Small Solar Installations

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Abstract: The paper considers small solar installations, which are developed and created at the Institute of Materials Science of the Academy of Sciences of the Republic of Uzbekistan. The authors of the article operate a Large Solar Furnace with a thermal power of 1000 kW and have extensive experience in operating and building solar high-temperature furnaces. Small solar installations are simple, cheap and easy to operate.

Keywords: Solar furnace, Concentrator, Facet, Focal plane, Solarradiant flux.

INTRODUCTION

The Large Solar Furnace with a thermal power of 1000 kW of the Institute of Materials Science of the Academy of Sciences of the Republic of Uzbekistan is a complex, expensive, unique installation [1]. There are only two such multifunctional installations for technological purposes all over the world - in France in the city of Odeillo and here in the Parkent region [2].

In Uzbekistan, there are usually 250-270 sunny days, which means that solar energy can be used all year round [3]. For the efficient use of solar resources, it is advisable to build small, simple, cheap concentrators of the solar radiant flux [4].

Figure 1: Innovative polygon with small solar concentrators, hybrid: wind-solar combined installation.

For this purpose, we have developed and created small solar concentrators for various purposes: parabolic-cylindrical concentrators, Fresnel linear mirror concentrators, solar cookers of various designs and shapes of the concentrator, a solid paraboloid concentrator with a diameter of 1.5 m, a small solar installation with a thermal power of 1.5 kW [5]. Figure **1** shows an "innovative testing ground" created by young scientists from the Institute of Materials Science.

Small Solar Furnace with a Power of 1.5 kW

(A) (B)

Figure 2: Small solar installation for technological purposes. A) a paraboloid solid concentrator with a diameter of 2 m; B) a composite heliostat 2.80 m in size with 16 facets 70x70 cm in size and a solar sensor to control the heliostat for the apparent movement of the Sun.

The Small Solar Furnace (SSF) built by us at the Institute of Materials Science of the Academy of Sciences of the Republic of Uzbekistan allows us to conduct technological experiments on the production of high-temperature, refractory, abrasive, wear-resistant, heat-resistant ceramic materials based on oxide minerals using highly concentrated solar radiation. Also, the 1500 W multifunctional small solar furnace allows to test materials for light fastness, convert a highly concentrated radiant flux of the sun into laser

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radiation, production of green hydrogen by thermolysis of wateretc. [6-9].

Table 1: The Main Characteristics of the Heliostat of a Small Solar Furnace

Parameters	Values
Total reflective surface area	7.84 square meters
Number of individual facets	16 pieces
Facet specular reflection coefficients	70-75%
Facet dimensions	70x70 cm
Facet thickness	6 mm
Reflective surface errors	Less than 1 arc minute
solar sensor	1 piece
Automatic control system of the heliostat according to the apparent motion of the Sun with an accuracy of one minute of arc	1 piece
Angle of rotation in azimuth	±50 degrees
Elevation rotation	0-70 degrees
The maximum speed of the heliostat	0,1 degree per second
Reflective surface	Backcoating aluminum
Maximum operating time per day	10 hours

Small Solar Furnace's Concentrator

The main characteristics of a small solar furnace with a power of 1.5 kW. One-piece concentrator with a diameter of 2 m, focal length 0.85 m, concentrator depth 0.29 m, concentrator rear reflective surface aluminum, concentrator surface area 3.16 m2, mirror reflectance 70%.

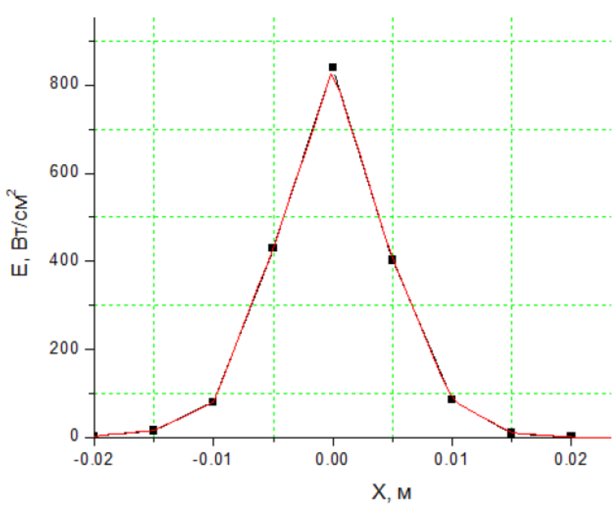

Figure 3: Calculated values of the density distribution of the concentrated radiant flux on the focal plane of the concentrator.

