Calculation of the thermal balance of the photocell during operation and removal of heat

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Abstract. The heat exchange of the photoelectric module with the environment and its changes in constant temperature were analyzed. Its temperature depends on the ambient temperature and the flux density of solar radiation, the heat balance equation is formed. The maximum concentration coefficient corresponding to the accepted limit temperature of 85 °C of the photocell was determined. It turned out that in the case of arbitrary installation of photoelectric modules, the maximum concentration coefficient does not exceed K = 3 at ambient temperature 25 °C, and K = 2,5 when installing the roof. An increase in the unit concentration coefficient in the summer leads to a constant temperature rise of the photocells to 18-22 °C, depending on the method of installation. A sandwich structural method of photoelectric module surface cooling was developed taking into account the increase in ambient temperature.

1. Introduction

The depletion of fossil fuel resources, as well as important environmental problems of conventional energy, have necessitated the search for new ways to generate energy. Photoelectric conversion of solar energy is one of the most promising methods. At the same time, the energy density of solar radiation is much lower than the energy density of conventional fuels [1]. Given the low overall utilization factor, the self-recovery period leads to a significant increase compared to conventional energy-based reciprocal power plants.

A large part of the cost of modern solar power plants is actually semiconductor solar cells. It is also possible to increase the surface area of expensive photocells without reducing the total output power by increasing the intensity of the incident radiation flux proportionally [2-4]. This is achieved using concentration systems of various designs. At the same time, an increase in the concentration coefficient leads to an increase in the temperature of the solar cell, which has a negative impact on the efficiency, maximum power and service life of the solar cell. For silicon-based photocells, the efficiency of solar energy conversion reaches a maximum value at a temperature of (-150 °C) ÷ (-100 °C) and is about 17%. As the temperature rises, it decreases and drops to 9% at 50 ºC [5]. The rate of decrease of Efficiency Factor (EF) is 0,05% / °C at 25 °C. Such a decrease in EF is particularly noticeable when using solar concentrators (due to high temperatures) and imposes certain restrictions on the concentration coefficient for surface exploitation processes. Determining the concentration limit is very important when choosing a concentrator design, as the increase in the concentration level has a negative impact on the accuracy of reflective surfaces, the quality of the whole optical circuit, the design cost, production, operation and maintenance of photo elements. Strict requirements are placed on the accuracy of the tracking mechanism. By making the concentration coefficient $K=2\div6$, the cost of solar power plants can be significantly reduced. This is usually done by removing the mechanism of tracking the sun and strict requirements for the quality of proportion.

In this scientific work, the task is to determine the constant temperature of the semiconductor photocell and the maximum level of solar radiation concentration without active cooling methods, as well as to increase the efficiency of the photocell.

2. Methods

The solar module is determined based on the energy balance equation. The flux of solar radiation absorbed by the solar element is partially converted into useful work, which is determined by the useful work factor η. The remaining energy

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causes the photocell to heat up. It is known [6] that silicon is practically transparent to infrared radiation with wavelength *l > 1,1 μm*, but this radiation is absorbed in the structural elements of solar cells and affects the constant temperature of photoelectric modules. Heat is transferred to the environment in three ways: radiation, convection, and heat transfer. In stationary mode, the amount of energy absorbed per unit of time is equal to the sum of useful work and total heat losses.

Assume that the integral energy flux P_0 is absorbed in the photoelectric module. Then the heat balance equation is:

$$P_0 = \eta P_0 + P_e + P_t + P_c \ , \tag{1}$$

here – by P_e radiation; P_t – through thermal conductivity; P_c – radiation currents transmitted to the environment by convection.

Radiation losses are determined according to Stefan-Boltzmann's law:

$$R = \varepsilon\sigma T^4, \tag{2}$$

where is the ε – blackness coefficient of the irradiated body.

In addition to radiation, light energy scattered from the celestial dome is also absorbed by the photocell, so (2) has the following form:

$$R = \varepsilon\sigma(T^4 - T_n^4), \tag{3}$$

here T_n – effective temperature of the sky.

to [7], it can be expressed as follows.

$$T_n = 0{,}0552 \cdot T_0^{1,5}, \tag{4}$$

where is T_0 – the ambient temperature.

