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Research and Calculation of the Coefficient for the Solar Radiation of a Flat Solar Collector

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Absract: This study deals with the study and the calculation of the coefficient of capture of solar radiation of a flat solar collector. The basic equations describing the energy balance of the flat solar collector. It is known that the surface of the transparent insulation the heat coming down: the flow of direct sunlight, the flow of the Sun's rays reflected from the mirrors and the flow of the scattered (diffuse) radiation from the sky, from the surroundings which are absorbed by the individual layers of the heating surface. Compiled energy balance equation, a single layer of the heat element. Because compiled equation for steady state surface density of captured radiation is equal to the surface density of the heat flow withdrawn from the working medium of the receiver element (coolant) or the average temperature of the latter does not differ from the ambient temperature. In the above case, capture ratio is plant efficiency. The equation shows that the surface density of the heat flow, coolant withdrawn from the receiver can be calculated as the surface density of the trapped radiation minus the conditional heat loss and efficient heat consumption for heating system. Flow captured radiation is not dependent on the heat capacity of the system. Through analysis and optimization of the solar energy collector carried on a flat cavity with a modified receiver with regard to the content of incident solar radiation.

Key words: Flat solar collector, solar radiation, thermal losses, thermal resistance, exergy, optimization

INTRODUCTION

Solar energy and renewable energy sources for the generation of thermal and electric energy without harm affect the environment (Zhai *et al*., 2013; Al-Sulaiman *et al*., 2011). The flat plate of the solar collector is the main component of solar heating and heat supply systems. The energy equation does not take into account the analysis of the efficiency of solar collectors, so, this is not a sufficient criterion for the efficiency of the solar collector (Dutta Gupta and Saha, 1990). It is necessary to optimize the design of the solar system and work. By Tyagi *et al*. (2007), Liu *et al*. (1995) and Torres-Reyes the efficiency and entropy of solar collectors were considered. Bejan *et al*. (1981) found that, the solar collector systems depend on the irreversibility of heat transfer (Amirgaliyev *et al*., 2018).

Compared to the flat plate, tubular collectors were evacuated from the point of view of exergy (Suzuki, 1988). The energy was calculated and the flat plate of the solar collector was analyzed (Jafarkazemi and Ahmadifard, 2013). The temperature of the liquid in the flat plate of the solar collector is equal to the ambient temperature (Luminosu and Fara, 2005). The optimum flow velocity was determined and the maximum efficiency of a flat plate was calculated (Farahat *et al*., 2009). Experimentally, found that the efficiency of solar collectors depends on the solar radiation, the geometry of the surface of the collectors in comparison with the flat plate of the solar heater (Akpinar and Koçyigit, 2010). Three solar power plants were compared experimentally where a heater with double covers made of glass and fins is more efficient than the other two (Alta *et al*., 2010).

The transformation of solar energy into electrical energy is getting more and more attention in recent years. Sunlight is the world's largest source of energy and the consumption of primary energy in the world. The true cause and magnitude of the waste and losses that are presented in this researcher are well suited for further research on more efficient use of solar energy will be determined by the exergy analysis method (availability analysis) (Hepbasli, 2008). To increase the efficiency and thermodynamic optimization of efficient solar energy systems, information can be used by Bejan *et al*. (1996).

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When a solar collector is used to convert energy, it is an exergy power not a way of collecting energy, to perform the required function (Kahrobaian and Malekmohammadi, 2008). With the help of the analysis of exergy, it is possible to calculate the exergy content of the incident solar radiation and the efficiency of the utilization of the solar energy of the entire system (Zamfirescu and Dincer, 2009). Exergy is the maximum amount of work to calculate the efficiency and solar radiation (Bejan, 1988). For more than 20 years, many works have been published including various approaches to this calculation. Among the first is Petela who calculated the maximum efficiency factor for determining the exergy of thermal radiation at (Temperature) T (Hepbasli, 2008). Currently, available for discussion of radiation exergy formulas proposed by several researchers (Zamfirescu and Dincer, 2009).

A new optimization method for parabolic solar collectors using exergy analysis was presented by Kahrobaian and Malekmohammadi (2008). Analysis of exergy and parametric study of the concentration of the solar collector was also presented by Tyagi *et al*. (2007). Kalogirou (2004) presented and analyzed the images of the reservoir model using the second law of analysis. A brief analysis of exergetic solar energy systems was presented by Hepbasli (2008). To determine the optimal performance parameters and design of exergic optimization of flat plates of solar collectors was submitted (Farahat *et al*., 2009).

