Подано методику розрахунку геометричних параметрів плоского дзеркального концентратора сонячної енергії. Отримано аналітичні залежності для обґрунтування ефективності застосування плоского дзеркального концентратора для різних азимутальних кутів орієнтації параметрів горизонтальної сприймальної поверхні повітряного колектора відносно інтенсивності надходження сонячних променів. Наведено результати експериментальних досліджень енергетичних характеристик роботи дзеркального концентратора у комплекті з повітряним колектором

Ключові слова: сонячна енергія, геліосушарка фруктів, дзеркальний концентратор, сприймальна поверхня, повітряний колектор

Представлена методика расчета геометрических параметров плоского зеркального концентратора солнечной энергии. Получены аналитические зависимости для обоснования эффективности применения плоского зеркального концентратора для различных азимутальных углов ориентации параметров горизонтальной воспринимающей поверхности воздушного коллектора относительно интенсивности поступления солнечных лучей. Приведены результаты экспериментальных исследований энергетических характеристик работы зеркального концентратора в комплекте с воздушным коллектором

Ключевые слова: солнечная энергия, гелиосушилка фруктов, зеркальный концентратор, воспринимающая поверхность, воздушный коллектор

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SUBSTANTIATION OF THE EFFECTIVENESS OF USING A FLAT MIRROR CONCENTRATOR IN THE SOLAR DRYER

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1. Introduction

In the modern world, to replace scarce traditional types of energy (electrical or thermal), alternative sources are increasingly used. One such source is solar energy that can be utilized for the generation of electrical energy or low-potential heat, particularly for drying wet materials of plant origin.

A significant disadvantage of solar energy is low intensity of radiation. In order to eliminate this shortcoming, flat mirror concentrators (FMC) are employed, which make it possible to increase the flow of sun rays onto the receiving surface of the air collector (AC). This makes it possible to improve performance efficiency of the solar dryer.

In many cases, however, the effectiveness of using FMC and the implementation do not match expectations. The reason most often is the designers' unjustified choice of technological tasks that do not take into consideration the peculiarities of receiving and generation of solar radiation under different modes of lighting, different from the natural solar flux. Therefore, it is expedient to consider separately the impact of various factors on the actual power of air collector, in particular:

1) angular orientation of parameters of the receiving surface of AC;

2) maximum degree of concentration of incident rays on the way to the light-sensitive coating of AC absorber;

3) coefficient of increase of energy illumination;

4) optimum values of a dihedral angle (focline) between the mirror and the collector (system of degree coordinates);

5) ray trajectories between the mirror and the collector.

At present, in order to correctly assess energy indicators when using FMC in the solar dryer, it is important to know not only the total intake of solar energy. It is also required to consider at which irradiance it arrives and at what time of day. In this regard, in order to enhance heat output of AC and capacity of the photovoltaic modules, it is expedient to use FMC. FMC have not been widely applied in heliotechnics up to now, in particular, for the solar dryer. This predetermines the relevance of choosing the optimal design of FMC whose effective application in the solar dryer is possible only based on the substantiation of its rational design and technological parameters.

2. Literature review and problem statement

There are currently many procedures for estimating efficiency of FMC based on the application of the algebra of radiation heat exchange flows, or using methods of geometrical optics. This is due to the fact that the main requirement for FMC is maximizing the intake of direct and scattered flows of sun rays on the horizontal AC surface.

Paper [1] reports results of research into energy characteristics of the photo electric module ISM-50 under two modes of lighting – by a natural flow of solar energy and by the flow intensified by a flat dihedral mirror concentrator. However, there are no quantitative characteristics of light flows, no linear and angular relations between elements of the optical circuit.

Article [2] presents geometric constructions and mathematical ratios only for systems with a multi-fold reflection, and a high degree of concentration, which are used in a limited number of installations. A typical consumer most often employs a single- or two-mirror system with a low degree of concentration.