Thus, the power of the radiation losses directed upwards from the surface of the photoelectric module P_{e1} is expressed as follows:

$$P_{e1} = \varepsilon\sigma(T^4 - T_n^4)S, \tag{5}$$

S – is the surface of the photoelectric module.

When mounting photoelectric modules on the ground, the back of the photocell is usually grounded and its effective temperature is close to the ambient temperature. Thus, the losses at the bottom of the photoelectric module are P_{e2}:

$$P_{e2} = \varepsilon\sigma(T^4 - T_0^4)S, \tag{6}$$

total losses through radiation P_e are:

$$P_e = P_{e1} + P_{e2} = \varepsilon\sigma S[(T^4 - T_n^4) + (T^4 - T_0^4)]. \tag{7}$$

P_t – losses in thermal conductivity are determined by the coefficient of thermal conductivity of air – λ:

$$P_t = \lambda S(T - T_0) \tag{8}$$

These losses are the same on both sides of the photoelectric module. Because the side surface area of the module is small, it is possible to ignore the heat losses of the side surface compared to the working surface. Since the thermal conductivity of air is low, it is expected that the losses through thermal conductivity will be much smaller compared to the losses through radiation and convection.

Convection force is calculated based on the theory of similarity. In the absence of active cooling, there is a state of free convection due to the Archimedean force acting on the heated volume of air. In this case, convection occurs in an infinite amount.

In general, convective heat transfer power P_c is defined by the following expression:

$$P_t = \alpha S(T - T_0) \tag{9}$$

where is the α – convection heat transfer coefficient.

The similarity criteria for calculating this coefficient are Nusselt numbers *Nu*, Prandtl *Pr* and Grashof *Gr*.

$$Nu = \frac{\alpha L}{\lambda} \tag{10}$$

where L – is the dimensional character of the task to be performed, in which case it is equal to the smallest volume of the planned photoelectric module. Prandtl number:

$$Pr = \frac{v}{a} v \tag{11}$$

where is the $v$kinematic viscosity of the air; a is the coefficient of thermal conductivity of air.

Grashof number:

$$Gr = \frac{g\beta(T - T_0)L^3}{v^2} \tag{12}$$

Here g is the acceleration of free fall; $\beta = \frac{1}{T} = \frac{2}{T + T_0}$ – coefficient of thermal expansion of air.

Nusselt number (*Nu)* Prandtl (*Pr)* in free convection mode and is a function of the Grashof numbers (*Gr)*:

$$Nu = C(Pr \cdot Gr)^n \tag{13}$$

For the horizontal position of the photoelectric modules during convection in infinite space, *C* and *n* in formula (13) are *C* = 0,135; n = 1/3 [8]. Then, taking into account (10) - (12), (13) will have the following appearance.

$$\alpha = \frac{\lambda}{L} C \left(\frac{g\beta(T-T_0)L^3}{\nu a} \right)^n \quad (14)$$

It is worth noting that the specific power of convection at the accepted value n = 1/3 – α does not depend on L. Since the specific losses through radiation and thermal conductivity are also not related to L, it can be concluded that the constant temperature of the photocell does not depend on its volume. This is confirmed by the results of digital experiments presented throughout the article. However, when the photoelectric module is placed at an angle to the horizon (14), the dependence on L can occur if the n – degree index in formula differs by 1/3.

Thus, the power dissipation in convective losses can be expressed as follows:

$$P_c = \alpha \cdot S \cdot (T - T_0) \quad (15)$$

It should be noted that convection occurs more intensively on the upper surface than on the lower part of the heated body. According to [7], to calculate convection on the upper surface, the coefficient C in (13) should be increased by 30% and for the lower surface by 30%. Thus, for the total convective flow we obtain the following expression:

$$P_c \cdot 1{,}3 + P_c \cdot 0{,}7 = 2 \cdot P_c$$

Considering (6), (8) and (15), we can write (1) in the following form:

$$KP_0(1-\eta) = \varepsilon\sigma[(T^4 - T_n^4) + (T^4 - T_0^4)] + 2\lambda(T - T_0)\left[1{,}35\left(\frac{2g}{\nu a}\frac{T-T_0}{T+T_0}\right)^{1/3}\right] \quad (16)$$

K – is the coefficient of concentration of solar radiation.