Gupta and Kaushik (2008) presented exergy performance for the maximum supply of exergy in a flat plate of solar air heaters. Efficiency and optimal operation of a flat plate of solar collectors under conditions of exergy supply was investigated by Kar (1985). In these studies, reservoir performance was assessed without taking into account the uneven distribution of the absorber temperature and the heat loss factor. In this study, we present a theoretical model, the determination of the thermal losses of planar solar collectors into the environment.

MATERIALS AND METHODS

The solar collector is the main heat generating unit of the solar installation from the energy, operational parameters which directly depend on the corresponding parameters of the solar installation. Therefore, most of the world’s inventions and patents registered in the world are concentrated mainly in the field of creating new designs and technologies for solar collectors.

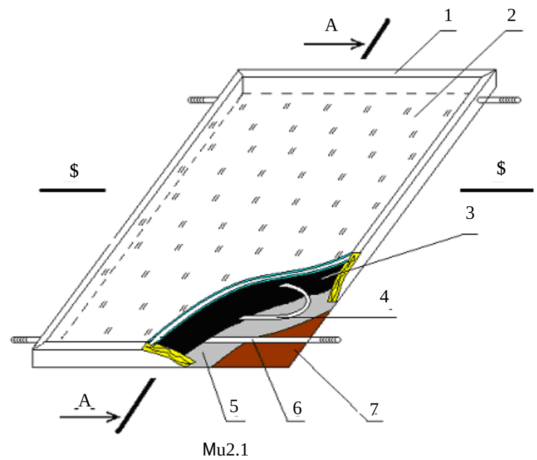

Fig. 1: Model of solar solar collector

To achieve this goal, we have developed principally new solar collectors on the basis of which a series of PGs for water heating will be created. Two variants of solar collectors are proposed:

- Plate collector with bitumen absorber
- Helical collector with semi-cylindrical reflector

A classic example of such a solar collector is a flat collector with a bitumen absorber (Fig. 1). To achieve this goal, it is proposed to implement a new approach to the design of solar collectors using modern materials, thereby achieving a significant reduction (2-3 times) of the cost of a solar power plant. The essence and novelty of the proposed method is that, unlike the well-known design principle, the collector contains a transparent double-glazed window 2 with double glass and reduced pressure as well as a perimeter frame 1. The bottom of the wooden frame 7 is made of 8 mm thick plywood. And a heat-insulating film 5 with foil is glued to them. In the gap, a flexible thin-walled stainless corrugated tube 4 Æ 16 mm is formed between the double-glazed window and the bottom of the frame in the form of a coil. The ends of the tube are attached to the inlet and outlet protruding pipes 6. The rest of the space is completely covered with bitumen 3 with a stamp 30 mm thick (Table 1 and Fig. 2).

The flux of solar radiation incident on a flat heat receiver consists of two components (Kahrobaian and Malekmohammadi, 2008):

$$E_{hr} = E_{sd} + E_{fs} \quad (1)$$

Where:

E_{sd} = A stream of direct solar radiation

E_{fs} = Flux of scattered radiation

Fig. 2: Full-scale model of a solar collector

Table 1: Technical characteristics of a flat solar collector

Flat solar collector	Values
Number of layers of transparent insulations	2
Area of one collector (m^2)	Дo2
Average temperature of water heating (°C)	60-80
Transmittance relative to solar radiation when the Sun's rays fall along the normal to the surface	0.89
Specific volume for coolant (l/m^2)	2.0
Absorption capacity in relation to solar radiation	0.99
Operating pressure (MPa)	0.7
Overall dimensions (m)	1×2
The product of the coefficient of optical efficiency and the efficiency factor of the absorbing panel	0.8
The product of the total coefficient of thermal losses of the collector and the efficiency factor of the absorbing panel	0.75
The ratio of the area of the heat-absorbing surface to the overall area	0.95
Collector weight (kg)	60
Service life, years	15

In turn, the solar energy is absorbed and converted into heat flow of the heat carrier in a flat heat receiver in the upper and lower parts:

$$E_{hr} = E_{total} + E_{str} \tag{2}$$

Where:

E_{total} = The total flux captured by the heat receiver surface through a transparent coating

E_{str} = The stream reflected from the mirrors at the bottom

As a result of the solution, we have:

$$q_{emk} = \frac{E_{no2\pi} - K_{np}\cdot\left(t_k^H - t_0\right)}{d_1 + \dfrac{K_{np}}{\dfrac{\lambda_k}{\delta_k}\cdot \pi d_2}} \tag{3}$$

The total amount supplied to the heat sink channels of the heat receiver is composed of heat absorbed by (directly) the surface of the heat sink channel and reflected from the semicylindrical reflectors.

