 + 0.01858(2.5 - 0.27)^2 = 0.363.$$

The cosine of the Zenith angle of the sun, for a given time, is $\cos \theta_z = 0.507$.

Then we find the atmospheric transmittance by formula (1):

$$\tau_s = 0.154 + 0.736 \exp \left( - \frac{0.363}{0.507} \right) = 0.513.$$

From equation (6), the flow of direct radiation to the surface normal to the beam in a clear sky, according to the results of measurements, will be equal to:

$$G_{\text{cak}} = 980 \cdot 0.513 = 502.74 \text{ W/m}^2.$$

In this case, using formula (7), we find the ratio of the scattered radiation flow to the flow of the transatmospheric falling onto the horizontal surface.

$$\tau_d = 0.271 - 0.294 \cdot 0.513 = 0.12.$$

Substituting the obtained value in equation (8) we get:

$$G_{\text{cd}} = 980 \cdot 0.507 \cdot 0.12 = 59.62 \text{ W/m}^2.$$

5. Conclusion
When using this method of estimating and calculating the radiation flux falling onto a horizontal surface for calculating solar installations used in the Central Chernozem region, the efficiency and accuracy of selecting such installations on a real area will increase, which will give a subsequent increase in productivity of up to 10%.

References
[1] Sheps R A, Yaremenko S A and Pereslavtseva I I 2017 Influence of solar energy on thermal protection of constructions Proc. of 1st Russian Scientific and Technical Conf. Devoted to the Memory of the Dr. Sci. Tech., Professor A A Sander: Energy Saving and Energy Efficiency at the Industrial Enterprises Housing and Communal Services pp 199-209
[2] Sheps R A, Portnova N V, Shchukina T V and Pereslavtseva I I 2018 The use of solar radiation in the application of energy-efficient walling Bulletin of Voronezh State Technical University 14(3) 46-51
[3] Sheps R A, Kushchev L A, Shashin A V and Lobanov D V 2017 Influence of dustiness of enclosing structures on the ability to absorb solar energy Privolzhsky Scientific J. 4(44) 51-59
[4] Fathi N Y and Samer A 2016 View factors of flat solar collectors array in flat, inclined, and step-like solar fields Trans. ASME. J. Sol. Energy Eng. 138 061005/1-8
[5] Vorotyntsev A V, Bolgov V A, Sheps R A and Shchukina T V 2018 Economic efficiency of the walling with the heat storage capacity Economics and Entrepreneurship 7-9 55-62
[6] Beccali M, Cellura M, Longo S and Guarino F 2016 Solar heating and cooling systems versus conventional systems assisted by photovoltaic: Application of a simplified LCA tool Sol. Energy Mater. and Sol. Cells. 156 92-100
[7] Hottel H C 1976 A simple model for estimating the transmittance of straight solar radiation through clear atmospheres Solar Energy 18 129
[8] Iqbal M 1983 An Introduction to Solar Radiation (Toronto: Academic)
[9] Spencer J W 1971 Fourier series representation of the position of the sun Search 2(5) 172
[10] Liu B Y H and Jordan R C 1960 The interrelationship and characteristic distribution of straight, diffuse and total solar radiation Solar Energy 4(3) 1