Equation (16) $g, \nu, \gamma, \alpha, \varepsilon, \eta, K$ and P_0 the solution at known values of allows to determine the steady-state temperature of the photoelectric module.

3. Results

The values of the initial parameters of the model are given in Table 1.

Table 1. Initial parameters of the model

Parameter	Designation	Value
Free fall acceleration	g	9,8 m/s^2
Kinematic viscosity of air	ν	14,95·10^{-6} m/s^2
Air heat transfer coefficient	λ	0,026 W/(m·K)
Air temperature coefficient	a	21,2·10^{-6} m^2/s
The irradiance coefficient of silicon	ε	0.85
The Efficiency Factor of the photocell	η	0.17
The intensity of the solar radiation flux absorbed by the photocell	P$_0$	700 W/m^2

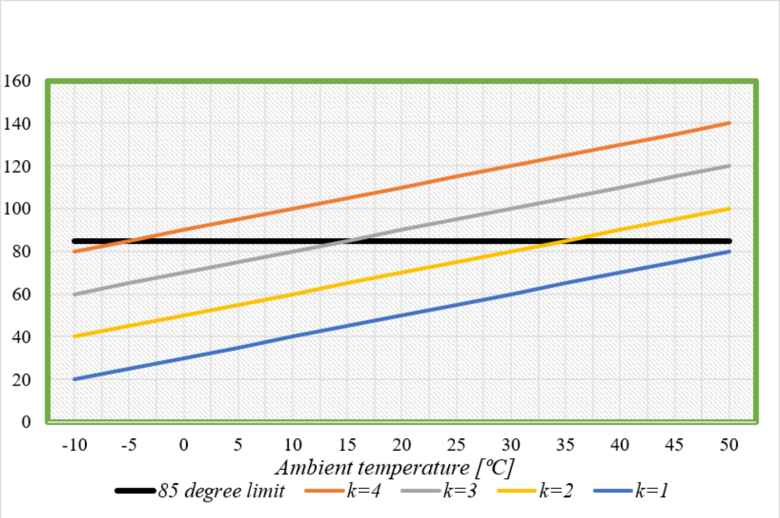

Fig. 1. Dependence of the temperature of photocells on ambient temperature at different concentration coefficients

Concentration coefficient from $K = 1$ to $K = 4$ are shown in Figure 1. The upper heating limit of the photocell is 85 °C. As can be seen from Figure 1, if the ambient temperature is higher than 20 °C, a concentration coefficient higher than $K = 3$ will cause the photocell to overheat, which requires additional measures for heat transfer (using a radiator – mandatory or passive).

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The calculations show that for any concentration coefficients under consideration, the increase in the photocell temperature increases with the increase in the ambient temperature and is 0,5 ºC for each level of ambient temperature. Depending on the ambient temperature, the value of *K* increases from 16,5 °C to 21,5 °C with each unit increase.

When the photoelectric module is installed on the roof, the thermal resistance of the bottom side is almost infinite, heat loss occurs only at the top of the photocell. In this case, equation (16) looks like this:

$$KP_0(1-\eta)=\varepsilon\sigma[(T^4-T_n^4)+(T^4-T_0^4)]+$$
$$+2\lambda(T-T_0)\left[0{,}176\left(\frac{2g}{\nu a}\frac{T-T_0}{T+T_0}\right)^{1/3}+1\right] \qquad (17)$$

It can be seen that in this case the situation with heat dissipation worsens, which leads to more heating of the photocells (the calculation results are shown in Figure 2). Now the concentration coefficient *K = 3* leads to overheating of the photocell as soon as the ambient temperature is about 5 °C.

