Method of calculation solar radiation intensity and its application in solar dryers-greenhouses for production of fruits and vegetables

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Abstract. In the presented study measurements of solar energy flux density are discussed in a horizontal plane in Almaty area in 5 years term. Comparing obtained and the previously existed data, solar energy flux density can be characterized by mathematical model, which describes the intensity of solar radiation. Months are selected in the database, for which amount of solar energy in a horizontal plane is averaged in hours. A calculation of coefficients for direct exposure in angular planes is conducted and it is averaged over 300 (30 days × 10 solar hours) for sunny hours from May to September. Horizontal transfer coefficients in an inclined plane are calculated using well-known methods with direct radiation coefficients and average cloud cover.
[Kassymbayev B., Atihanov A., Karaivanov D., Zhumagulov Z., Mukatay N., Okey N. **Method of calculation solar radiation intensity and its application in solar dryers-greenhouses for production of fruits and vegetables.** *Life Sci J* 2014;11(10):687-689] (ISSN:1097-8135). http://www.lifesciencesite.com. 107

Keywords: Solar dryer, solar energy, solar radiation, pyranometer, climate, greenhouse, solar systems, convective dryer

Introduction

Nowadays, problems associated with tasks arising from a food program of the country, fuel and energy and environmental problems are becoming the major problems, which national economy is facing. The effect of solar energy use is perceptible, in particular, during an implementation of the most energy-intensive thermal manufacturing processes in solar systems [1].

The use of solar energy is an important reserve in an improvement of energy supply of agricultural processing equipment. A large energy intensity of processes of drying, as well as trends of drying equipment and technology development in recent years, require not only an improvement of their design, but also a search for alternative solutions of the problem [2]. A thorough overview of principles of solar energy, its functioning, design and economical aspects of solar thermal processes exists [3].

Radiation resources of republics of Central Asia can allow to successfully use solar energy for that purpose during 6-7 months of year [4]. An implementation of solar energy, based on the application of greenhouse effect is the most effective in southern areas, where in the period vegetable raw materials processing, high densities of solar radiation (from 0° up to 10 °W/m, and more) are registered, and fabrication of valuable products is estimated in hundreds of thousands tons per season [5]. To formulate accurate thermal models, a calculation of accurate solar radiation input and overall heat transfer coefficient is important, as it affects the greenhouse energy and mass balance [6]. An implementation of solar energy separately or in combination with an additional source of energy is used for drying herbs, mushrooms, tobacco, vegetables, fruit and many other products [7].

Sunlight spectral changes that affect quality and quantity of incoming solar radiation are valuable and can be achieved with the help of certain types of facing materials [8].

Development of optical properties of facing materials is focused on a high transfer of light, a reduction of thermal energy losses (for higher latitudes) and a reduction of heat input by radiation (for lower latitudes) [9]. Important issues are an improvement of energy efficiency of a greenhouse and use of renewable sources of energy, such as solar power systems [10].

Materials and methods

The proposed methodology is designed to reflect an assessment of a factor of convective air drying of solar collector with periodic and continuous action. In order to create a basis for a calculation from available solar energy and an assessment of drying processes with different durations, a method was developed, based on continuous measurements (2009-2013) of the existing base and climate data.

Solar energy flux density in a horizontal plane was tested with pyranometer. Pyranometer LI-200 is designed to measure global solar radiation, agricultural purposes, meteorology and solar energy studies. Pyranometer converts signal to a digital multimeter with main error of ± 0.01 %, and interface can be connected to the computer for continuous recording at intervals of 1 minute. For measuring the system is calibrated at the Kazhydromet of Almaty. The database is processing during a month an average daily total solar radiation. Transfer speed of direct radiation from a horizontal plane averaged at 300 (30 days × 10 solar hours) is calculated as the ratio in average for each hour for sunny hours from May to September. A long-term assessment of solar system of measurements, generated by the database, is processed and presented as a continuous function of average time for a selected month.

Experimental results

Measurements results are presented in the form of average daily total solar radiation from May to September in the period of 2009-2013. Data for daily average for total solar radiation measurements are compared with the existing climate data in table 1. In order to use that data for a long-term assessment of systems, solar energy selection by month is used. A selection by month is conducted in a way which ensures that measured total solar radiation is the closest to the corresponding value of original climate data.

Table 1. Processing of measurements data by month

Average daily total solar radiation in a horizontal plane – MJ/m² for northern latitude φ = 43.15 (Almaty)						
	Period	May	June	July	August	September
Measurements	2009	20.37	23.25	20.75	16.12	19.38
Measurements	2010	23.02	20.29	19.65	16.60	10.49
Measurements	2011	21.15	20.32	17.29	13.39	10.09
Measurements	2012	19.79	20.25	17.00	12.26	7.17
Measurements	2013	16.15	19.08	18.07	12.21	10.08
Average	2009-2013	20.68	21.29	19.02	14.46	11.03
Handbook [11]		20,52	22.66	23.62	20.79	16.96
NASA [12]	10 years period	20.99	22.14	19.94	15.34	9.76
NASA [12]	22 years period	20.99	21.63	19.58	15.04	9.86

An approximation of functions of average solar radiation intensity Hx, (W/m ^{2}) is represented as a fourth degree polynomial expression for each month in table 2. Equation is valid during each hour, thus, in May and June – 5 to 18 hours, in July and August – 6 to 18 hours, and in September – 6 up to 17 hours.