Let us consider the basic equations describing the energy balance of a flat solar collector. It is known that, the surface of the transparent insulation of the heat receiver falls: the stream of direct sunlight, the flux of solar rays reflected from the mirrors and the flux of diffuse (diffuse) radiation from the sky from surrounding objects that are absorbed by separate layers by the heating surface. The heat fluxes released in separate layers of insulation and on the surface of the receiver are proportional to the surface radiation density E. The corresponding proportionality coefficients k are the radiation absorption coefficients in the individual layers of the system.

The heating surface of the solar receiver is insulated with a layer of transparent insulation with air interlayers which have transverse anti-convection barriers which form sealed cavities. Since, transparent coatings are opaque to the receiver's own temperature radiation and insulation elements, the heat transfer process can be considered in each interlayer.

The equation of energy balance of a separate layer of the element of the heat receiver will have the following form (Zhai *et al*., 2013):

$$q_v + \frac{t_{v+1} - t_v}{\dfrac{1}{k_{v+1}} - \dfrac{1}{k_0}} = \frac{t_v - t_{v-1}}{\dfrac{1}{k_v} - \dfrac{1}{k_{v-1}}} + c_v \cdot p_v \cdot \frac{dt_v}{d\tau} \tag{4}$$

Actually, for the receiver itself, the energy balance Eq. 5 can be represented in the following form:

$$\frac{t_k - t_p}{\dfrac{1}{k_p} - \dfrac{1}{k_k}} = q_p + \frac{t_p - t_k'}{\dfrac{1}{k_n} - \dfrac{1}{k_k'}} + c_k \cdot p_k \cdot \frac{dt_k}{d\tau} + c_k' \cdot p_k' \cdot \frac{dt_k'}{d\tau} \tag{5}$$

Solving Eq. 8 and 9, we find:

$$q_p = \sum \frac{k_p}{k_v} \cdot q_v - (k_p - k_k).(t_p - t_v) - \sum c_v \cdot p_v \frac{k_p}{k_v} \cdot \frac{dt_v}{d\tau} \sum c_v \cdot p_v \frac{k_p}{k_v} \cdot \frac{dt_v}{d\tau} \tag{6}$$

Where:

t = The temperature (°C)

q = Surface densities of heat fluxes released in separate layers and the flow of W/m^2 transferred from the receiver to the coolant

k = The coefficient of heat transfer from individual layers to the surrounding atmosphere (W/(m×°C)

c = Heat capacity of the material of the layers (W/(kg×°C)

p = The weight of the respective layers, per unit area of their area (kg/m^2)

t = The time (h)

Equation 6 for practical calculations is inconvenient, since, it contains derivatives, simplifying can bring Eq. 6 into a form more convenient for engineering calculations:

$$\begin{aligned}&\sum c_v \cdot p_v \frac{k_p}{k_v} \cdot \frac{dt_v}{d\tau} + \sum c_v' \cdot p_v' \cdot \frac{k_k}{k_v'} \cdot \frac{dt_v'}{d\tau} = \\ &\frac{dt_p}{d\tau}[\sum c_v \cdot p_v (\frac{k_p}{k_v})^2 + \sum c_v' \cdot p_v' \cdot (\frac{k_k}{k_v'})^2 = C\end{aligned} \quad (7)$$

where, C is the effective heat capacity of the installation, referred to the unit area of the receiving surface. The surface densities of the heat flux released in separate layers of transparent isolation and at the surface of the receiver can be represented as products of the surface radiation density by the corresponding absorption coefficients of the layers and, accordingly, the first term of Eq. 7 can be represented as follows (Zhai *et al*., 2013):

$$\sum \frac{k_p}{k_v} q_v = E; \ \sum \frac{k_p}{k_v} k_v = \gamma E \quad (8)$$

Where:

γ = The capture coefficient
E = The surface density of the captured radiation

From Eq. 8 considered, it follows that under steady-state conditions, the surface density of the captured radiation is equal to the surface density of the heat flux removed from the receiver element by the working substance (coolant) or the average temperature of the latter does not differ from the ambient air temperature. In the case considered, the catch factor is equal to the efficiency of the installation.

