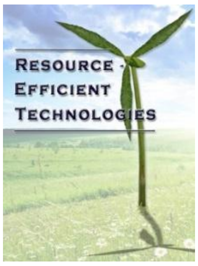
Resource-Efficient Technologies 4 (2021) 1–9

Resource-Efficient Technologies

journal homepage: http://reffit.tech



Research Paper

WAYS TO INCREASE THE EFFICIENCY OF SOLAR PANELS OPERATING IN ISOLATED POWER SUPPLY SYSTEMS

A.S. Sorogin[1] , R.N. Khamitov[2,1]*

[1] Tyumen Industrial University,
38, Volodarsky street, Tyumen, 625001, Russia

[2] Omsk State Technical University,
11, Mira avenue, Omsk, 644050, Russia

Abstract

To cool solar panels in hot season, it is necessary to use special cooling devices. The most optimal way of cooling is the use of liquid cooling, realized by means of a pump. This article provides an overview and evaluation of ways to cool solar panels using various devices. **The relevance** of the research is caused by the need to reduce the temperature of solar panels in order to increase the output power in the hot season. **The main aim** of the research is to compare and choose the most optimal way to cool solar panels. **Methods:** comparative analysis, mathematical modeling in the ANSYS environment. **Results.** Comparative characteristic of TEM, radiators, fans and liquid cooling is given, an example of cooling a solar panel using liquid cooling to spray a liquid flow of 29 l/min is calculated. The panels will cool down from 45 to 35 °C in 4,7 minutes. For one EasySunSolar solar panel with a capacity of 100 W, costing $100, taking into account electrical work, an additional heat sink module will cost about $50.

Keywords: Solar panels, cooling of solar panels, ANSYS, thermo-electrical elements, efficiency of solar panels.

1. Introduction

Today, due to the cheaper production of solar panels, there is a tendency to increase capacity in the solar energy sector, however, the use of solar energy in the industrial sector remains an expensive undertaking, whereas solar energy has become more affordable for isolated power supply systems [1]. The quality, stability and unit power of the solar battery are improved. However, there are still a number of unresolved problems. One of which is the increased temperature of the solar module when irradiated by the sun with infrared and visible spectrum. Thus, the output power of the solar battery grows with the increase in the intensity of solar radiation, but at the same time, due to increase in the surface temperature of the solar module, its efficiency decreases.

Experiments have shown that when using solar panels in summer, clear time with intense solar radiation, the modules are heated, the idle voltage and maximum output power decrease with increasing module temperature, and the short-circuit current increases [1, 2]. The module degrades faster due to elevated temperatures and produces less possible power (Fig. 1). Thus, with an increase in the luminous flux from 1400 to 2000 W/m^2, the solar battery heats up from 30 to 78 °C, the efficiency decreases from 14,7 to 6 %, the power of the solar battery decreases by 14 MW – from 112 to 98 MW [3].

---

* Corresponding authors: Khamitov R.N.
E-mail: apple_27@mail.ru

☆ Peer review under responsibility of Tomsk Polytechnic University.
https://doi.org/10.18799/24056537/2021/4/317

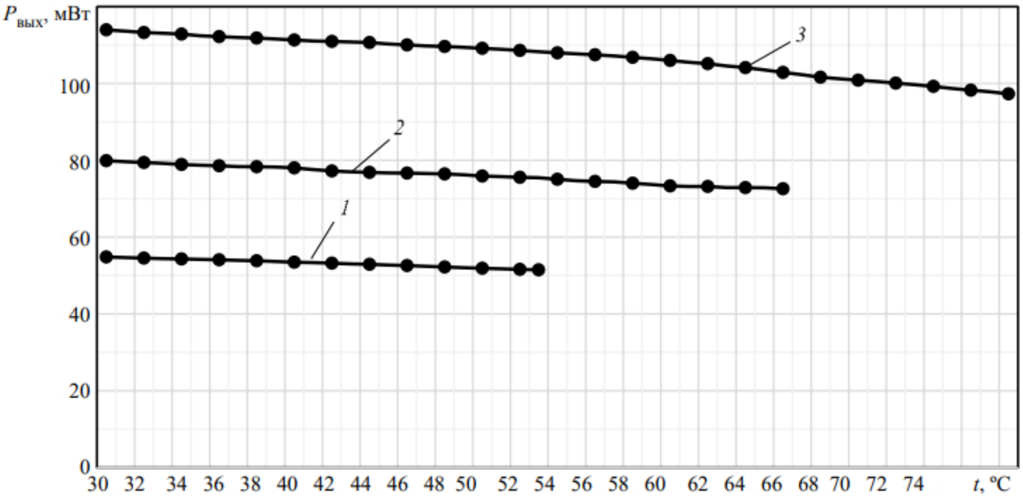


Fig. 1. Graph of a solar panel unit power dependence on solar cell surface heating temperature when the intensity of the luminous flux changes (1 – F=800 W/m²; 2 – F=1400 W/m²; 3 – F=2000 W/m²)

Currently, it is important to determine the most efficient and economical method of heat removal for solar panels, which provides an increase in their output power when heated during operation as part of isolated power supply systems.

