Receiver Efficiency as a Determining Criterion for the Effectiveness of a Solar Tower

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Abstract

Concentrated solar energy as a source of renewable energy has a high potential for solving the current energy crisis. The article considers the energy balance of the solar tower air circuit and the efficiency of the solar station receiver. The method of its calculation is determined. It is shown that the solar tower receiver is important and determines the efficiency of the entire solar station. The physical essence of energy losses and the efficiency of structural elements of the solar tower receiver are investigated in detail to build an optimization function. A new approach to the construction of the objective function for optimizing the parameters of the open-type receiver of the solar concentrated station is proposed.

Keywords Concentrated solar power plants, volumetric receiver, renewable energy, energy efficiency, energy balance.

DOI Number: 10.48047/NQ.2022.20.16.NQ880365 **NeuroQuantology2022;20(16):3602-3609**

INTRODUCTION

The need to use renewable energy sources is determined by the following factors:

- rapid growth of demand for electric energy;
- energy independence of countries from fossil fuels;
- exhaustion of explored reserves of organic fuel in the nearest future;
- environmental pollution by nitrogen and sulphur oxides, carbon dioxide, dust residues from fossil fuel combustion, radioactive contamination and thermal overheating when using nuclear fuel [1].

Solar energy is widely used for the production of low potential heat and for the production of electricity. In the first case, flat solar collectors are used that do not concentrate (coolant - water, air, antifreeze). In the second - electricity from the light flux can be produced in two ways: by direct conversion in photovoltaic installations or by heating the coolant, which performs work in a thermodynamic cycle. Concentrated solar power plants (CSP) are used to use high potential thermal energy [2].

LITERATURE REVIEW AND PROBLEM STATEMENT

Energy and exergy efficiency of different CSP elements (turbine, generator, pumping group) is above 90 % [3]. The energy efficiency of the receiver does not reach 90 %, and the exergy efficiency is at best 60 %. Therefore, it is possible to achieve the highest efficiency with the lowest economic investment by improving the CSP receiver technology. To determine the levels of variation of the input parameters of the model, their significance (understanding their quantitative and qualitative impact on the defined output parameters), consider the energy and exergy balance of receiver.

The optimal configuration of the receiver cannot be calculated separately and is considered in conjunction with other parts of the solar tower[4]. Therefore, consider the balance of the receiver as a block with input and output parameters. Considering the energy balance of the air circuit of a solar tower with an open porous receiver, it is possible to write down the direct circuit efficiency

$$\eta_{rec}^{air} = \frac{Q_{use}^{air}}{I_{rec}},$$

Q_{use}^{air}– the heat energy transferred from the primary air heat transfer medium to the next circuit is defined as the difference in enthalpy between the air at the inlet and outlet of the heat exchanger or reactor in which the energy is transferred, kW;

I_{rec} – the solar radiation flux on the inclined receiver surface, kW;

and inverse balance

$$\eta_{csp}^{air} = \frac{I_{rec} - Q_{out}^{air} - Q_{refl}^{rec} - Q_{emi}^{rec} - Q_{h.tr}^{CSP} - Q_{loss}^{mirror} - W_{fan}}{I_{rec}},$$

$$I_{rec} - Q_{out}^{air} - Q_{refl}^{rec} - Q_{emi}^{rec} - Q_{h.tr}^{CSP} - Q_{loss}^{mirror} = \Delta H_f$$

Q_{out}^{air} – energy loss with the physical heat from the air leaving the solar plant to the environment, kW;

Q_{refl}^{rec} - energy loss by reflection of solar radiation in the porous absorber into the environment, kW;

Q_{emi}^{rec} - energy loss by emission (convective and radiation losses) in the porous absorber to the environment, kW;

$Q_{h.tr}^{CSP}$ – heat loss from the air circuit surface of the solar tower pipe and heat exchange to the environment, kW;

Q_{loss}^{mirror} – losses of solar energy from uneven arrival of solar radiation from mirrors, kW;