To enhance the heat output of AC, authors of paper [3] propose using FMC in the morning and in the evening. In many cases, however, effectiveness of the implemented installations does not match expectations. The reason is the designers' unjustified choice of technological solutions of FMC that do not take into consideration the peculiarities of generation of AC under the modes of lighting, different from the natural solar flux. That is why the main disadvantage of AC as a source of heat is the instability of output power due to daily irregularity in the intake of solar energy, with a random component for variability of weather.

FMC are usually not used in the traditional heating solar installations, equipped with AC and thermal accumulators, because the processes of generation and consumption in them are typically shifted in time. Instead, flat mirrors are often employed in photovoltaic systems for autonomous power supply in order to build up power of generation without additional photovoltaic modules, which is described in paper [4]. In this case, when the uniform lighting is required, mirrors are rigidly coupled to the photovoltaic modules on turning platforms that synchronously follow the Sun. However, due to the technical complexity of AC tracking mode and a small degree of concentration of FMC they do not use in the solar technical systems.

Authors of paper [5] perform analysis of drying plants using solar energy and substantiate design-technological parameters. The calculations come down to the alignment and stabilization of the drying mode during changing lighting conditions applying a backup electrical heater. Such a possibility of operational change at the same time of the two parameters of heat carrier – temperature and speed in the morning and in the evening – was implemented by turning on an electrical heater. However, the authors of proposed installation did not take into consideration the use of FMC to increase the input flow in the morning and in the evening, instead of turning on the electric heater.

The effectiveness of FMC was proved when investigating performance of photovoltaic modules in article [6], in which photocurrent and efficiency increase in proportion to the input flow. Thus, based on the results of comparative studies, the performance of photovoltaic modules grows by 38 % at additional concentration of rays with two FMC arranged by the scheme of a dihedral focline. However, the proposed method did not consider components of the cross-section of direct flow between the mirror and the collector and its normal relative to their planes.

A dependence of the degree of concentration of sun rays on the size of the mirror and the choice of the optimum angle of its inclination to the plane of the collector is given in paper [7]. In particular, for the case of normal angle of lighting according to the scheme shown in Fig. 1, coefficient of increase in energy illumination of the receiving surface is calculated from formula

$$k = 1 + \rho \cdot \frac{L}{S} \cdot \cos\alpha \cdot \cos(180 - 2\alpha), \quad (1)$$

where k is the coefficient of increase in energy illumination; ρ is the coefficient of mirror reflection; L and S are the areas of FMC and AC, respectively; α is the angle of deviation of FMC.

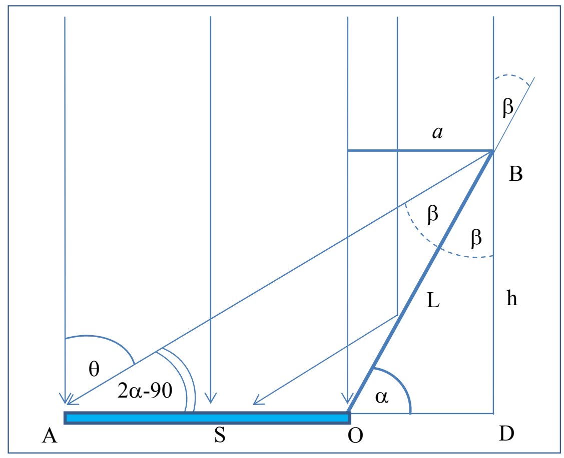

Fig. 1. Schematic of the path of rays reflected by a flat mirror of length L

It was established that in the case of a single flat mirror, an increase in the energy illumination of a photovoltaic module is achieved with the least expenditures at equality of planes $L \approx S$, angle of deviation $\alpha = 58...60^o$, coefficient of increase in energy illumination $k \approx 1.25$. The procedure described is very general and does not meet modern achievements in solar engineering. In particular, flows of energy illumination through translucent enclosures are calculated according to the recommendations of construction climatology [7]. They include tables of standard averaged flows of energy from direct and scattered radiation at clear skies. It enables estimation through tabular values of the mean energy illumination of the receiving surface and a factor of cloudy sky. For most of the applied problems, such estimations can be replaced (without compromising their accuracy) with the ready results of calculations for surfaces of the typical orientation, available at the NASA web-site [8].