2. Influence of solar radiation intensity on solar panel heating and power output reduction

Since solar panels (hereinafter SP) do not convert all the sun energy into electricity, but only part of it, the rest of energy heats the module. The increase in the solar panel temperature due to intense sunlight radiation in excess of the operating temperatures set in the passport data leads to decrease in the width of the band gap of the semiconductor material. The saturation current increases due to the lower value of the energy required for conversion of electron-hole pairs [4]. But at the same time, the short-circuit current increases slightly, and the no-load voltage decreases, which reduces the output power of the SB module.

To determine the effect of temperature on the output power of the SP, you can use the expression:

$$P_P = P_0(1 + \beta \Delta t), \tag{1}$$

where P_P – solar panel power, W; P_0 – solar battery power at 25 °C, W; β – temperature power factor, $°C^{-1}$; Δt – temperature change, °C [3].

The temperature power factor varies from –0,2 to –0,4 $°C^{-1}$ when changing by 1 °C. The temperature power factor for monocrystalline silicon is about –0,4 $°C^{-1}$ [3]. The output power drops by 0,4 % when the temperature value of the module increases by one degree above the value of the operating temperature of the SB.

There are three ways to remove heat from a heated body:

1) convection;
2) thermal conductivity;
3) radiation.

Convection is a type of heat transfer in which energy is transferred by layers of liquid or gas. Convection is associated with the transfer of matter, so it can only be carried out in liquids and gases; convection does not occur in solids. As an example, this method of heat removal can be used when blowing the SP or cooling with liquid in contact with a heated SP.

Thermal conductivity is used when there is a temperature difference between a body or a solar battery and another body, including the air around the module. The ability of a solar battery to transfer heat to another body is characterized by the thermal resistance of solar battery materials.

The temperature difference between the bodies determines the direction of heat transfer from one material to another:

$$\Delta t = R_t P_h \ , \tag{2}$$

where Δt – temperature difference, °C; R_t – thermal resistance of a surface that emits a heat flux, W^{-1}; P_h – heat flow from the solar panel, W [5].

The module thermal resistance depends on material resistivity and thickness. The area of the heat-conducting surface, the thickness of the layer and the coefficient of thermal conductivity λ (W/(m·°C) are also involved in determining the thermal resistance.

To calculate the thermal resistance for complex layered structures, separate coefficients must be added in series or in parallel. Thus, part of the losses may occur due to convection heat exchange when the material is blown with air. It is more difficult to calculate the coefficient of convection heat transfer, so it is obtained empirically for certain materials and conditions [5]. Also, heat distribution over the solar panel can be calculated in the ANSYS Workbench software package (Fig. 2, 3).

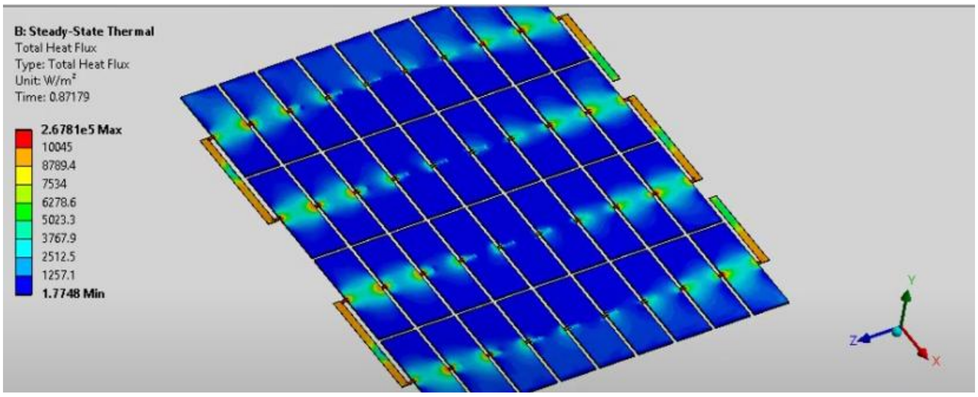


Fig. 2. Influence of heating of conductive elements on a solar battery in the ANSYS software package [6]

