Exergy analysis of the potential of solar irradiation

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Abstract. In the study, determining the input value of the exergy of solar irradiation entering the frontal surface of the solar collector has become an issue. Several sources of information have been studied, and then a calculation method has been proposed. The article presents the calculation of the input exergy value for the exergy analysis of the solar irradiation potential. The result of the work performed is a computing program that calculates the solar energy supplied to the solar collector and can be used at any latitude and altitude above sea level.

1. Introduction
One of the most important questions in the study of the exergy analysis of the solar irradiation potential is what power of solar irradiation falls on the front surface of the solar collector. Power depends on many factors: latitude and altitude of the setup, cloud cover, solar collector shading, time of day and date. In addition, the power value changes throughout the day. The aim of the work is to study the results of previous studies [1], [2], [3], [4] and derive a calculation methodology in accordance with these results, or to propose a fundamentally new calculation methodology. The methodology for calculating the input solar power will allow calculating the efficiency of any type of solar collector in any region.

2. Methods
The object of this study is the loss of exergy of solar irradiation when passing through the atmosphere, depending on the geographical latitude of the solar collector installation and its height above sea level. Based on the available data (the power of solar irradiation in space is 1366.5 W/m² and the power coming per square meter of the earth's surface at sea level when the Sun is at its zenith is 1050 W/m²), the change in the power of solar irradiation is modeled depending on the height above sea level and the angle of sunrise above the horizon. The calculation formulas are based on the dependence of the power of solar irradiation on the density of the atmosphere and the path length of the sun's rays in the atmosphere. Further, the obtained calculation results are compared with the measurements of solar irradiation.

3. Results and Discussion
As an example, let us consider losses in a vacuum solar collector, because it is an experimental setup for carrying out measurements. The exergy flux of solar irradiation incident on the surface of the collector is equal to the sum of the transmitted exergy flux and the exergy losses. Exergy losses in the solar collector are divided into optical and thermal losses. Thermal losses are part of solar energy, which is converted into thermal energy in the solar collector, but is not used to heat the coolant and
dissipating in the surrounding air. Thermal losses are divided into heat-conduction losses, convection losses, and irradiation losses.

Optical loss is a part of solar energy that is not converted to thermal energy, when it gets to the solar collector. Optical losses are divided into:

1. loss of exergy flow due to blocking the solar irradiation flux by dust, dirt, scratches, or snow on the glass surface;
2. loss of exergy flow due to shading the collector surface by a support frame or visor;
3. loss of exergy flow due to cloud cover;
4. loss of exergy flow due to the fact that the rays are not incident on the solar collector at right angles;
5. loss of exergy flow due to the fact that not the entire collector area is occupied by a light-absorbing coating;
6. loss of exergy flow due to reflection from a spherical tube;
7. loss of exergy from shading the pipe by adjacent pipes;
8. loss of exergy flow in case the glass does not pass some part of the spectrum;
9. loss of exergy flow due to absorption inside the glass.

One of the goals of the research is to determine what power of solar irradiation reaches the Earth at different geographical latitudes. The power of solar irradiation outside the atmosphere of the Earth is 1366.5 W/m². This value is not suitable for determining the exergy flux incident on the surface of the collector, because large losses of solar irradiation power occur in the Earth’s atmosphere.

The loss of solar irradiation power in the atmosphere depends on the density of the atmosphere and the length of the path along which the sun's rays travel in the atmosphere. The density of the atmosphere depends on the temperature, pressure and height of the observer above sea level. The length of the path depends on the height of the observer above sea level and the height of the sun above the horizon.

In international monographs and journals, the path length of sunlight in the atmosphere is called “Air Mass”. To calculate the path length of sunlight in the atmosphere, a number of sources were analyzed [1], [2], [3], [4].

As a result of the study, a new option is proposed for calculating the power of solar irradiation incident on the collector. In the sources [1], [2], [3], [4], the path length and power of solar irradiation, depending on the angle of the sun rising above the horizon, vary linearly, and when calculating the power of solar irradiation entering the surface of the solar collector, the density of the atmosphere is not taken into account.