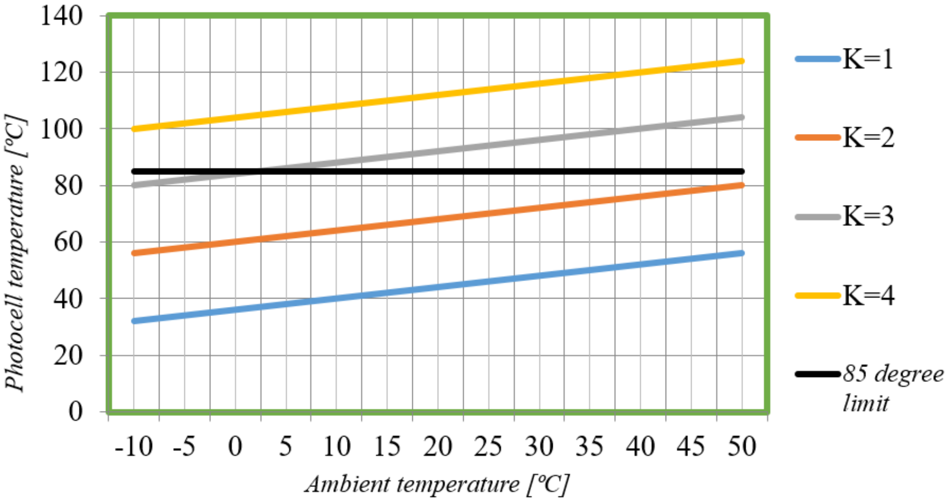

Fig. 2. The temperature dependence of the temperature of the photocell mounted on the roof

As a result of the increase in ambient temperature due to the high convection power, the rate of rise of the photocell temperature decreases by 20% and is 0,38 -0,4 ºC for each level of outdoor temperature. At the same time, the dependence on the concentration coefficient increases by 12-17%, and its unit growth corresponds to 18,5-25 °C.

The additional heating of the photocells mounted on the roof depending on the ambient temperature is shown in Figure 3. Typically, at a temperature of 25-30 °C, an increase in the device temperature to 7-13 °C is observed, which reduces the maximum concentration coefficient by one unit.

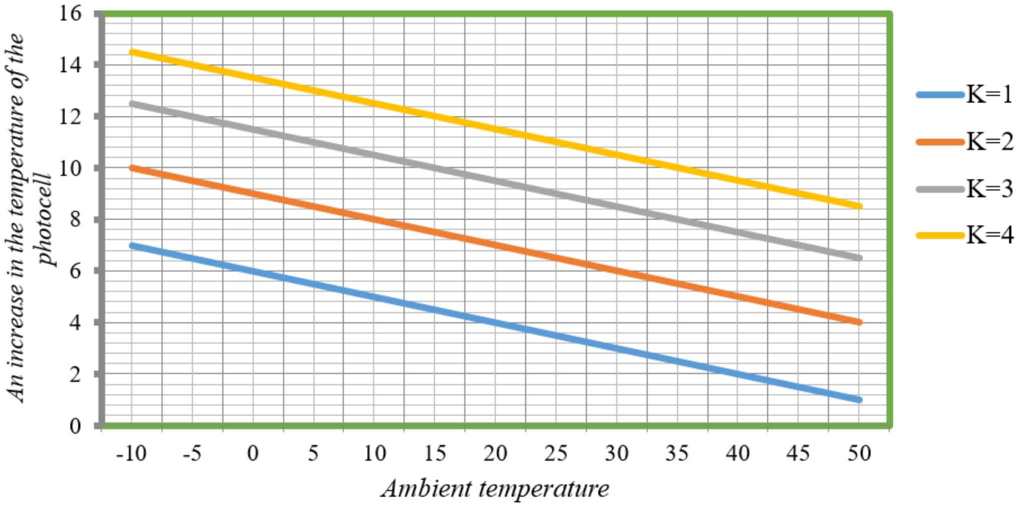

Fig. 3. The dependence of the additional heating of roof-mounted photocells on the ambient temperature

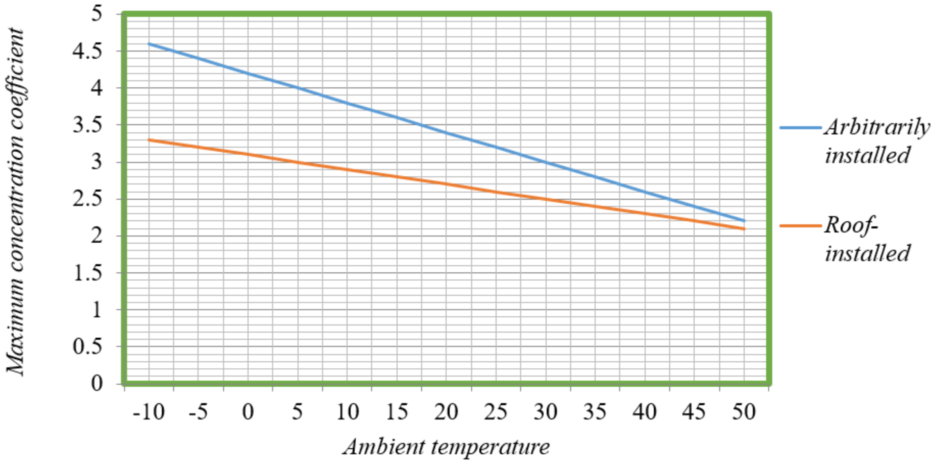

Fig. 4. Dependence of the maximum concentration coefficient on the ambient temperature