W_{fan} - power for internal air circuit needs, in the simplest case this is fan operation, kW;

or in relative terms

$$\eta_{csp}^{air} = 1 - q_{out}^{air} - q_{refl}^{rec} - q_{emi}^{rec} - q_{h.tr}^{CSP} - q_{loss}^{mirror} - K_w,$$

this $q_{out}^{air} = \frac{Q_{out}^{air}}{I_{rec}}$; $q_{emi}^{rec} = \frac{Q_{emi}^{rec}}{I_{rec}}$; $q_{h.tr}^{CSP} = \frac{Q_{h.tr}^{CSP}}{I_{rec}}$; $q_{loss}^{mirror} = \frac{Q_{loss}^{mirror}}{I_{rec}}$; $K_w = \frac{W_{fan}}{I_{rec}}$.

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Energy loss with the physical heat from the air leaving the solar plant to the environment, kW

$$Q_{out}^{air} = \left(H_{out}^{air} - H_{amb}^{air}\right) \cdot (1 - ARR) \cdot \varepsilon,$$

H_{out}^{air} – enthalpy carried with air, kJ/s;

H_{amb}^{air} – enthalpy brought in with ambient air, kJ/s;

ARR – air return ratio;

ε – a delay factor related to the time required to heat the exhaust air to a given temperature, for the stationary case = 1;

Each kg of dry air contains 125.98 kJ/kg of energy at 1 bar and 150 °C and 832.48 kJ/kg at 800 °C [5]. Achieving an ARR from 0.6 to 0.9 allows the system to feedback approx. 38 kJ/kg of energy. Therefore, the practical target for improvement of the new model is to achieve an ARR above 0.9.

For a typical calculation of the energy efficiency of a solar tower with volumetric receiver of open type, it is customary to take $I_{rec} = 1000$ kW/m² flux density in the aperture plane and 800 °C hot air temperature [6], $\Delta H_f = 1000\ kJ/kg$[7-9].

The five parameters are the defined output factors of the model. Each of these elements is responsible for different physical principles of energy conversion and depends on the complex parameters that have been proposed.

Energy loss by emission (convective and radiation losses) in the porous absorber to the environment in this case does not consider energy losses with the loss of returned air, since losses due to ARR reduction are considered in energy loss with the physical heat from the air leaving the solar plant to the environment. These costs depend on the thermal insulation of the circuit and the surface temperature of the absorber.

Energy losses during the reflection of solar radiation in a porous absorber into the environment is determined by the extinction coefficient.

Solar energy losses from uneven solar radiation from the mirrors depend on the dynamic parameters of the mirror field control program and the number of target points on the receiver. There is a function that combines the geometric dimensions of the receiver and the characteristics of the mirror field. Mirror losses for CSP depend on the number of target points, control system, geometric size and shape of the receiver. For a 4x5 meter receiver we have $q_{loss}^{mirror} \approx 0.2$. But this type of loss can be almost completely compensated by modern control systems and optimization of the number of mirrors.

The calculated efficiency equation on the reverse balance will clearly show which losses contribute most to the reduction in efficiency of the air circuit of a solar tower with an open porous receiver. Parasitic power consumption is approximately 2-10% of the total power generated [10].

Assessment of the efficiency of heat use in solar stations, regardless of their complexity, until recently was based on the application of the first law of thermodynamics, which reflects the quantitative side of thermal processes in these installations.

Exergy analysis of open-type receivers of tower solar stations considers the qualitative differences in the spatial arrangement of its elements and the irreversibility of real processes based on the joint use of the first and second laws of thermodynamics. Exergetic analysis of the receiver considers not only quantitative but also qualitative characteristics of the available energy potential in its various elements, the degree of their perfection and irreversibility of individual processes occurring in these elements and in the receiver as a whole.

The links established in the exergy analysis between the thermodynamic characteristics and technical and economic indicators of the receiver of the solar station make it possible to assess the effectiveness of its work, as well as to identify ways and means of improvement.

The basis of exergetic analysis is the concept of exergy. There are two types of exergy: exergy of such forms of energy, which are not determined by entropy, and exergy of matter and energy flows, which are characterized by entropy. The former includes mechanical, electrical, electromagnetic and other types of energy; the latter include forms of energy such as internal energy of matter, energy of chemical bonds, heat flow.

