Modeling of a solar radiation flow on an inclined arbitrarily oriented surface

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Abstract. Knowledge of the radiation components incoming at a surface is required in studies of climate and renewable energy technologies. An algorithm for calculating the flux of solar radiation on variously oriented and inclined surfaces is proposed. The algorithm is based on Voeikov Main Geophysical Observatory model. The model deals with such gases as H₂O, CO₂ and O₃, which absorb radiation in the UV and visible regions of the spectrum. This model takes into account direct solar radiation, diffuse radiation from the atmosphere and the earth's surface coming on horizontal surface only. The main goal of the work is to develop a flow calculation algorithm for variously oriented surfaces. Good results are obtained, differences in values of direct and diffuse solar radiation between modeling and experience data do not exceed 10%, which is quite satisfactory for engineering calculations. In this paper emphasis is on implementation on calculating the flux for actual state of an atmosphere, including the effects of anthropogenic and man-made pollution.

1. Introduction

Accounting for heat and light energy of solar radiation is necessary in the design, construction and operation of residential buildings and other engineering structures. In summer in southern regions of Russia, the abundance of solar heat at high air temperatures adversely affects the human thermal sensations, therefore, to create normal conditions for his life, it is necessary to take measures to reduce the impact of solar heat on the building.

The absorbed solar radiation can serve as an additional source of energy, which makes it possible to reduce energy consumption for some regions in winter. It makes the heating period shorter and provides a significant economic effect.

Nowadays, when traditional sources of energy are being depleted, and new ones are not yet sufficiently developed, the task of energy saving will remain relevant for many years.

A properly designed solar building can reduce the heating load in winter and the air-conditioning load in summer.

Now in Russia, the energy consumption of existing residential and public buildings is three times higher than the energy consumption in technically developed countries with similar climatic conditions.

Solar energy is a serious alternative to traditional energy already at the present time, contrary to the widespread view that its practical use is a matter of the distant future.

It is not by chance that a great interest in pilot construction causes such a direction as “energy efficient buildings”. For example, papers [1, 2] devoted to the consideration of this direction define “an energy efficient building” as “a building which includes a set of architectural and engineering solutions that
best meet the goals of minimizing energy expenditure on the provision of a microclimate in the building’s premises”. This scientific and experimental direction in construction has appeared as a consequence of the global energy crisis of the 70s.

The first such building was built in 1974 in the city of Manchester (New Hampshire, USA) in order to identify the total energy saving effect of the use of architectural and engineering solutions aimed at saving energy resources.

Thirty years ago, the use of solar radiation heat was provided when creating energy-efficient buildings.

It also produces tangible results in the Nordic countries: the heat of solar radiation was used during the renovation of a residential building in Copenhagen (56°N) in 1994–1995.

A passive solar collector for heating the supply air in the ventilation system and solar collectors for preparing hot water in the hot water system were arranged. This system allows you to cover 60–65% of energy costs for hot water.

In our country the use of solar radiation heat is not still very common. The simplest and cheapest way to use solar energy is to heat domestic water in solar collectors. There is also the interesting practice of creating a favorable environment for the life of people in megalopolises by planting roofs. This experience is widespread in different countries[3]. The technique requires that information is available on the levels of incoming solar radiation to surfaces of different inclination in order to calculate the levels of plant insolation.

In Russia the income of solar radiation is registered by the state meteorological service using a network of actinometric stations. The results of actinometric observations have been published in special scientific and applied reference book on climate of the USSR since 1961. They provide information on solar radiation falling on surfaces both horizontal and normal to the beam, as well as annual and monthly sums under various cloud conditions. But such data does not exist for all settlements.

2. Materials and methods

There are programs that recalculate solar radiation for variously oriented inclined surfaces. They are based on data of actinometric stations. As already mentioned, data does not exist for all settlements. Often the value of solar radiation is determined by certain empirical relationships that do not allow to take into account the real state of the atmosphere.

The software developed by the authors provides for the calculation of the intensity of direct, scattered and total solar radiation on the non-shaded surface of any orientation, located at any angle to the horizon.

The calculation of the intensity of solar radiation on a horizontal surface is based on the climate model [4, 5] The model makes it possible to calculate short-wave radiation fluxes in a multicomponent cloudy atmosphere with allowance for multiple scattering and absorption. The cloud height and its score and water storage are the necessary physical parameters for taking into account clouds cover.