For the equator, when the Sun is at its zenith: the power of light passing through the atmosphere depends only on the density.

\[ \frac{dt}{I} = -d\rho \]  

Integrating the right and left sides of the equation and substituting the integration limits for the density from 0 to \( \rho \), and for the irradiation power from \( I_0 \) to \( I \), obtain (Figure 1):

\[ I = I_0 \cdot e^{-\rho} \]
Figure 1. The dependence of the power of solar irradiation on the height of the observer above sea level. The observer is at the equator. The Sun is at its zenith. The height of the observer above sea level is zero.

For the general case, it is necessary to take into account the path that the sun's rays pass through the atmosphere (Figure 2, 3):

- $S$ – the path length of sunlight through the atmosphere;
- $R$ – radius of the Earth (6371 km);
- $H$ – significant atmospheric altitude (40 km).

\[
S = \frac{\sqrt{H^2 + 2RH + R^2\sin^2h}}{R + H}, \text{ km}
\]  \hspace{1cm} (3)

Figure 2. Calculation of the path of sunlight in the atmosphere.
Figure 3. The dependence of the path length of the sun's rays in the atmosphere on the angle of the sun rising above the horizon.

For the general case, the power of solar irradiation incident on the collector is:

\[ I = I_0 \cdot e^{\left(-\frac{M \cdot R_0}{101325, Pa} \cdot \left(1 - \frac{L \cdot H_{obs}}{T_0} \right) \cdot \frac{h}{R \cdot \left(T_0 + L \cdot H_{obs}\right)} \right) \cdot \left(\frac{H^2 + 2 \cdot R_{Earth} + R_{Earth}^2 \cdot \sin^2 h - \sinh R_{Earth}}{40000}\right) \cdot 0.215}, \text{ W/m}^2 \]  

(4)

\( P_0=101325, \text{ Pa} - \text{ standard atmospheric pressure at sea level;} \)

\( T_0=288.15, \text{ K - standard temperature at sea level;} \)

\( g=9.80665, \text{ m/s}^2 - \text{ gravity acceleration;} \)

\( L=-0.0065, \text{ K/m - the average value of the vertical component of the temperature gradient in the troposphere;} \)

\( R=8.314447, \text{ J/molK is the universal gas constant;} \)

\( M=0.0289644, \text{ kg/mol - molar mass of dry air;} \)

\( H_{obs} - \text{ the height of the observer above sea level;} \)

\( H=40000-H_{obs} - \text{ the height of the atmosphere above the observer;} \)

\( h - \text{ the height of the Sun above the horizon;} \)

\( R_{Earth}=6371000, \text{ m is the radius of the Earth.} \)

As a result of the work, a program has been developed for calculating the energy received by the surface. The surface is perpendicular to the Sun. Cloudiness is not taken into account. Calculation can be carried out for any latitude and altitude above sea level. Some calculation results are presented below (Figure 4-6).
Figure 4. The dependence of the height of the Sun above the horizon and power on time. June 21st. Location – Novosibirsk.

Figure 5. Graph of changes in the energy of solar irradiation during the year. Location – Novosibirsk.
Figure 6. The dependence of the annual energy of solar irradiation on latitude

Conclusions
With the help of the program written as a result of the study, one can find out how much exergy of solar irradiation the solar collector receives, evaluate the efficiency of its installation in any region and calculate the power of the solar collector for any day, at any time of the year and at any altitude above sea level. The computing program may serve to find out the power of solar irradiation and the amount of energy that can be obtained from the sun for a certain period of time at a given altitude and latitude. Thus, the written program allows answering a number of questions rising after the installation of a solar collector, namely: whether it is necessary to install a solar collector in a particular region; whether it is necessary to use the collector all year round or only during a certain period of the year; how many solar collectors a particular consumer needs; and how quickly the collector installation will pay off.

References
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