In paper [9], a fixed air collector for almost all day is lightened with incident rays, which corresponds to a particular case of irradiation in the sunny afternoon. Quantitative evaluation of the effectiveness of flat mirrors at incident illumination of the receiving surface is partially shown in studies. The authors confine themselves to considering mutually perpendicular arrangement of the mirror and the receiving plane. It is shown that the overlapping area of the sunny bunny and the receiving surface are calculated using three ratios, depending on the height of the Sun above the horizon and its azimuth at morning and evening. Thus, at a deviation from the mutual orthogonality of the mirror and the collector, one should separately construct the path of rays, perform appropriate calculation of the effectiveness of concentration, and verify it experimentally.

During cloudless weather, the main incoming flow consists of direct sun rays while the intensity of those scattered by skyline and reflected by the environment is an order of magnitude less. That is why parameters of the concentrator are calculated only relative to direct sun rays while the contribution of a diffusion component to the AC capacity can be detected only experimentally.

Thus, in order to increase AC performance of a solar dryer, we propose the use of FMC. In many cases, however, effectiveness of the implemented installations does not match expectations. The main reason is the designers' unjustified choice of technological solutions that do not take into consideration the peculiarities of generation of radiation-convective heat exchange under the modes of lighting, different from the natural solar flux. That is why it is advisable to consider the character of the impact of separate factors on the actual capacity of AC. Thus, a crucial aspect for making a decision when employing FMC in the solar dryer is the substantiation of its optimal design and technological parameters.

3. The aim and objectives of the study

The aim of present research is the substantiation of optimal geometrical ratios of the flat mirror concentrator and air collector relative to the angles of orientation and arrival of energy illumination (solar energy).

To achieve the set aim, the following tasks had to be solved:

– to devise a procedure for the calculation of effective application of the flat mirror concentrator for different angles of orientation of arrival of energy illumination (solar energy) on the receiving surface of the air collector;

– to verify adequacy of results of theoretical and experimental studies.

4. Materials and methods for the substantiation of effectiveness of using a flat mirror concentrator in the solar dryer

Establishment of the optimal values of dihedral angle (focline) between the mirror and the collector relative to the angle of incidence of sun rays on the surface of AC implies finding the equations of borders of the "sunny bunny" in the plane of collector. Since FMC are typically rectangular in shape, instead of the equations of borders it is possible to use coordinates of dimensional points of the "sunny bunny".

Despite the simplicity of the set task, solving it in a general case leads to rather cumbersome expressions. That is why we shall demonstrate below a solution to the problem for the variants widely used in practice when the mirror concentrator and the collector have the same size and are arranged at angle α.

A flat mirror concentrator is placed back to back to the receiving surface at angle α whose optimal value depends on the ratio of the transverse dimensions (apertures) of the receiving surface of air collector (S_{ac}) and mirror (L).

In the case of following the Sun, geometry of enhancing the flow of solar energy by a flat mirror corresponds to schematic (Fig. 2). In line with a given schematic, the mirror can be mounted on any side of AC.

Thus, the fixed collector is almost always illuminated by the incident rays. That is why it is more appropriate to mount FMC for them from both directions – western (in the morning) and eastern (in the evening) – to enhance incident flows of the morning and evening irradiation. Optimizing requirement for them is the maximum coverage of the receiving surface of collector with reflected rays at minimally permissible area of the mirror. Moreover, in contrast to the solar modules, thermal collectors allow uneven illuminance and incomplete coverage by reflected rays.

At perpendicular flow of direct rays and at equal width of the collector and the mirror, coefficient of concentration does not exceed 1.25. Increasing it by widening the mirror is irrational because of disproportionate costs. Therefore, for the case of incident illumination width L of the mirror concentrator is accepted such that it equals width of the collector S_{ac}. A corresponding schematic of ray path is shown in Fig. 3 [11]. In order to calculate a degree of concentration, all angular magnitudes will be expressed through the angle of disclosure of a dihedral focline, formed by the planes of the collector and the mirror α.