The catch factor the main optical-thermal characteristic of a solar installation is smaller in magnitude than the total coefficient. Let's call the sum $k_p(k)$ of the coefficients of heat transfer from the coolant to the ambient air through a transparent and opaque isolation with the total coefficient k, the thermal losses of the element of the solar installation and the product of k by the temperature difference Coolant and ambient air conditional heat loss which is less than true for as much as the steady-state capture mode, the radiation is less E absorbed. Introducing this notation, we represent Eq. 8 in the following form:

$$q_v = \gamma E - k(tp - t_v) - c\frac{dt_p}{d\tau} \quad (9)$$

This equation is differentiated with respect to time τ:

$$q_v = \gamma E = k(tp - t_v) - c\frac{dt_p}{d\tau} \quad (10)$$

$$q_v - \gamma_E + k(t_p - t_v) = -c\frac{dt_p}{d\tau} \quad (11)$$

$$\frac{q_v - \gamma E + k(t_p - t_v)}{c} = -\frac{dt_p}{d\tau} \quad (12)$$

The resulting equation, integrate the τ-time and find from this Eq. 13 the time τ:

$$\frac{1}{k}\int \frac{-d((t_p - t_v)k + q_p - \gamma E}{q_p - \gamma E + k.((t_p - t_v)} = \int d\tau \quad (13)$$

Further, we find the radiation trapping coefficient during the time τ:

$$-\frac{c}{k}\ln\left|q_p - \gamma E + k \cdot ((t_p - t_v)\right| = \tau \quad (14)$$

$$\ln\left|q_p - \gamma E + k \cdot ((t_p - t_v)\right| = -\frac{\tau k}{c} \quad (15)$$

$$\ln\left|q_p - \gamma E + k \cdot ((t_p - t_v)\right| = \frac{\tau k}{c} \ln e \quad (16)$$

$$\ln\left|q_p - \gamma E + k \cdot ((t_p - t_v)\right| = \ln e^{-\frac{\tau k}{c}} \quad (17)$$

$$\gamma E = q_p + k(t_p - t_v) - e^{-\frac{\tau k}{c}} \quad (18)$$

The solution of Eq. 18 with respect to the capture coefficient can be finally, presented in the following form:

$$\gamma = \frac{q_p + k(t_p - t_v) - e^{-\frac{\tau k}{c}}}{E} \quad (19)$$

The use of analysis of exergy for solar solar collectors helps designers achieve an optimal design and gives direction to reduce exergy losses. The concept of exergy is one of two ways of the second analysis of the law and the entropy of generation from irreversibility is another method. Nevertheless, both methods give essentially identical results. The use of the concept by the exergy method is preferable, since, it directly gives the system work that is achievable for ideal processes (Suzuki, 1988).

RESULTS AND DISCUSSION

Results and discussion. For calculation of thermal, geometric and exergetic models are presented in the