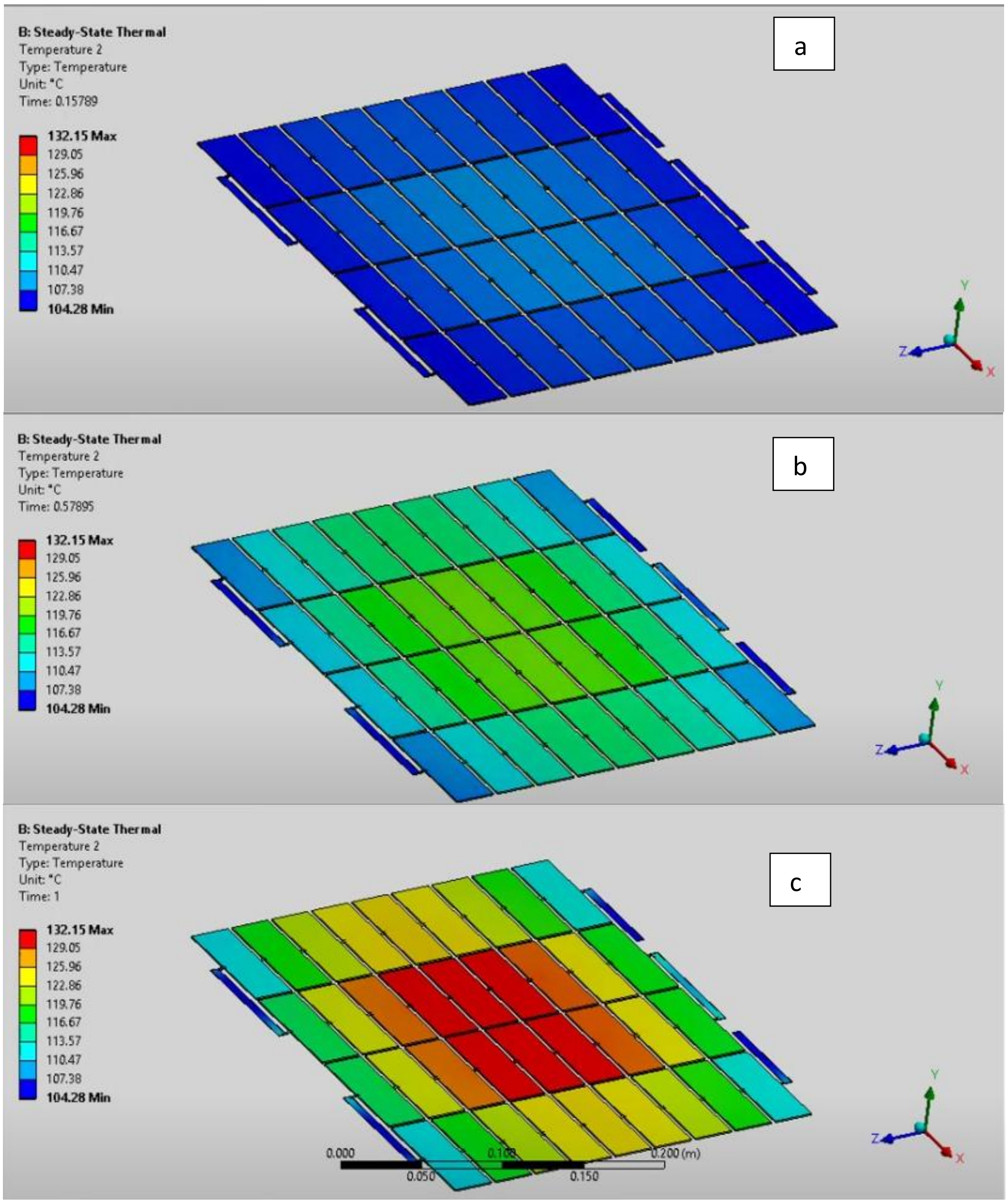


Fig. 3. Effect of solar heating on the solar battery in the ANSYS software package at heating temperature: a) T=40 °C; b) T=45 °C; c) T=55 °C [6]

The solar battery can give off heat with the help of radiation. The operating temperature of the solar module is set as a result of the equilibrium of heat absorbed in the air and heat escaping into the environment. Such thermal energy is estimated according to the Stefan–Boltzmann law, taking into account heat losses as a result of the difference between the heat received from the outside and the heat radiated in the environment. In such cases, it is necessary to take into account the radiation ability of the surface of the material, which varies from 0,3 to 0,95, taking into account the temperature difference between the SB and the ambient temperature.

Based on the methods of heat extraction, the cooling systems are divided into:

- passive module temperature reduction systems;
- active module temperature reduction systems;
- systems using optical filters.

Authors of the work [6] studied the effect of temperature on the characteristics of monocrystalline silicon and confirmed the negative effect of high temperatures on voltage and output power. Also, experimental studies on the effect of temperature on the solar module in the hot climate of Malaysia were described in [1]. In [7], the authors experimentally proved a significant effect of temperature increase on the efficiency of a cell with a constant illumination value.

3. Solar battery cooling systems based on radiators

A radiator is a cooling device in which a metal with high thermal conductivity is used to remove heat from a photocell. Thus, in [8], the authors investigated the decrease in the temperature of photovoltaic panels on a clear July day, using various devices for heat removal of air with ribbed walls and passive cooling. It turned out that the maximum temperature of the panel for the angle of inclination of 45° was less than for the angle of 135°. The study showed that the efficiency of the SB when using the radiator was increased by 6,97 and 7,55 % compared to the reference case for the installation angles of the ribs 90° and 45°.

The results of an experimental study of changes in the operating temperature of a photovoltaic module with and without an active cooling system, in order to assess the electrical characteristics of the photovoltaic module, are given in [9]. Two monocrystalline silicon solar modules with a peak efficiency of 13 % were used in the experiment under conditions (25 °C, 1000 W/m^2). One of the modules was used as a reference, and the other, made of aluminum, was installed in the lower part of the photovoltaic panel as a radiator, on which a brushless DC fan was installed.