One such solar furnace was sold to the Hyderabad Institute of Powder Metallurgy (Republic of India), and the second to Egypt, the Taba Metallurgical Institute.

Table 2: Main Parameters of Small Solar Furnace Concentrator

Parameters	Values
Concentrator diameter	2.0 m
Reflective surface area	3.46 m^2
Focal length	0.85 m
Opening angle	120^0
Reflective surface	Aluminum Reflection coefficient 70-75%
Reflective surface accuracy	3 minutes

Heliostat Facet Alignment for a 1500 W Small Solar Furnace

Theoretical Part

One of the complex problems in the operation of Solar Furnaces (SF) is the preservation of the initial alignment and the constant assessment of accuracy, and adjustment, if necessary, of the optical surface of the heliostat.

To align the SSF heliostat, one of the simplest and at the same time providing good accuracy is the adjustment method using an auxiliary screen.

Let us determine the calculation formulas for the coordinate (on the heliostat) of the image of sighting targets (marks on the screen) and the accuracy characteristics of this heliostat adjustment method.

Let us introduce the following systems of Cartesian coordinates:

1. General coordinate system. Beginning at the center of the heliostat, axes directions: X_1 to the zenith, Y_1 to the west, Z_1 to the south (toward the concentrator)

2. Heliostat coordinate system. Beginning at the heliostat center, axes directions: Z_2 along the heliostat normal, X_2 along the heliostat height, Y_2along the heliostat width (to the west).

3.Screen coordinate system. Start in the center of the screen, axes directions: Z_3 along the screen normal (to the south), X_3 along the mark height, Y_3 along the mark width (to the west). Let now $R(x_t , y_t , z_t)$ the point of intersection of the optical axes of the telescope (theodolite) relative to the first system. Then, when setting the heliostat in the above way, its angular coordinates are determined from the formulas:

$$tgA = \frac{x_t}{z_t} \quad tgh = \frac{x_t}{\sqrt{y_t^2 + z_t^2}} \tag{1}$$

Note that the coordinates of the point R are determined in terms of the coordinates of the screen center (x_0, y_0, z_0). The center of the screen is located at a distance of 18 m from the center of the heliostat in the direction constituting with the optical axis of the concentrator 10 degrees.

Let's denote by P(x_3, y_3, z_3=0) the coordinates of the sighting target under consideration (brand on the screen) in the screen coordinate system. We translate the coordinates of this point into the heliostat system. First, we translate the coordinates into a common system:

$$\begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} = T_2(-\phi)\begin{pmatrix} x_3 \\ y_3 \\ z_3 \end{pmatrix} + \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} \tag{2}$$

and now to the heliostat system

$$\begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} = T_2(-h)T_1(A)\begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} \tag{3}$$

or

$$\begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} = T_2(-h)\,T_1(-A)T_1(-\phi)\begin{pmatrix} x_3 \\ y_3 \\ z_3 \end{pmatrix} + T_2(h)T_1(-A)\begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} \tag{4}$$

where T_1 and T_2 are matrices of counterclockwise rotations around the X and Y axes.

After simple transformations, taking into account z = 0, we obtain:

$$\begin{aligned} x_2 &= x_3(cosh cos\phi + cos A\, sin h\, sin\phi) - y_3\, sin A\, sinh \\ y_2 &= x_3\, sin A\, sin\phi + y_3\, cos A \\ z_2 &= x_3(sinh\, cos\phi - cos A\, cosh\, sin\phi) + y_3\, sin A\, cosh + d \end{aligned} \tag{5}$$

where d is the distance between the heliostat center and point T.

Let us now determine the image coordinate (x, y) in the heliostat system. In the heliostat system, the image of the point P(x_3 , y_3 , z_3) will be the point P' with coordinates (x_3, y_3, -z_3) . The observer at the point N(0,0,d) sees the image on the surface of the heliostat at the point determined by the intersection of the heliostat plane and the straight line passing through the points P' and N. The equation of this straight line has the form:

$$\frac{x}{x_3} = \frac{y}{y_3} = \frac{z-d}{-z_3-d} = t \tag{6}$$

Since the plane of the heliostat is described by the equation z=0, therefore:

$$t = \frac{d}{d+z_3} \tag{7}$$

and finally:

$$x = \frac{d}{d+z_3}x_3 \qquad y = \frac{d}{d+z_3}y_3 \tag{8}$$

Let us now consider the issue of errors arising from inaccurate determination of the calculated coordinate. Without loss of generality, we will assume that the center of the considered facet is used instead of the calculated point (x, y) as the point where the observer should see the image of the sighting target. Then the direction of the facet normal is defined as follows:

$$\vec{N}_F = \vec{C} + \vec{D} \tag{9}$$

where

$$\begin{aligned} &\vec{C}(x_3 - x_c, y_3 - y_c, z_3 - z_c), \\ &\vec{D}(x_m - x_c, y_m - y_c, z_m - z_c) \end{aligned} \tag{10}$$

and (x_c, y_c, z_c) are the coordinates of the center (or an arbitrary point) of the adjusted facet in the heliostat system, the index m refers to the coordinate of the observer. In this system, it is obvious that the calculated direction of the normal N has components (0,0,1). Thus, the resulting error is equal to:

$$\sigma = arccos\frac{\vec{N}\,\vec{N}_0}{|\vec{N}||\vec{N}_0|} \tag{11}$$

According to this method, for each facet of the heliostat, the error corresponding to a unit of length is determined:

$$\sigma_L = \frac{\sigma}{\sqrt{(x-x_k)^2 + (y-y_k)^2}} \tag{12}$$

For a facet heliostat, as shown by numerical calculations, these values are very close to each other. The quantity:

$$\bar{\sigma}_L = \frac{\sum_{k=1}^{49} \sigma_{lk}}{49} \quad (13)$$

The experience of using this method of alignment in the Big Solar Furnace, Parkent, Uzbekistan (BSF) shows that the accuracy of heliostat alignment according to the proposed method is about one minute for facets without surface error. When adjusting bevels with surface errors, the adjustment accuracy depends on the magnitude of the surface error. At the same time, by assessing the distortion of the image of the sighting target (brand on the screen), it is possible to determine the operating state of the reflective surface of individual facets.

Practical Implementation of the Methodology

Since the size of the SSF heliostat is 2.8x2.8m, the screen should have a size of at least 4.8x4.8m (5.6x5.6m). For alignment, a theodolite is used as a telescope. Experiments have shown that in order to see at least one facet of the heliostat in the field of view of the theodolite and at the same time to see the marks on the screen and the heliostat, the theodolite must be located at a distance of 25-30 m. However, the latter circumstance is desirable, but not necessary, since changing focusing of theodolite can be sequentially seen marks on the screen and the heliostat. With this in mind, the distance from the heliostat to the heliostat was chosen to be 20 m. The SSF heliostat, by its design, cannot take a vertical position - this position is characterized by a zenithal angle of ≈12degrees. For the lowest position of the heliostat along the zenith (12degrees), the center of the screen should be located from the level of the lower row of the heliostat at a height of $2.8 + 20\text{tg}12^0 \approx 7.05$ m, which is high enough and it is not advisable to install the screen at such a height (difficulties and inconvenience of the adjustment process, low accuracy of the screen installation and etc.). If it is required that the lower row of marks on the screen be at ground level, then for this the heliostat must assume a position in which the zenithal angle has a value of about 3^0. This position can be achieved if several connecting tubes of the heliostat frame are temporarily removed from the lower row of facets.

In this case, if the screen also has an inclination of 3 degrees, the marks on the screen are located on the tops of a square with a size of 80 cm, and there is no need to use the calculated coordinates of the marks on the heliostat. The centers of the facet heliostat can be used as these coordinates.

Let us determine the accuracy requirement for the installation of marks, *i.e*. adjustment accuracy (combination of heliostat and screen marks). Let L be the distance between the heliostat and the screen, α-inaccuracy of the facet normal. Then, if the normal has an inaccuracy of 1 minute, the reflected beam deviates from the correct direction by 2 minutes. From here, to achieve the minute accuracy of the adjustment, we have $L\ \text{tg}2\alpha \approx 1.1636$ cm.

To align the heliostat, a flat screen 4.8x4.8m in size was made and installed. It consists of 49 symmetrical stamps (crosses) spaced 80 cm apart.