Table 2. Intensity of solar radiation

Month	Function	
May	$H_X = 0{,}0875\tau^4 - 3{,}58\tau^3 + 36{,}98\tau^2 + 27{,}49\tau - 641{,}2$	$R^2 = 0{,}9937$
June	$H_X = 0{,}0452\tau^4 - 1{,}828\tau^3 + 10{,}3\tau^2 + 214{,}05\tau - 1121{,}4$	$R^2 = 0{,}991$
July	$H_X = 0{,}02105\tau^4 - 9{,}652\tau^3 + 140{,}1\tau^2 - 668{,}3\tau + 903{,}4$	$R^2 = 0{,}9971$
August	$H_X = 0{,}2317\tau^4 - 10{,}96\tau^3 + 170{,}2\tau^2 - 961{,}6\tau + 1775{,}3$	$R^2 = 0{,}9908$
September	$H_X = 0{,}2774\tau^4 - 12{,}92\tau^3 + 203\tau^2 - 1223{,}9\tau + 2478{,}2$	$R^2 = 0{,}994$

Data on average daily intensity of solar radiation is estimated by a distribution of total solar radiation for each hour in a month. Obtained data is presented in table 3.

Table 3. Daily average solar radiation intensity in a horizontal plane by hour %

Average daily solar radiation intensity in a horizontal plane by hour %					
Hour	May	June	July	August	September
5	0.48	0.10	0.12	0.00	0.00
6	3.32	3.06	2.09	1.42	0.35
7	5.88	5.63	4.78	3.92	3.08
8	8.02	7.74	7.45	6.78	6.74
9	9.63	9.35	9.76	9.49	10.37
10	10.67	10.43	11.47	11.64	13.25
11	11.09	10.97	12.40	12.96	14.91
12	10.92	10.99	12.48	13.27	15.08
13	10.20	10.49	11.71	12.54	13.73
14	9.00	9.53	10.17	10.86	11.05
15	7.45	8.15	8.04	8.42	7.46
16	5.70	6.44	5.57	5.56	3.61
17	3.94	4.48	3.12	2.70	0.38
18	2.38	2.38	1.11	0.43	0.00
19	1.30	0.27	0.05	0.00	0.00

Average monthly solar radiation falling on inclined surfaces, is defined by the equation:

$$H_H = k_H . H_X \, , \qquad (1)$$

where NH is average monthly daily intensity or total radiation falling on a horizontal surface and an obtainment of a coefficient of solar radiation transmission in an inclined plane.

Projections of a coefficient of a relationship between solar radiation intensity under inclined and horizontal planes are calculated:

$$k_H = \left(1 - \frac{H_{\partial\phi}}{H_x}\right) k_{\Pi P} + \frac{H_{\partial\phi}}{H_x}\left(\frac{1+\cos\beta}{2}\right) + \mu\left(\frac{1-\cos\beta}{2}\right). \qquad (2)$$

Three members of the equation, considering an influence of direct, diffuse and reflected radiation from the Earth (is reflection coefficient of environment). Ratio of average daily diffuse radiation to total NDF Hx is a function of cloud Px.

Transfer speed of direct solar radiation is calculated as follows:

$$k_{\Pi P} = \frac{k_{30}}{k_X} = \frac{\cos 30}{\cos\theta_{сл}} \, . \qquad (3)$$

In the equation 3 values in one minute for each day for selected above month are calculated. Obtained values are averaged for each hour. Results for average daily values for each hour, during daylight hours are shown in table 4.

Table 4. The average daily values for each hour

	$k_{ПР} = k_{30} / k_X$					
	May	June	July	August	September	October
6:30	0.618	0.553	0.571	0.679	1.242	1.003
7:30	0.872	0.804	0.829	0.950	1.259	2.113
8:30 AM	0.981	0.921	0.945	1.051	1.277	1.683
9:30 AM	1.038	0.984	1.006	1.100	1.285	1.573
10:30 AM	1.068	1.017	1.038	1.125	1.289	1.528
11:30 AM	1.081	1.032	1.052	1.136	1.291	1.511
12:30 PM	1.081	1.032	1.052	1.136	1.291	1.511
1:30 PM	1.068	1.017	1.038	1.125	1.289	1.528
2:30 PM	1.038	0.984	1.006	1.100	1.285	1.573
3:30 PM	0.981	0.921	0.945	1.051	1.277	1.683
4:30 PM	0.872	0.804	0.829	0.950	1.259	2.113
5:30 PM	0.616	0.553	0.586	0.679	1.242	1.873
Average	0.943	0.894	0.906	1.01	1.274	1.682

The total solar radiation on a horizontal plane from climate change data is divided by percentage (shown in the table) of 3 hours. In average from daily values for each hour of solar radiation total solar radiation is calculated on inclined plane hours. On the basis of cost characteristics of energy analysis process and an availability of solar energy, coverage coefficient of renewable sources of energy in the long term is estimated.

Closing remarks

During the measurement database has been created on solar radiation in the form of a continuous function of time and total solar radiation in hours. Calculated average value of coefficients of direct solar radiation transfer in inclined plane in hours allows to obtain a long-term assessment of continuous and periodic processes of solar energy absorption.

Conclusion

1. In the presented study multifunction solar dryer-greenhouse was designed and its construction was justified, design documentation was prepared and it was manufactured at the pilot plant of Kazakhstan Research Institute for Agriculture Mechanization and Electrification, Almaty. Equipment has been installed in training and production sector of Kazakhstan National Agrarian University and transferred by formal document for further exploitation.
2. In accordance with the requirements specification, the experimental model of equipment utilizing energy from solar batteries with total power of about 5-6 kilowats was manufactured and mounted.
3. Innovative patent for the invention Republic of Kazakhstan "Solar dryer-greenhouse" No. 26684 from 02.06.2013 was obtained.

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6/20/2014

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