The temperature of the photovoltaic module with a cooling system was 30 % higher than the ambient temperature, and 70 % higher without cooling. Consequently, the idling voltage of a solar battery with a cooling system was higher than the voltage of a photovoltaic module without a cooling system.

The air channels connected to the back of the panel were investigated in [10], where the efficiency of solar modules with and without active cooling was compared. During the study, the effect of operating temperature on the efficiency of a hybrid photovoltaic/thermal solar system was experimentally established. It was noticed that with the solar cells temperature increase, the electrical efficiency also decreases, both during cooling and for the case without cooling, but for the case of cooling, the electrical efficiency was higher.

After the experiments, a linear proportional relationship between the temperature of the photovoltaic panel and solar irradiation was revealed.

The authors [11] investigated a solar collector performance using forced and natural air circulation for heat removal. The air duct has been modified to increase heat transfer from the duct walls to the airflow. The study showed that the electrical efficiency of the system directly depends on the intensity of solar radiation, the temperature of the solar cells and the power consumed by the fans. The electrical efficiency in the case of forced convection did not always increase with an increase in the number of fans, however, the optimal number of fans to ensure the highest efficiency was determined.

Devices with cooling fins are used to cool electrical devices. In [12], the authors used aluminum ribs in combination with a cotton wick in the form of a passive cooling system to maintain the temperature of the solar panel.

The cooling system included: an aluminum plate (630×100×60 mm) with a cotton wick, which was attached to the back of the photocells. According to the results of experiments, the maximum temperature of the photovoltaic panel decreased by 12 % due to the use of a cooling system, and its output power increased by 14 %.

Similar studies were carried out in [13], where the necessary length of the ribs was theoretically calculated to determine the necessary increase in the power of the solar panel during passive cooling with phase transition material (PCM). It was noticed that the temperature of the photocells on the ribs decreased in comparison with the body without ribs. The fin lengths of 25, 30 and 35 mm provided the preferred cooling of the solar cells.

In the study [14], the performance of solar cells was increased with the help of cooling fins during natural convection. Two panels with a power of 37 watts were used, 9 aluminum ribs were attached to one of the panels to the back. According to the results of the study, the element temperature for a photovoltaic panel with cooling fins was reduced by 4,2 % compared to a panel without fins, and the average output power increased by 5,5 % in the case of a photovoltaic panel with fins.

According to the analysis of methods of heat removal, temperature reduction and increase in the output power of the SB, for the most part they ensure the efficiency of the SB, but their use for industrial-scale SES requires additional significant capital investments. However, for isolated SES of limited capacity, such methods of reducing the temperature and increasing the efficiency of solar panels could play an important role and increase the efficiency of photovoltaic SES.

4. Liquid cooling systems for solar panels

Cooling by spraying liquid on the panel. Some studies have experimentally investigated the effect of water cooling on photovoltaic modules. Thus, the authors [15] experimentally investigated the effect of cooling with a water spray on both sides of a solar battery on the efficiency of a photovoltaic panel under conditions of the greatest solar radiation (Fig. 4). The results were obtained for three cases: cooling from the front side, cooling from the back side and from both sides, and the results were compared with the case without cooling.

The experiment showed that water cooling had a corresponding effect, namely a decrease in efficiency, and the best case was simultaneous cooling of the photovoltaic panel on both sides.

In [16], the authors conducted studies of the solar panel characteristics using the water cooling method on a solar energy simulator of twenty halogen lamps with a total power of 500 watts. Two single crystal panels with a power of 50 watts were used in the test. To spray water, a pump was used that operated on the basis of a DC motor and attached to the front surface of one panel, while the other panel was used as the base.

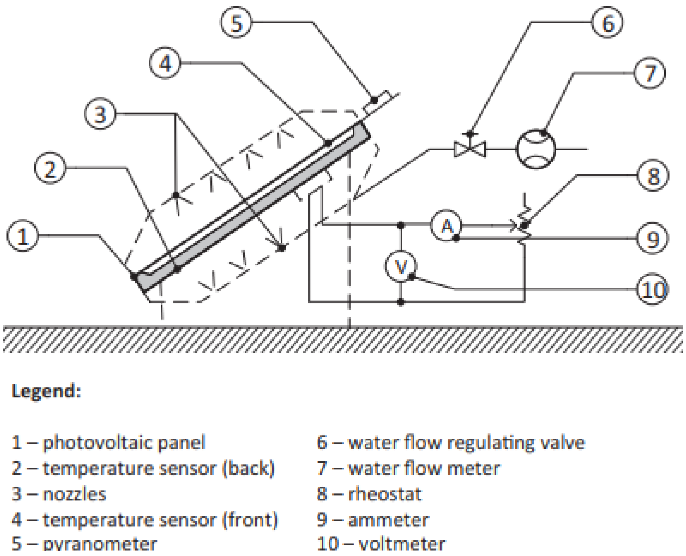


Fig. 4. Schematic layout of the specific experimental setup

According to the results, the operating temperature of the solar battery with a water cooling system decreased by 5–23 °C, and its output power increased by 9–22 %.