The exergy of a substance in a closed volume with thermodynamic parameters U, S, T, p and V is determined by the relation

$$e_v = (U - U_0) - T_0(S - S_0) + p_0(V - V_0)$$

e_V - specific (per unit mass) exergy of a substance;

U_c, S_0, T_0, p_0, V_0 - internal energy, entropy, temperature, pressure and volume of a substance at full equilibrium of the analyzed system with the environment.

The formula expresses the exergy of a substance in a closed volume in a process that ends with the alignment of the corresponding parameters of the system and the environment. When calculating the exergy of a working body (exergy carrier) in a closed system in two different states, the equation is reduced to the form

$$\Delta e_v = \Delta U - T_0 \Delta S + p_0 \Delta V$$

$\Delta U, \Delta S, \Delta V$ - changes in the parameters of substances during the transition from one state to another.

Determination of the exergy of matter in the movement of material and energy flows

$$e_{\text{т}} = q - T_0(S - S_0),$$

q is the specific heat flux carried by the substance;

S - entropy of the substance in the flow.

For ideal gases thermomechanical exergy is defined by the expression

$$e_{\text{т}} = c_p\,(T - T_0) - T_0\,[c_p \ln(\frac{T}{T_0})] - R\ln(\frac{p}{p_0})$$

where Cp is the specific heat capacity of the substance;

p and T - pressure and temperature of the substance in the flow;

R - gas constant.

The chemical component of the exergy associated with the thermodynamic parameters of the chemical reaction is calculated using various semi-empirical relations. Thus, for gases and liquids, the relations between their chemical exergy and the higher heat of combustion have been established, for example, in the processes of evaporation, rectification and drying

$$e_x = K Q_{\text{в}}^{\text{cr}}$$

where the coefficient K is equal to 0.975 (gases) and 0.95 (liquids) if the substance molecule contains more than one atom carbon.

When energy is transferred from the porous medium to the flow, its maximum efficiency decreases. If the heat receiver is a flow with temperature T_f, the specific exergy of the heat flow is

$$e_{h/t} = q_v \left(1 - \frac{\overline{T}_f}{\overline{T}_s}\right)$$

Loss of exergy in the receiver due to heat exchange with the environment

$$e_{emi} = q_{emi} \left(1 - \frac{T_0}{\overline{T}_s}\right),$$

q_{emi}- energy losses to the environment.

Exergy coefficient of absorber in relation to the environment [11]

$$E_{abs} = \dot{m}_{air} c_{p\_air} \left[\left(T_{air}^{out} - T_{air}^{in}\right) - T_0 ln\left(\frac{T_{air}^{out}}{T_{air}^{in}}\right) \right].$$

In this case, the uncertainty of the receiver exergy coefficient is given by 3605

$$\delta E_{abs} = \sqrt{\left(\frac{\delta E_{abs}}{\delta \dot{m}_{air}}\right)^2 (\delta \dot{m}_{air})^2 + \left(\frac{\delta E_{abs}}{\delta T_{air}^{out}}\right)^2 (\delta T_{air}^{out})^2 + \left(\frac{\delta E_{abs}}{\delta T_{air}^{in}}\right)^2 \left(\delta T_{air}^{in}\right)^2 + \left(\frac{\delta E_{abs}}{\delta T_0}\right)^2 (\delta T_0)^2}.$$

The efficiency of the receiver, in addition to affecting the efficiency of the entire solar power plant, as its element, also connects the efficiency of the concentrator field, the efficiency of the cooling circuit, the efficiency and size of the energy storage and the type of coolant. It is the type of receiver that sets the conditions for determining other parameters of the concentrated solar power plant. Total exergy losses in the receiver are estimated at one third of the exergy losses of the entire CSP, including the thermochemical storage [12]. Therefore, it is proposed to choose such initial model criteria that fully describe the efficiency of the solar tower receiver. As a rule, the efficiency of the receiver is found by the numerical model without dividing it into components [13, 14]. But this approach does not make it possible to analyze the dependent factors of influence on the receiver of the solar station, so for the modeling of the receiver it is considered as its indicators. The efficiency of an open receiver as the efficiency of its elements [15]

$$\eta_{rec}^{air} = \eta_{sp} \cdot \eta_{abs} \cdot \eta_{rad} \cdot \eta_{conv} \cdot \eta_{cond}$$