The Sequence of Adjustment of the Facet Heliostat

First of all, it is necessary to install the theodolite in the center of the screen in its plane. Further, it should be noted that at first it is necessary to choose the basic direction of the heliostat normal (the normal of one of the facets), to which the normals of the other facets are reduced. This is usually the normal of the central heliostat. To select it, the central facet (heliostat) is installed in such a way that the mark of the central facet and the exit round hole of the theodolite (the central mark of the screen) are combined in the field of view of the theodolite. However, if it is found (visual observation or observation with the help of a theodolite of the state of alignment of the remaining facets) that the alignment of the central facet is violated, then it must first be adjusted. If this is not done, the entire surface is adjusted to the new base normal. Therefore, before starting the adjustment of the heliostat, it is necessary to control the state of adjustment of all facets and select the most appropriate basic direction (averaged normal) as the base one. This can be achieved by changing the positions of the heliostat and at the same time achieving the minimum difference between the heliostat and screen brands for all facets. After performing this operation, *i.e*. the choice of the base normal, it is necessary to fix the position of the heliostat (the position cannot be changed further).

Then, the individual facets of the heliostat are sequentially adjusted. For this work, 2 operators are needed - the first on theodolite, the second on the heliostat. The first operator first places the theodolite on the center of the facet to be adjusted and marks the corresponding mark on the screen. Then, at his command, the second operator, using adjusting bolts (there are three of them), bring the screen brand to the heliostat brand. At the same time, if the screen brand is at the top and bottom, it uses the upper adjusting bolt (if the fac*et al*ong the upper bolt rested against the heliostat frame, then it is necessary to use the lower two bolts). If the mark is on the left or right, the bottom two adjusting bolts are used. This process continues until the adjustment of this facet. Then they move on to the next facet to be adjusted. In this case, it is not allowed to adjust the position of the theodolite itself. And in this sequence all facets of the heliostat are adjusted.

The marks on the facets are applied in their centers. If, when moving from one facet to another, the distance between their centers differs from 40 cm, then the distance between the corresponding screen marks should also not be 80 cm, but double the distance between the centers of the facets. This can be noted on the screen or kept in mind when aligning. For example, if the distance between facets is 39.5 cm, then the corresponding distance on the screen is 79 cm, *i.e*. as a mark, use a point located 1 cm (80-79) from the original in the appropriate direction.

Sun Sensor Adjustment

The adjustment of the solar sensor is carried out according to the location of the focal spot of the furnace. Therefore, first of all, it is necessary to install a screen in the focal plane of the furnace (in principle, it should be a water-cooled white, diffusely reflecting screen, but some kind of refractory sheet or refractory brick can be used for this purpose). The focal plane of the furnace is located at a distance of 85 cm from the top of the paraboloid. The focal point on this plane is defined as the point of intersection of the horizontal and vertical lines of sight. For these lines, 4 marks are marked on the hub. On a properly installed screen, two perpendicular coordinate axes are plotted, the intersection of which is the focal point.

The sensor is adjusted using four sensor adjustment screws. Two bolts are used to change the horizontal position and two for the vertical position. With the help of these bolts, a circular symmetrical spot is achieved at the focal point of the furnace. In this case, only with the correct position of the sensor is the minimum size of the focal spot achieved [10].

Smelting and Synthesis of Materials on a Small Solar Furnace

In solar high-temperature furnaces, various types of melting plants are used to melt materials. According to the principle of work and purpose, they can be classified. The following common types of melting furnaces can be noted:

- melting furnace type "Hat";
- Centrifugal furnace;
- Batch-continuous furnace;
- Ladle furnace.

Many years of experience in the operation of the Large Solar Furnace with a thermal power of 1000 kW shows that melting furnaces of the “Hat” type and batch-continuous operation are more productive.

The ladle furnace is intended for experimental melts in small portions with constant stirring during the melting process in order to achieve homogeneity of the melted material and to avoid delamination of the melt products. Melting on this furnace makes it possible to achieve superheating of the melted product and then to carry out a one-time unloading of the entire portion. Controlling the furnace with the help of swings makes it possible to have a continuous stream of melt drain and adjust its intensity. The design of the furnace provides for a one-time loading of material in a certain volume. The melting process in a ladle furnace is periodic. The furnace is installed on a coordinate trolley (table), together with which it has all the degrees of freedom necessary for experiments. Ceiling *i.e*. the upper inner part of the furnace is polished before each melting and is used as a reflector of energy coming from the lower part of the concentrator, due to which the already melted material is additionally heated and maintained in a liquid state in a horizontal position.

When the material is rocked in the liquid phase, it moves from one part of the furnace to the opposite one through the focal spot. Passing through the focal spot, the material is constantly heated and mixed, thus achieving homogeneity of the fused material [11,12].