Cooling by means of a heat exchanger. Some studies are devoted to the study of the performance of solar panels using active cooling water using a heat exchanger. For example, in [17] a study was conducted to increase the electrical efficiency of a hybrid thermal-photovoltaic system. The cooling unit consisted of a heat exchanger and seven water pipes attached to the back of the panel. The electrical efficiency was improved at a water flow rate of 0,3 l/s compared to other flow cases.

The authors [18, 19] studied the characteristics of a hybrid photovoltaic system with water cooling. According to [18], the efficiency of solar panels due to cooling by a rectangular heat exchanger was 13,07 %, and for solar cells without cooling – 7,82 %.

The work [19] was carried out in the conditions of the city of Dhahran (Saudi Arabia) to study improving a solar battery performance in hot climate. A heat exchanger and an insulated storage tank for cooling water were connected to the back of the 230 W solar cell.

The operating temperature of the photovoltaic panel has noticeably decreased, to about 20 %, and the electrical efficiency has increased by 9 %.

As a comparison, Table 1 shows the parameters of devices for various types of solar panel cooling in the sources considered.

Table 1. Comparative table of characteristics of cooling devices for a solar battery

Parameter	Thermoelectrical element TEC1-12704	Aluminum radiator 48×11×100 mm	Cooler Gdstime 9225	Liquid Cooling Pump 370B-PUMP
Power consumption P, W	48	0	1,44	1,8
Cooling capacity, W	35,6	12	35	40
Efficiency, %	50	–	80	60 %
Operating temperature range, °C	–55 …+83	–100…+660	–40…+90	–20…+60
Cost of 1 piece, rub	335	393	675	542
Required quantity, pcs	9	10	10	10
Possibility of generating additional electricity	+	–	–	–
Frequency of maintenance	1 time/2 years	2 times/ year	1 time/2 years	–
Maintainability	–	–	+	–
Total duration of work, years	23	20–25	4	3
Dimensions, mm	40×40×4	100×48×11	92×92×25	25×25×81

To use a certain type of solar battery cooling in isolated systems, it is necessary to take into account the cost of materials and the costs associated with electrical installation work. To evaluate and determine the most optimal type of cooling of one EasySunSolar UL15 solar battery with a capacity of 100 watts, a technical and economic analysis was carried out, the data of which are presented in Table 2. As a calculation of the cost of electrical work, the value of 20 % of the cost of materials was taken.

Table 2. Composition of various types of cooling for the Solar Panels and their cost, taking into account electrical work (in prices for May 2022)

Type of cooling	Materials	Quantity, pcs	Cost, rub	Cost of electrical work, rub	Total, rub
Using Peltier elements (liquid cooling)	Peltier Elements TEC1-12704 HY510 thermal paste	9	173 (1557)	6444*0,2=1288	7732
	Aluminum coolant tanks 200×40×10	1	88		
	TOTACHI SUPER LONG LIFE COOLANT 4L	3	430 (1290)		
	Liquid circulation capacity 5 l	1	979		
	ALPHA BATTERY FB 12V	1	628		
	7,2 ah lead-acid battery	1	877		
	Pump 12V 370-V	3	224 (672)		
	Silicone tube 5×7 5 m	1	353		
Using Peltier elements (cooling with radiators)	Peltier Elements TEC1-12704 HY510 thermal paste	9	173 (1557)	2666*0,2=533	3199
	Aluminum radiator 100×41×8	1	88		
	ALPHA BATTERY FB 12V	3	112 (336)		
	7,2 ah lead-acid battery	1	877		
Using the liquid on the front side of the panel	Pump 12V 370-V	3	224 (672)	2530*0,2=506	3036
	ALPHA BATTERY FB 12V 7,2 ah lead-acid battery	1	877		
	Silicone tube 5×7 5m	1	353		
	Liquid circulation capacity 5 l	1	628		
Using air cooling	Axial fan 6W	6	857 (5142)	6019*0,2=1203	7222
	ALPHA BATTERY FB 12V 7,2 ah lead-acid battery	1	877		

According to Table 2, the most optimal price solution for cooling, taking into account the costs of electrical work, is the cooling option using Peltier elements and radiators (3199 rub.) and the option using liquid cooling on the front side of the panel (3036 rub.).

As an example of cooling, let's choose liquid cooling of a solar panel.

The cooling frequency of photovoltaic panels is determined by the heating rate of the panels. By calculating the temperature of the module, depending on the time, you can set the heating rate of photovoltaic panels and the cooling frequency. The modular temperature of T_m is calculated using the following equation [20]:

$$T_m = T_{sur} + \frac{F(NOCT-20)}{800}, \tag{3}$$

where *F* – solar radiation, W/m^2; T_{sur} – ambient temperature, °C; *NOCT* – nominal operating temperature of the cell, °C. *NOCT* depends on the ambient temperature during sunrise $T_{восх}$.