By determining the limit temperature (*T)* of the photocell, it is possible to solve equations (16) and (17) with respect to the concentration coefficient (*K)* and thus determine the dependence of the maximum allowable concentration coefficient on the ambient temperature. This relationship is shown in Figure 4.

As mentioned above, during operation, the photoelectric panel, especially if it is equipped with a concentrator, its surface and back surface will have high thermal energy, and this will mainly cause the voltage value in the photoelectric device to drop. If the surface temperature of the photocell is higher than the upper heating limit, this temperature will cause the photocell to overheat, regardless of whether the photoelectric device has a concentrator or not. As a result, the efficiency of the PV module deteriorates. As an additional measure for this heat transfer, the following method gives good results (Fig. 5).

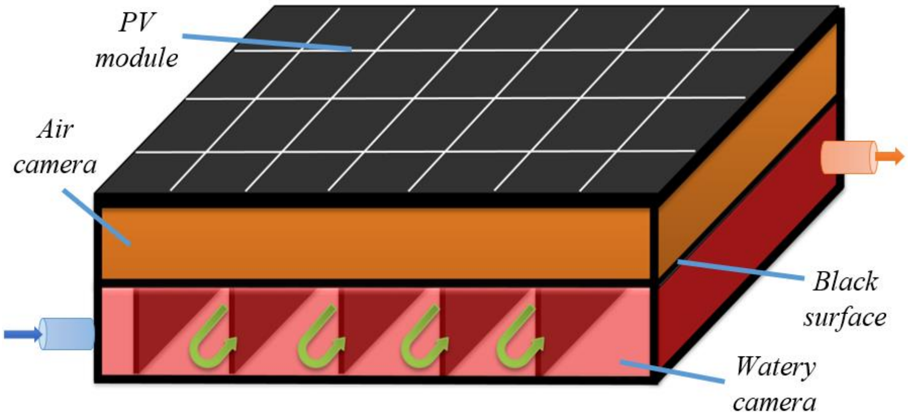

Fig. 5. Photoelectric module cooling system

The cooling system can be mandatory or passive.

The heat extracted by the aqueous chamber can be directed through the working fluid to other energy devices, in particular to the combined bioenergetic device for heating the substrate [9, 10].

The intended result of this research work is to cool the photoelectric module through the working fluid and increase the efficiency. Also, the thermal energy obtained from the working fluid can be optimized in the bioenergetic device operation process in subsequent studies.

4. Conclusion

1. The constant temperature of a photocell does not depend on its geometric dimensions in the horizontal position.
2. Unless special measures are taken to cool the photocells, the maximum concentration coefficient is limited to values $K = 2{,}5 \div 3$. A high coefficient of *K* allows the system to run more efficiently in the morning and evening, but causes it to overheat at noon.

3. When the ambient temperature is *25 ºC*, an increase in the concentration coefficient by one leads to an increase in the temperature of the photocell of an arbitrarily mounted device on the ground by about *18 ºC* and by 22 ºC for a roof-mounted device.
4. The above conclusions apply to conditions where $P_0 = 700\ W/m^2$, *which* corresponds to the maximum energy flux of solar radiation in summer for a latitude of $41 \div 45^o$. At higher latitudes, the maximum concentration coefficient increases with decreasing P_0 and can be obtained by solving equations (16) or (17) with respect to *K*.
5. The efficiency of the device can be increased by cooling the photoelectric module through the working fluid and directing the heat energy obtained from it to heat another power system. We have drawn some conclusions in this regard in our previous work.

In addition, calculations show that in the absence of concentration, overheating of the photocell is not observed in real conditions. However, even small concentrations of solar radiation ($K>2$) lead to the need to cool the photocell.

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