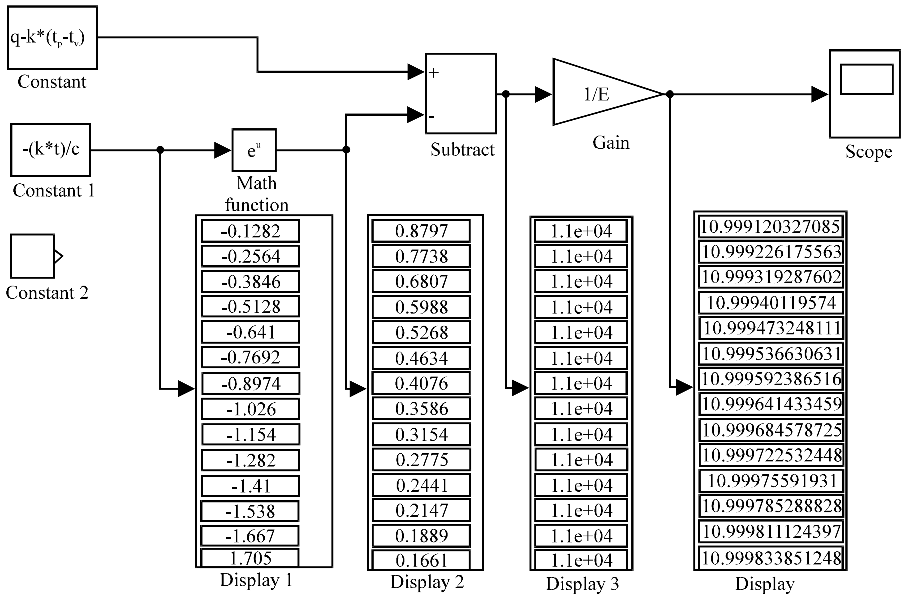

Fig. 3: Algorithm for calculating the radiation capture factor in the MATLAB Software package (Simulink)

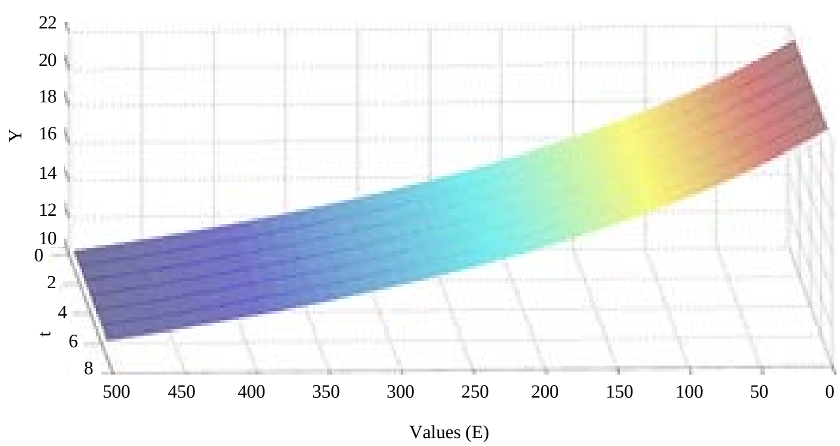

Fig. 4: Dependence of the capture coefficient on time, solar radiation and the surface density of the captured radiation

calculation program MATLAB. In the program, some of the geometric parameters and operating conditions can be variable. The objective function and its constraints are non-linear and have been developed numerically with the optimization of the MATLAB tools (Fig. 3).

In Eq. 19, the receiver radiation capture coefficient obeys an exponential regularity which is plotted as a function of time in accordance with Fig. 4. Equation 19 makes it possible to determine the functional dependence of the capture coefficient on time, solar radiation and thermophysical parameters of the receiver.

The calculated capture factor as a function of time shows that the surface density of the heat flux removed by the coolant from the receiver can be calculated as the surface density of the trapped radiation minus the conditional heat losses and the effective heat consumption for heating the system (Fig. 5). The flux of captured radiation does not depend on the heat capacity of the system (Wu *et al*., 2010):

$$\gamma_i = \gamma_0 * \cos \quad (20)$$

Where:

- γ = The radiation capture coefficient incident on the receiver at an angle
- i and γ_0 = The same value but for the rays normally incident on the receiver

Y-exponent of degree, depending on the design of transparent insulation, usually in the range of 0.5-1.5. For our case, when one layer of transparent coating we take the exponent of 1.5.