Calculated as follows:

$$NOCT = 20°\mathrm{C} + T_r \; . \tag{4}$$

According to equations (3), (4), it can be concluded that the heating rate of the solar panel depends on the ambient temperature, illumination and the value of *NOCT*. The latter has a constant value, illumination and temperature are variable values. Solar radiation, ambient air temperature and module temperature were measured between sunrise and sunset during the day in June 2021 (Tyumen region, Nizhnetavdinsky district, Kuskurgul village).

The modular temperature T_m was calculated using equation (3) and compared with the measured temperature of the module. The calculated and measured temperature of the module is shown in Fig. 5.

$$Q_{cool} = Q_{SP} \; . \tag{5}$$

The cooling time t is determined from the following energy balance [12]:

$$\dot{m}_w \times t \times c_w \times \Delta T_w = m_g \times c_g \times \Delta T_g \; . \tag{6}$$

Hence the cooling time *t*:

$$t = \frac{m_g \times c_g \times \Delta T_g}{\dot{m}_w \times c_w \times \Delta T_w}, \tag{7}$$

where $\dot{m}_w$ – mass of water consumption; m_g – mass of glass; c_w – water specific heat capacity; c_g – glass heat capacity; ΔT_w – increase in water temperature; ΔT_g – change in glass temperature due to water cooling; *t* – time required to cool the solar panel to a moderate temperature 35 °C.

The mass flow rate of water $\dot{m}_w$ is calculated by the equation [12]:

$$\dot{m}_w = \rho_w \dot{V} \; , \tag{8}$$

where ρ_w – water density; $\dot{V}$ – volume flow.

The mass of the glass m_g is calculated by the equation [19]:

$$m_g = \rho_g A_g x_g, \tag{9}$$

where ρ_g – tempered glass density; A_g – photovoltaic panel surface area; x_g – thickness of the glass covering the photovoltaic panel.

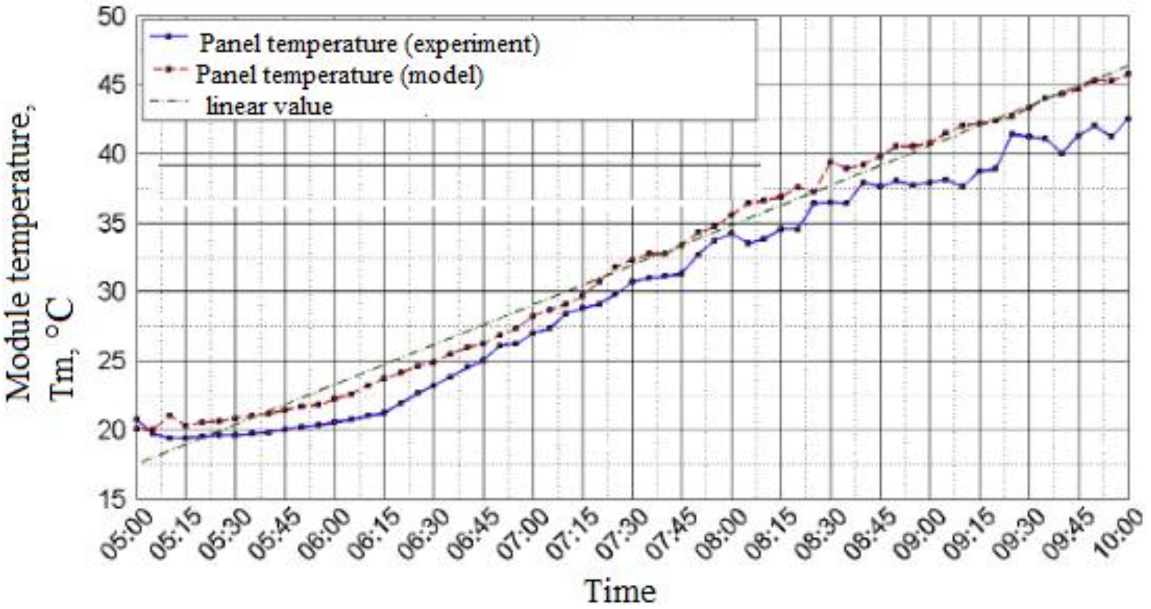


Fig. 5. Module temperature calculated and measured in June 2021 in the Tyumen region, Nizhnetavdinsky district, Kuskurgul village

We believe that water heat capacity, c_w and glass heat capacity, c_g, are constant, since the temperature change of water and the photovoltaic panel is small. The temperature of the photovoltaic panel before and after cooling is 45 and 35 °C, respectively. It is assumed that the maximum permissible temperature of the photovoltaic panel is 45 °C, after which the photovoltaic panel should begin cooling by spraying water on the panel until its temperature drops to 35 °C. ΔT_v is the change in the cooling water temperature before and after cooling in Fig. 5, the temperature of the module calculated and measured in June 2021.

It is assumed that the temperature of the water coming out of the panel is the same as the temperature of the panel after cooling, i. e. 35 °C. It is assumed that ΔT_w is equal to the difference between the temperature of the hot water coming from the panel to the tank and the temperature of the water coming out of the tank, i. e. 35 and 25 °C, respectively. Equation (7) was solved to determine the dependence of the cooling time t on the water flow, and the results are presented in Fig. 6.