η_{sp} is efficiencies based on receiver spillage, the unused radiation hitting the sections around the receiver aperture;

η_{abs} is efficiencies based on receiver absorption;

η_{rad} is efficiencies based on receiver radiation;

η_{conv} is efficiencies based on receiver convection;

η_{cond} is efficiencies based on receiver conduction.

DECISIONS AND DISCUSSIONS

The efficiencies based on receiver spillage is determined by the ratio of the amount of solar radiation incident on the receiver surface to the reflected amount of solar radiation by the heliostat field. In addition to the field parameters and aiming points, this parameter will be affected by the shape and size of the receiver

$$\eta_{sp} = \frac{I_{rec}}{I_{mirror}}.$$

The efficiency based on receiver absorption is defined as the ratio of the amount of thermal energy received by the receiver (increase in the internal energy of the receiver, loss of thermal energy and energy transferred to the coolant) to the power of sunlight received on the surface of the receiver. The absorption of solar irradiation by the absorber surface is calculated using the raytracer FEMRay [16]. In addition to the absorber geometry of the absorber geometry, the distribution functions also depend on the absorption capacity of the absorber material and the direction of incidence solar radiation

$$\eta_{abs} = \frac{Q_{rec}}{I_{rec}}.$$

The efficiencies based on receiver radiation is the efficiency of retention and effective heat transfer deep into the absorber and is determined by heat losses due to radiation of thermal energy by the heated receiver into the environment Q_{loss_r}. Q_{loss_r} can be calculated according to the Stefan Boltzmann law.

$$\eta_{rad} = \frac{Q_{rec} - Q_{loss\_r}}{Q_{rec}}$$

or

$$\eta_{rad} = \frac{Q_{internalized}}{Q_{rec}},$$

$Q_{internalized}$ – heat energy internalized by the receiver.

$$Q_{internalized} = \Delta U_{rec} + \Delta H_f + \Delta H_{f\_loss} + Q_{loss\_en}$$

ΔH_f - change of fluid enthalpy;

ΔU_{rec} - change in the internal energy of the receiver;

ΔH_{f_loss} - increase in the enthalpy of air that has not reached the absorber; 3606

Q_{loss_en} - energy losses to the environment.

The efficiencies based on receiver convection is the ability of the receiver to maintain balance between forced convection and natural convection and prevent losses of returned air or air receiving heat energy from the receiver

$$\eta_{conv} = \frac{\Delta U_{rec} + \Delta H_f + Q_{loss\_en}}{Q_{internalized}}.$$

Convective heat losses depend on the geometric dimensions, orientation and design of the receiver, as well as wind speed and direction.

The efficiencies based on receiver conduction is indicator of the quality of thermal insulation of the system

$$\eta_{cond} = \frac{\Delta U_{rec} + \Delta H_f}{\Delta U_{rec} + \Delta H_f + Q_{loss\_en}}.$$

Thus, the main initial factors for building the receiver optimization model are defined.

Function of the target

$$\eta_{rec}^{air} = \eta_{sp} \cdot \eta_{abs} \cdot \eta_{rad} \cdot \eta_{conv} \cdot \eta_{cond} \rightarrow max$$

In expanded form

$$\frac{I_{rec}}{I_{mirror}} \cdot \frac{Q_{rec}}{I_{rec}} \cdot \frac{Q_{internalized}}{Q_{rec}} \cdot \frac{\Delta U_{rec} + \Delta H_f + Q_{loss\_en}}{Q_{internalized}} \cdot \frac{\Delta U_{rec} + \Delta H_f}{\Delta U_{rec} + \Delta H_f + Q_{loss\_en}} \to max$$

$$\frac{\Delta U_{rec} + \Delta H_f}{I_{mirror}} \to max$$

Input parameters of the absorber model:

- Dislocation vector k_y, k_z
- Pore shape and size, d_1,d_2,d_3, m
- Number of pores - n, pcs/m^3.
- Thermophysical parameters of absorber material, λ_s, c_{p_s}, ρ_s
- Thermophysical parameters of fluid, λ_f, c_{p_f}, ρ_f
- Optical parameters of the absorber material σ_β
- Optical parameters of the heat carrier σ_{af}, σ_{sf}

Input parameters of the absorber model with fluid=air:

- Dislocation vector k_y, k_z
- Pore shape and size, d_1, d_2, d_3, m
- Number of pores - n, pcs/m^3.
- Thermophysical parameters of absorber material, λ_s, c_{p_s}, ρ_s
- Optical parameters of the absorber material σ_β

The main condition of production capacity $H_{hot}^{air} = \dot{M}^{air} C_p^{air} T_{hot}^{air} = const$

Input parameters of the receiver model for constructive calculation

- Geometry sizes: H_x,H_y, H_z,
- Number of module absorber, A_{abs}/A_{rec}
- Shape of the receiver R_{xz}

Input parameters of the receiver model for thermal calculation

- Mass flow, $\dot{M}^{air}$ kg/s
- External environment: gradP, T_o
- Air temperature T_{out}^{air}, T_{hot}^{air}

Output parameters of the absorber constructive calculation:

- efficiency absorber area is calculated as the ratio of the actual heat flux to the maximum possible heat flux corresponding to an absorber with an infinite surface$\eta_{absorber}$=Q/Q_∞
- efficiency absorber NTU is most commonly given as a function of the number of transfer units NTU=$k_{ef}S_v/W_{min}$

Output parameters of the model:

- efficiencies based on receiver spillage η_{sp}=*f*(H_x,H_y, H_z, R_{xz});
- efficiencies based on receiver absorption η_{abs}= *f*(d_1, d_2, d_3 *n*, k_y, k_z, σ_β, R_{xz}, A_{abs}/A_{rec});
- efficiencies based on receiver radiation η_{rad}= *f*(d_1, d_2, d_3, *n*, k_y, k_z, λ_s, c_{p_s}, ρ_s, R_{xz}, A_{abs}/A_{rec}, *M*);
- efficiencies based on receiver convection η_{conv}= *f*(R_{xz}, A_{abs}/A_{rec}, *M*, H_x, H_y, H_z, *gradP*, T_{out}^{air});
- efficiencies based on receiver conduction η_{cond}= *f*(H_x, H_y, H_z, *gradP*, T_o, $T_{hot}^{air}, T_{out}^{air}$).

CONCLUSION

According to the results of calculations of the imaginary solar tower, the following relative distribution of the receiver efficiency is obtained (fig.1).

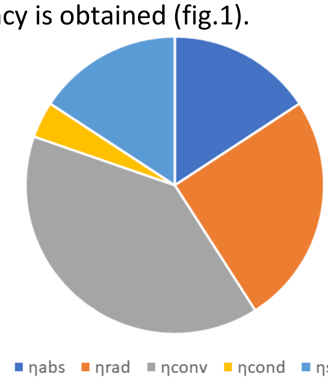

Fig.1 – The result of calculating the efficiency of the CSP receiver

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That is, the efficiency of the receiver in a stationary process depends only on the ratio of changes in the thermal energy of the fluid to the supplied solar energy. This formulation of the problem allows to calculate the overall efficiency of the receiver, but does not allow to optimize its structure. Therefore, for the problem of improving the structure of the receiver, it is necessary to adhere to the following initial factors of the model: η_{sp} is efficiencies based on receiver spillage; η_{abs} is efficiencies based on receiver absorption; η_{rad} is efficiencies based on receiver radiation; η_{conv} is efficiencies based on receiver convection; η_{cond} is efficiencies based on receiver conduction.

To describe the heat transfer processes in a porous medium, we need the values of the following independent model parameters.

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