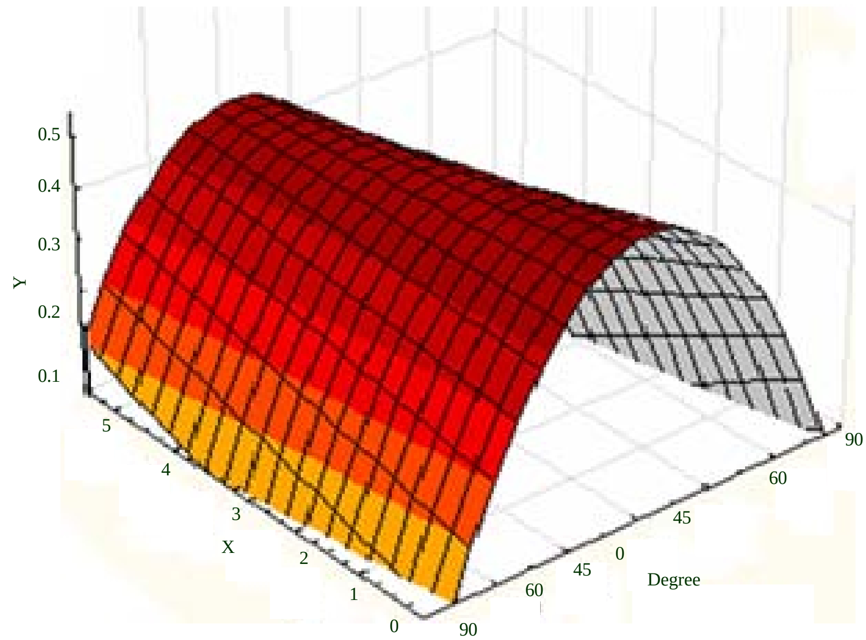

Fig. 5: Calculated capture coefficient versus time τ

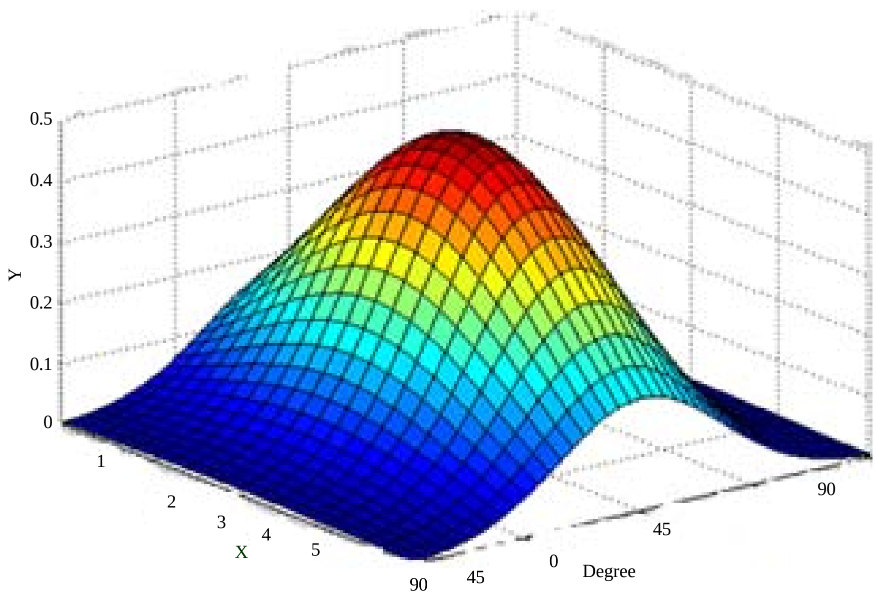

Fig. 6: Coefficient of radiation capture depending on the angle of incidence of rays on the surface of a flat heat receiver from the zenith point

According to the known trapping indicatrix, it is possible to calculate the trapping factor and the surface density of the heat receiver for any given distribution and along the directions of energy brightness, the radiation incident on the receiver in accordance with Fig. 6.

According to the known trapping indicatrix, it is possible to calculate the trapping factor and the surface density of the heat receiver for any given distribution and along the directions of energy brightness, the radiation incident on the receiver.

CONCLUSION

The coefficient of catching parallel beams for a given installation depends only on their direction, since, the values of the absorption coefficients kc depend on the direction and the ratio kp/kg for each layer represents constant factors. Dependence on the direction of the coefficient of capture of parallel rays the indicatrix of trapping is the main characteristic of the radiation receiver. For most receivers with transparent isolation, the capture indicatrix depends only on the angle i of the incident rays on the surface of the receiver. This dependence is accurate enough for most technical calculations.

Analysis and optimization of the exergy of solar energy was carried out on a flat collector with a modified cavity receiver taking into account the content of incident solar radiation. Applying the heat balance equation, the calculated capture coefficient versus time τ and the radiation capture coefficient were obtained as a function of the angle of incidence of the rays on the surface of the flat heat receiver from the zenith point. Increasing the efficiency of exergy with increasing temperature at the receiver to the optimum temperature is achieved and then begins to decrease. The main values of dimensionless exergy losses in this analysis are obtained by absorbing heat transfer, loss of exergy due to optical and thermal leakage losses. The dimensionless loss of exergy due to the increase in heat as the temperature of the receiver increases and the dimensionless destruction of the exergy is reduced. The method of analysis of exergy (availability analysis) presented in this article is well suited for the further purpose of more efficient use of solar energy as it gives the cause and the true amount of waste and losses to be determined. Such information can be used in the thermodynamic optimization of efficient solar energy systems and to improve the efficiency of existing ones.

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