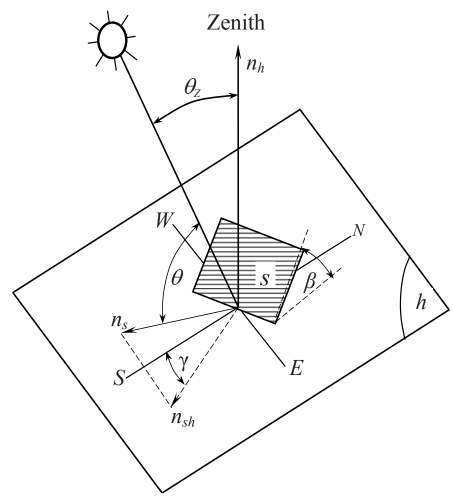

Fig. 2. Angular orientation parameters of receiving surface S: θ_z – zenith angle; θ – illumination angle; h – plane of horizon; n_s – normal to plane S; n_{sh} – projection of normals n_s onto the plane of horizon; γ – azimuth angle (coordinate) of the receiving surface; β is the angle of inclination to the horizon; NS – the line of the meridian [10]

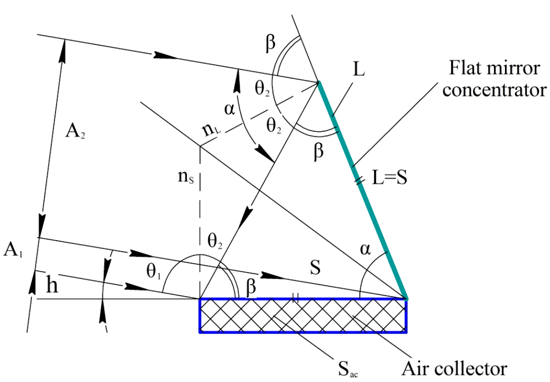

Fig. 3. Path of rays between the mirror and the collector: L and S are, respectively, the width of mirror and collector; α – disclosure angle of the concentrator; A_1 and A_2 – cross section of the incoming direct and reflected flows; n_s and n_L – normals to planes S and L; θ_1 and θ_2 – angles of incidence of rays on the collector and the mirror; h and β – angles of slip and reflection of rays

At a requirement of uniform illumination by reflected rays of the surface of collector, a reflected ray is the base of an isosceles triangle (method of geometrical optics). Thus, the following obvious relations follow from the construction shown in Fig. 3:

$$\left.\begin{aligned} &\beta = 90° - \frac{\alpha}{2}, \\ &\theta_2 = 90° - \beta = \frac{\alpha}{2}, \\ &h + \beta = \alpha \text{ or } h = \alpha - \beta = \alpha - 90° + \frac{\alpha}{2} = \frac{3}{2}\alpha - 90°, \\ &\theta_1 = 90° - h = 90° - \frac{3}{2}\alpha + 90° = 180° - \frac{3}{2}\alpha. \end{aligned}\right\} \quad (2)$$

The slip angle varies within $0<h<90°$. Then the upper bound of the angle of disclosure is determined from the following inequality:

$$h = \frac{3}{2}\alpha - 90° < 90° \text{ or } \alpha < 120°.$$

Thus, the lower bound of the angle of disclosure α is equal to 60°, because otherwise the reflected extreme ray will shift to the right from the edge of the collector. That is why this magnitude does not go beyond the interval:

$$60° < \alpha < 120°.$$

Flow gain coefficient is equal to the ratio of the total energy illumination of the collector $E=E_1+E_2$ to the illumination only by direct rays E_1. E_1 and E_2 are calculated from the corresponding cross sections of the incoming direct and reflected flows of sun rays A_1 and A_2:

$$E_1 = A_1\cos\theta_1;\ E_2 = \rho A_2 \cos\theta_2,$$

where ρ is the reflection coefficient of the mirror, $\rho=0.8$ [6].