Other physical parameters that have to be considered are optical depth of atmospheric aerosol, single scattering albedo and asymmetry factor. Those are the parameters that enable us to consider atmospheric aerosol.

The model uses a standard atmosphere model and an average annual ozone profile for mid-latitudes.

The model deals with three gases which absorb radiation in the UV and visible regions of the spectrum. They are $H_2O$, $CO_2$ и $O_3$, the calculation of the shortwave radiation fluxes is made for wavelengths from 0.125 to 4 μm. The entire interval is divided into three sections:

1. 0.125–0.31 μm - ultraviolet radiation;
2. 0.31–0.75 μm - visible light;
3. 0.75–4 μm – near-infrared solar radiation (NIR).

Radiative transfer in different spectral intervals is determined by various factors. The choice of models and calculation methods should take these factors into consideration.

It is necessary to solve the transport equations for a scattering and absorbing atmosphere for calculation fluxes in the visible spectrum.

The considered algorithm for calculating the downward flux of solar radiation allows us to represent
the flux as a sum of direct and diffuse radiation, which is necessary for further recalculation for inclined surfaces.

Direct solar radiation flux on an arbitrarily oriented inclined surface $S$ [6]:

$$S_i = S_m \cos i$$  \hspace{1cm} (1)

where $S_m$ is irradiance distribution on a surface normal to the sun; $i$ is the angular distance.

The angular distance $i$ cosine can be accounted as follows:

$$\cos i = \cos \alpha \sin h + \sin \alpha \cos h \cos (\psi_S - \psi)$$  \hspace{1cm} (2)

where $\alpha$ is the angle of inclination of the surface relative to the horizontal plane; $\alpha = 90° - \Theta$; $\Theta$ represents the zenith angle; $h$ is the zenith the sun’s position angle; $\psi_S$ is sun azimuth; and $\psi$ is the surface azimuth.

For this purpose the sun’s position angle and azimuth can be evaluated as follows:

$$\cos(\psi_S) = \frac{\sin \delta \sin \varphi - \sin \delta}{\cosh \varphi}, \quad \sin(\psi_S) = \frac{\cos \delta \sin \theta}{\cosh \varphi},$$

$$\sin h = \sin \delta \sin \varphi + \cos \delta \cos \theta$$  \hspace{1cm} (3)

where $\delta = 0.4091 \cdot \sin(0.01717 \cdot (N - 80.5486))$ is the sun declination; $N$ is Julian day number; $\varphi$ is latitude; $\theta$ is local hour angle of true sun.

Direct solar radiation flux on an arbitrarily oriented inclined surface $S_i$ can be evaluated as follows:

$$S_i = S_m \left[ \cos \alpha (\sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \theta) + \sin \alpha \{ \cos \psi_S \left( \tan \varphi \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \theta \right) - \sin \delta \sec \varphi \} + \psi_S \cos \delta \sin \theta \} \right].$$  \hspace{1cm} (4)

The last equation can be evaluated as follows:

$$S_i = S_m \left( A_i + B_i \cos \theta + C_i \sin \theta \right)$$

$$A_i = \cos \alpha \sin \varphi \sin \delta + \sin \alpha \cos \psi_S (\tan \varphi \sin \varphi \sin \delta - \sin \delta \sec \varphi)$$

$$B_i = \cos \alpha \cos \varphi \cos \delta + \sin \alpha \cos \psi_S \cdot \sin \varphi \cos \delta \sin \delta \sec \varphi$$

$$C_i = \sin \alpha \sin \psi_S \cos \delta.$$  \hspace{1cm} (5)

Let $t_1$ and $t_2$ denote the hour angles, determining the moments of the beginning and end of illumination of the inclined surface. They are the roots of the equation:

$$A_i + B_i \cos \theta + C_i \sin \theta = 0.$$  \hspace{1cm} (6)

The global irradiation coming on an inclined surface $Q$ is obtained by summing three components:

$$Q = S + D + R,$$

where $S$ is an intensity of direct solar radiation on an inclined surface; $D$, $R$ diffuse radiation coming on an inclined surface from the atmosphere and the earth's surface, respectively.