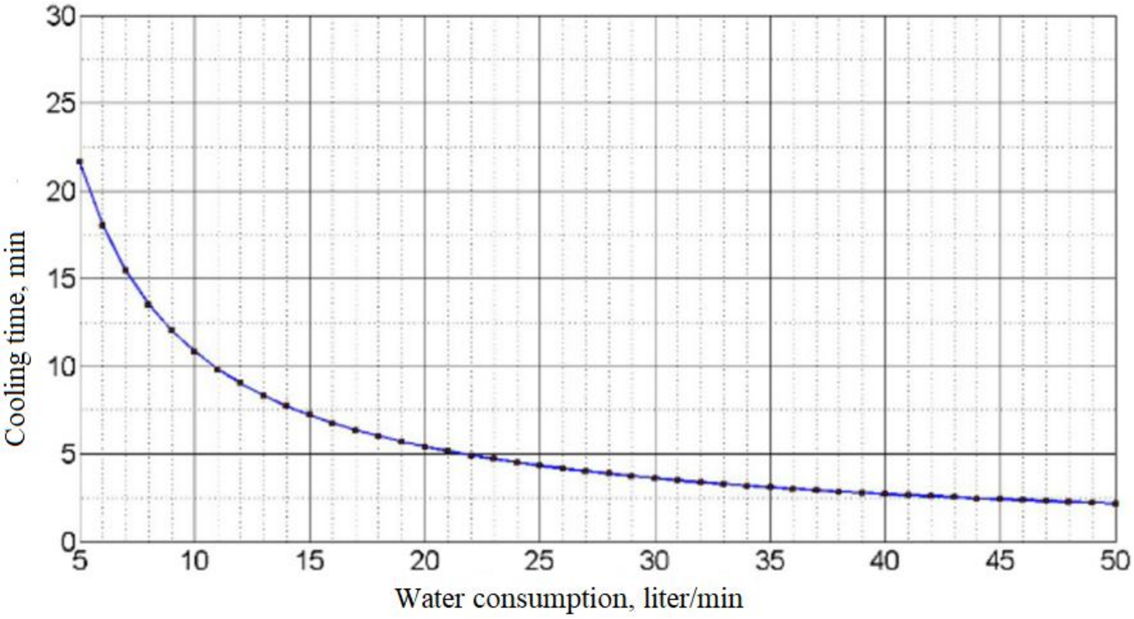


Fig. 6. Cooling time t versus water flow rate V, assuming ΔT_w=ΔT_g=10 °C.

From Fig. 6, it can be concluded that as the coolant flow rate increases, the time required for cooling the SB decreases. If the pump operates in such a way that it sprays water onto the photovoltaic panels at a flow rate of 29 l/min, this will cool the photovoltaic panels from 45 to 35 °C in 4,7 minutes. In this case, it can be concluded that the cooling rate of photovoltaic panels is 2,0 °C/min, and water spraying should be stopped in 4,7 minutes.

It should be noted that the issue of determining the maximum or rational values of the capacities of isolated SES when using SB with additional heat sink modules, allowing an isolated SES to be economically profitable, is poorly considered in the literature and additional research is needed here.

5. Conclusion

1. The most optimal price parameter for cooling one solar panel operating in isolated SES is liquid cooling, implemented using a pump on the front side of the panel with an approximate cost of 3036 rubles (in prices for May 2022), taking into account electrical installation work.
2. The liquid cooling method of one solar panel operating in isolated SES provided the highest cooling rate of photovoltaic panels to a value of 2,0 °C/min.
3. In order to determine the rational values of the capacities of isolated SES when using SB with additional heat sink modules, allowing an isolated SES to be economically profitable, it is necessary to conduct additional research.

References

[1] Zaini N.H., Ab Kadir M.Z., Izadi M., Ahmad N.I., Radzi M.A.M., Aziz N. The effect of temperature on a mono-crystalline solar PV panel. 2015 IEEE Conference on Energy Conversion (CENCON), 2015, pp. 249–253. DOI: 10.1109/CENCON.2015.7409548

[2] Swar A. Zubeer, Mohammed H.A., Ilkan M. A review of photovoltaic cells cooling techniques. E3S Web of Con-

ferences, 2017, vol. 22, 00205. DOI: 10.1051/e3sconf/20172200205

[3] Gulkov V.N., Kolesnichenko I.D., Korotkov K.E. Investigation of the effect of heating solar modules on the efficiency of radiation conversion. Proceedings of Saint Petersburg Electrotechnical University Journal, 2019, no. 1, pp. 10–16. Available at: https://izv.etu.ru/en/archive/2019/1/10-16 (accessed 20 April 2021).

[4] Vliyanie temperatury na effektivnost solnechnykh batarey [The influence of temperature on the efficiency of solar panels]. Available at: https://vk.com/wall-66711818_685 (accessed 20 April 2021).