Hence

$$k = \frac{A_1\cos\theta_1 + \rho A_2\cos\theta_2}{A_1\cos\theta_1} = 1 + \rho\frac{A_2\cos\theta_2}{A_1\cos\theta_1}.$$

Both cross sections are the functions of an angle of disclosure of the concentrator α:

$$A_1 = S\cdot\sinh = L\cdot\sin\left(\frac{3}{2}\alpha - 90°\right) = = -L\cdot\sin\left(90° - \frac{3}{2}\alpha\right) = -L\cos\frac{3}{2}\alpha, \quad (3)$$

$$A_2 = L\cdot\sin(\alpha - h) = L\cdot\sin\left[\alpha - \left(\frac{3}{2}\alpha - 90°\right)\right] = = L\cdot\sin\left(90° - \frac{\alpha}{2}\right) = L\cdot\cos\frac{\alpha}{2}. \quad (4)$$

After reduction and elementary trigonometric transformations, we shall obtain an expression for the coefficient of concentration of solar power:

$$k = 1 + \rho\frac{A_2\cos\frac{\alpha}{2}}{A_1\cos\left(180° - \frac{3}{2}\alpha\right)} = 1 + \rho\frac{\cos^2\frac{\alpha}{2}}{\cos^2\frac{3}{2}\alpha}. \quad (5)$$

In the case of horizontal arrangement of the collector, the slip angle equals angular height of the Sun above the horizon, which is supplementing that of the zenith. For the collector, oriented towards southern direction and tilted at angle to the horizon, the angle of slip is counted from the plane of the receiving surface. Then it is more convenient to employ illumination angle θ_1, which can be calculated from ratio (2).

The progress of AC illumination by the sum of direct and reflected flows is calculated from formula

$$E_\beta(\tau) \simeq k(\tau)\cdot R_\beta \cdot E^{\max}\cos\pi\frac{\tau}{\tau_c}. \quad (6)$$

where τ is the time counted from the moment of solar noon, h; R_β is the factor of average monthly intake of solar radiation, which is calculated by the tabular values of average monthly azimuthal angle of Sun set [8]; $E^{\max}$ is the maximum energy illumination of the horizontal surface of air collector, W/m^2; τ_c is the duration of arrival of solar energy, s; τ is the transmittance coefficient of solar radiation.

The values of $E^{\max}$ and duration of light day τ_c for a slanted surface are established experimentally.

The obtained expressions make it possible to calculate the flow gain factor of the arrival of solar energy (5) and maximum energy illumination (6).

5. Results of performance efficiency of the flat mirror concentrator in a solar dryer

The performance efficiency of a flat mirror concentrator depends on the gain coefficient of the flow of solar energy k and optimum angle of disclosure α of FMC.

According to the procedure for calculating the geometrical optics, described in chapter 4, we determined numerical values for a gain coefficient of the flow of solar energy k from the optimal angle of disclosure of FMC α. The results are summarized in Table 1.

Table 1

Values of gain coefficient of the flow of solar energy k

Parameters	Indicators											
α	65	70	75	80	85	90	95	100	105	110	115	120
h	7.5	15	22.5	30	37.5	45	52.5	60	67.5	75	82.5	90
θ_1	82.5	75	67.5	60	52.5	45	37.5	30	22.5	15	7.5	0
k	8.45	6.00	4.44	2.88	2.16	1.8	1.58	1.44	1.35	1.28	1.23	1.20

An analysis of the obtained results showed that when using FMC, a gain in the flow of energy illumination on a slanted surface of AC in the morning from 7:00 to 10:00 $E^{\max}$ is from 456 to 965 W/m^2, and in the evening period from 17:00 to 20:00 – from 734 to 223 W/m^2 (Fig. 4). Thus, the energy illumination of the external surface of AC grew by 1.2 times, and heat output – by 1.3 times.

Graphic dependence k=f(α) makes it possible to graphically determine the optimal angle of deviation of FMC in order to increase the flow of energy illumination on a slanted surface of AC (Fig. 5).