The diffuse radiations can be expressed as:

$$D = \frac{D_{h} \left( 1 + \cos \alpha \right)}{2}; \quad R = \frac{Q_{h} \cdot A \cdot (1 - \cos \alpha)}{2}$$  \hspace{1cm} (7)

where $D_{h}$ is diffuse solar radiation entering a horizontal surface; $Q_{h}$ is global irradiation coming on an horizontal surface; $A$ is an average monthly albedo of the earth surface of the areas adjacent to the inclined surface.
Equations (7) are true if $D_{\text{hor}}$ and $Q_{\text{hor}}$ are isotropy. The isotropic approximation leads to significant errors in estimating radiation fluxes on inclined surfaces especially for clear condition. Downward bias is observed for surfaces facing towards the sun, and upward bias is observed for the opposite direction of the sun. Errors are reduced for cloudy condition. This decrease is various for differently oriented surfaces. This decrease is various for differently oriented surfaces.

The assumption of isotropy gives a satisfactory result in the convergence of measured and calculated flows in continuous cloud case.

3. Performance assessment

The values of direct, scattered and total radiation on a horizontal surface and vertical surfaces are presented in the work [7]. Data are presented for the main eight orientations for July.

For these conditions calculations were performed using the software package. Comparison of tabular data and calculation results is shown in figures 1, 2.

**Figure 1.** Total $Q$ (●), straight $S$ (▲) and diffuse $D$ (■) radiation coming to the horizontal surface in July: a solid line is the results of the calculations; a dashed line is the reference data.

**Figure 2.** The total $Q$ (●) and direct $S$ (▲) radiation coming to the vertical surface of the southern orientation in July: the solid line is the calculation results, the dashed line is the reference data.

The results of calculations of total solar radiation for various latitudes on a horizontal surface agree well with the corresponding values in [7]. Differences in values of direct and diffuse solar radiation do not exceed 10%, which is quite satisfactory for engineering calculations.

The downward bias of the total flux is a consequence of the assumption that the streams of diffuse radiation are isotropic for walls of southern orientation.

The model allows the effect of the aerosol on the illumination of an arbitrary surface to be taken into
account. Several optical models of the aerosol and models of the vertical profile of the optical depth of the aerosol layer are presented in [8]. Two vertical aerosol profiles, urban and continental, were used in the calculations. They are recommended for urban industrial and rural continental areas, respectively.

The effect of the aerosol layer on the direct radiation fluxes was considered. Data on the registration of direct solar radiation fluxes at two actinometric stations is presented in figure 3. These actinometric stations are Leningrad and the village of Voeikovo. They are situated at the same latitude (60°N) and are recommended as a model for urban industrial and rural continental areas.

In a large city, the annual intake of total radiation is underestimated due to a decrease in direct radiation. Values of direct radiation for the entire year at the station Leningrad are less than Voeikovo due to the high dust content of the atmosphere.

![Figure 3](image-url)

*Figure 3.* The average monthly daily amount of direct solar radiation $S$, coming to a horizontal surface at meteorological stations in Leningrad (full line) and Voyekovo (dashed line), and the results of calculations for models of urban (□) and continental (●) aerosol.

Calculations performed using different models of the aerosol layer showed that the urban aerosol model describes the situation at Leningrad station well, and the continental model at Voejkovo station.

Thus, this model can be used to quantify the solar radiation fluxes, taking into account the actual state of the atmosphere, including the effects of anthropogenic and man-made pollution.

4. Conclusion
Interest in the calculation of solar radiation fluxes on variously oriented and inclined surfaces exists, and in recent years it has increased, which is associated with the development of renewable energy sources.

In Russia, the registration of solar radiation is carried out by the state meteorological service using a network of actinometric stations. The results of actinometric observations were published in special reference books between 1961 and 1990. They provide information on solar radiation falling on surfaces both horizontal and normal to the beam, as well as annual and monthly sums under various cloud conditions. Data on the arrival of radiation on walls of different orientations are given only for the month of July with a cloudless sky. These directories are published in limited editions, information is presented in tabular form.

Foreign computer databases on solar radiation have a more convenient form for presenting information, but their disadvantages include the absence of comprehensive comments on the use and a small number of Russian observation points.

The algorithm described above provides for the calculation of the intensity of direct, scattered and total solar radiation on an open surface of any orientation, located at an arbitrary angle to the horizon.
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