[5] Dzhumaev A.Ya. Analiz vliyaniya temperatury na rabochiy rezhim fotoelektricheskoy solnechnoy stantsii [The analysis of influence of temperature on operating conditions photo-electric solar station]. Tekhnicheskie nauki – ot teorii k praktike. Sbornik statey po materialam XLVI mezhdunarodnoy nauchno-prakticheskoy konferentsii [Technical sciences – from theory to practice. Collection of articles based on the materials of the XLVI International Scientific and Practical Conference]. Novosibirsk, SibAK, 2015. No. 5 (42). Available at: https://sibac.info/ conf/tech/xlvi/42263 (accessed 20 April 2021).

[6] Subhash Chander, Purohit A., Anshu Sharma A., Nehra S.P., Dhaka M.S. Impact of temperature on performance of series and parallel connected mono-crystalline silicon solar cells. Energy Reports, 2015, vol. 1, pp. 175–180. DOI: 10.1016/j.egyr.2015.09.001

[7] Zaoui F., Titaouine A., Becherif M., Emziane M., Aboubou A. A combined experimental and simulation study on the effects of irradiance and temperature on photovoltaic modules. Energy Procedia, 2015, vol. 75, pp. 373–380. DOI: 10.1016/j.egypro.2015.07.393

[8] Popovici C.G., Hudișteanu S.V., Mateescu T.D., Cherecheș N.C. Efficiency Improvement of Photovoltaic Panels by Using Air Cooled Heat Sinks. Energy Procedia, 2016, vol. 85, pp. 425–432. DOI: 10.1016/j.egypro.2015.12.223

[9] Farhana Z., Irwan Y.M., Azimmi R.M.N., Razliana A.R.N., Gomesh N. Experimental investigation of photovoltaic modules cooling system. 2012 IEEE Symposium on Computers & Informatics (ISCI), 2012, pp. 165–169. DOI: 10.1109/ISCI.2012.6222687

[10] Teo H.G., Lee P.S., Hawlader M.N.A. An active cooling system for photovoltaic modules. Applied Energy, 2012, vol. 90, issue 1, pp. 309–315. DOI: 10.1016/j.apenergy.2011.01.017

[11] Tonui J.K., Tripanagnostopoulos Y. Improved PV/T solar collectors with heat extraction by forced or natural air circulation. Renewable Energy, 2007, vol. 32, Iss. 4, pp. 623–637. DOI: 10.1016/j.renene.2006.03.006

[12] Chandrasekar M., Senthilkumar T. Passive thermal regulation of flat PV modules by coupling the mechanisms of evaporative and fin cooling. Heat and Mass Transfer, 2016, vol. 52, pp. 1381–1391. DOI: 10.1007/s00231-015-1661-9

[13] Taieb Nehari, Mohamed Benlakam, Driss Nehari. Effect of the fins length for the passive cooling of the photovoltaic panels. Periodica Polytechnica Mechanical Engineering, 2016, vol. 60 (2), pp. 89–95. DOI: 10.3311/PPme.8571

[14] Gotmare J.A., Borkar D.S., Hatwar P.R. Experimental investigation of pv panel with fin cooling under natural convection. International Journal of Advanced Technology in Engineering and Science, 2015, vol. 03, Special Iss. 02, pp. 447–454.

[15] Nizetic S., Coko D., Yadav A., Grubiši-Cabo F. Water spray cooling technique applied on a photovoltaic panel: The performance response. Energy Conversion and Management, 2016, vol. 108, pp. 287–296. DOI: 10.1016/j.enconman.2015.10.079

[16] Amelia A.R., Irwanto M., Leow Wai Zhe, Gomesh N., Safwati Ibrahim, Anuar M.A.M. Cooling on photovoltaic panel using forced air convection induced by DC fan. International Journal of Electrical and Computer Engineering (IJECE). 2016, vol. 6, no. 2, pp. 526–534. DOI: 10.11591/ijece.v6i1.9118

[17] Hussien Hashim A., Numan Ali H., Abdulmunem Abdulmunem R. Improving of the photovoltaic / thermal system performance using water cooling technique. IOP Conference Series: Materials Science and Engineering, 2014, vol. 78, 012020. Available at: https://iopscience.iop.org/article/10.1088/1757-899X/78/1/012020 (accessed 5 March 2021).

[18] Ahmer A.B. Baloch, Haitham M.S. Bahaidarah, Palanichamy Gandhidasan, Fahad A. Al-Sulaiman Experimental and numerical performance analysis of a converging channel heat exchanger for PV cooling. Energy Conversion and Management, 2015, vol. 103, pp. 14–27. DOI: 10.1016/j.enconman.2015.06.018

[19] Bahaidarah H., Abdul Subhan, Gandhidasan P., Rehman S. Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions. Energy, 2013, vol. 59, pp. 445-453. DOI 10.1016/j.energy.2013.07.050

[20] Alonso Garcia M.C., Balenzategui J.L. Estimation of photovoltaic module yearly temperature and performance based on nominal operation cell temperature calculation. Renewable Energy, 2004, vol. 29, Iss. 12, pp. 1997–2010. DOI: 10.1016/j.renene.2004.03.010

Received: June 23, 2021