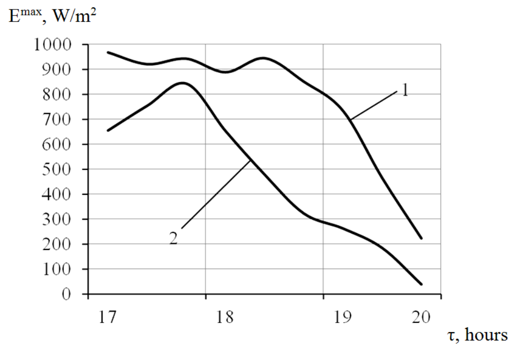

Fig. 4. Energy illumination of the slanted surface of AC in the evening: 1 — with a concentrator; 2 — without concentrator

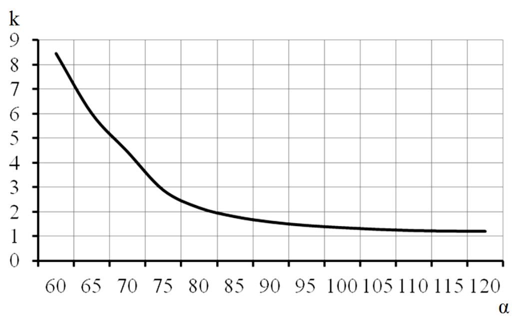

Fig. 5. Dependence of gain coefficient of the flow of solar energy k on the disclosure angle of concentrator α

It follows from graphic dependence shown in Fig. 5 that an increase in the energy illumination of AC is achieved with the least expenditures at *L*=*S* with angle of inclination from 90° to 120° and the flow gain coefficient k from 1.8 to 1.2.

Therefore, research results allow us to propose optimal opening angles of FMC. In this case, an increase in the energy illumination on a slanted surface of AC is achieved with the least expenditures at *L*=*S* with an opening angle from 90° to 120° and the flow gain coefficient of solar energy k from 1.8 to 1.2.

6. Discussion of results of research into effectiveness of using a flat mirror concentrator in a solar dryer

Using FMC increases requirements to the accuracy of AC orientation towards the Sun. The effectiveness of applying FMC was proved during research into performance of photovoltaic modules whose photocurrent and efficiency grow in proportion relative to the incoming flow of energy illumination by 38...59 % [6].

The FMC in question has spectral selectivity that makes it possible to create a narrow-band filter concentrator. Such a property of the mirror concentrator is its main advantage over other existing concentrators when use it in a solar dryer. This makes it possible to separate the incoming solar radiation into two components: the visible spectrum, by concentrating it on the concentrator, and the "thermal" spectrum, which will be sent to the absorber of AC.

Thus, there is no need in creating a device to follow the Sun. When the Sun moves across the sky, the concentration of the radiation incident on the receiver is achieved by employing a system of degree coordinates. This system is derived from the optimal indicators of the gain coefficient of the flow of solar energy *k*, applied onto a holographic film.

We substantiated efficiency of using FMC in a solar dryer based on the enhancement of maximum energy illumination that arrives on the horizontal plane of AC in the form of direct solar radiation.

The devised analytical dependences (2)–(6) allow us to estimate efficiency of using FMC for different azimuthal angles of orientation of the system of degree coordinates.

When utilizing FMC, a growth in the energy illumination of AC is achieved with the least expenditures at *L*=*S* with angle of inclination from 90° to 120° and the flow gain coefficient *k* from 1.8 to 1.2.

However, our study does not include a design-technological scheme of FMC, which would be very appropriate for the proper estimation of energy indicators when using FMC in the solar dryer.

Thus, the application of FMC in the solar dryer makes it possible, in the morning and in the evening, to improve annual average capacity of incoming solar radiation on the receiving surface of air collector by an order of 3.41 kW/m² during daylight [12]. This enables receiving, amplifying, and directing to the absorber of AC from 1.5 to 2.3 kW·h of energy per day from 1 m² of FMC.

7. Conclusions

1. We substantiated optimum geometric ratios for the path of rays between the mirror and the collector in the form of degree coordinates a. The analytical dependences (2)–(6) are proposed that make it possible to estimate the efficiency of using FMC for different azimuthal angles h and q_1 of orientation of parameters of the horizontal receiving surface of AC S and a system of degree coordinates a.

2. Based on the conducted research, we determined rational values of dihedral angle (focline) α between the mirror and the collector that are 90...120°. It was established that a gain coefficient of the flow of solar energy *k* is attained with the least expenditures from 1.8 to 1.2.

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