Experiments carried out on solar furnaces show that the highest melting performance is achieved when the zone with the maximum concentration of light energy is located on the vertical surface of the melted materials [13]. The material heat treatment plant, which creates favorable heating conditions, has the highest melting capacity and allows the melting of large and small batches of materials.

The maximum heat fluxes occur on surfaces perpendicular to the optical axis of the concentrator. Therefore, for high-performance melting, it is necessary that the material surface irradiated by the concentrator has the form of a vertical wall and makes a right angle with the optical axis. However, it is impossible to obtain a vertical wall from powders. Therefore, it is convenient to create a vertical wall from small extruded elements. When melting, the front elements are sintered to form a single body, which is held by the melt solidified upon contact with the cooled surface of the furnace [12, 13].

For continuous organization of the melting process, a device in the form of a water-cooled flat annular shape (a melting furnace of the "hat" type) can be used. Pressed elements are placed in the annular plane in a continuous ring in the form of a vertical wall relative to the lower surface. If the device is tilted at a certain angle, then the vertical wall will be aligned with the focal plane in the working area. This causes the organization of the discharge of the molten material (during melting) in the form of a jet in the center of the working area and the preservation of this condition during rotation of the device [12].

Passing through the focal plane, the section of the furnace is freed from the material, which melts and flows down. As the furnace rotates, the liberated section goes beyond the focal zone, and another section with a full load takes its place. When leaving the focal zone, the vacated area is loaded with a new batch of material. It should be noted that the setup also allows simple experiments on testing materials for light fastness. Additionally, the method and device allows for such processes as hardening of materials when establishing special modes of heating and cooling [14].

One of the most common melting methods is to use the melted material itself as a crucible. In this case, the melting of the material occurs up to a certain depth of the material, and then it is necessary to bring an unmelted portion of the material into the focal zone. To ensure draining of the molten material, it is possible to prepare the source material in the form of a rod with a diameter of its size corresponding to the size of the image of the sun on the focal plane of the furnace. As the end of the rod melts, the next section of the rod is fed into the focal zone.

Special melting crucibles are used for melting powdered materials. They vary in form and purpose. In this case, the melting temperature of the crucible material must be higher than the melting temperature of the starting material.

In some cases, it is required to obtain molten material in the form of spheroids with a radius of fractions of millimeters. In these cases, so-called dispersants are used. This device is used to crush the spherical molten material. To obtain spheroids, it is necessary to achieve sintering of the molten material. The molten material, breaking away from the melt, under the influence of the force of surface tension in air, takes the form of a ball. The size of the ball depends on the viscosity of the melted material (the separation of the ball from the melt occurs when a certain mass of the ball is reached). Usually the size of the ball is a few millimeters. If this molten ball, before reaching a solid state, hits some surface, then it is divided into smaller parts, which also take the form of a ball. Moreover, the size of the newly formed ball depends on the composition of the melted material, the temperature state at the moment of impact, the impact force, etc. For this reason, some parameters of the dispersant can only be determined experimentally. The output material of the dispersant are small molten balls of different radii. Using a sieve with different resolutions, the balls are sorted by size.

For the 1500 W solar furnace, the following smelting methods can currently be applied:

- use of the melted material itself as a crucible;
- use of the source material in the form of a rod with a diameter of its size corresponding to the size of the image of the sun on the focal plane of the furnace.

CONCLUSIONS

A small solar oven allows you to get the body temperature in the focal zone of the concentrator more than 2000 degrees Celsius. Such an installation automatically monitors the apparent movement of the Sun, and the scattering spot is stationary, which ensures ease of operation of the furnace. One or two people are enough to conduct high-temperature research at the focus of a small solar furnace.

- A solar oven with a thermal power of 1500 W was developed and manufactured.
- A method for adjusting the reflective surface of the heliostat has been developed.

- A technology for manufacturing reflective mirrors has been developed.

- A bench was developed for measuring the reflection coefficient of heliostat mirrors.

- An automated heliostat tracking system for the Sun has been developed.

- Developed instrumentation to determine the optical-energy characteristics of the furnace.

- A method for calculating the optical-energy characteristics of the furnace has been developed, taking into account real influencing factors.

The prepared technical passport, combined with a technical description and operating instructions, is intended for studying a solar installation with a thermal power of 1500 W and contains all the necessary information about the device, the principle of operation and design of the incoming mechanisms and blocks, as well as the rules for operating a solar installation.

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