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Study of Vertically Oriented Solar Battery by Exposure of Concentrated Solar Radiation

A. K. Esman[1], G. L. Zykov[1], V. A. Potachits[1], V. K. Kuleshov[1]

[1]Belarusian National Technical University (Minsk, Republic of Belarus)

Abstract. Solar power is one of the largest sectors of the global electric and heat power industry. In search of new energy sources, scientists and engineers around the world are increasingly turning their attention to solar batteries, which can be a suitable replacement for non-renewable energy sources. Vertically oriented solar batteries will generate electricity throughout the daylight hours, which eliminates use of additional equipment. The paper proposes a 3D model of a solar battery with a vertical orientation of its modules, as well as the calculation and evaluation of temperature characteristics and the range of efficiency variations obtained under conditions of both the diurnal and seasonal changes in ambient temperature, and the po-wer density changes of concentrated solar radiation, the maximum values of which were chosen equal to 1; 5 and 10 kW/m². The dependences of the maximum values of the solar battery temperature and the temperature gradient inside it, as well as the dependences of the minimum, average and maximum values of the radiative heat flux to the solar battery surface in the presence and absence of temperature stabilization of the heat sink backside versus the time of day in the middle of January and July have been plotted. As calculations have shown, at the solar radiation concentration of 10 kW/m², the efficiency in July is increased by more than 2 times due to the use of thermoelectric converters in the battery. Moreover, according to the obtained results, when the solar modules are oriented vertically, temperature gradients and, consequently, the total efficiency of the solar battery and power generation time will be greater compared to the horizontal position of the solar modules, which will reduce operational costs.

Keywords: solar battery, solar module, 3D model, COMSOL Multiphysics, heat transfer, temperature stabilization, temperature gradient, radiative heat flux, efficiency

Исследование вертикально ориентированной солнечной батареи при воздействии концентрированного солнечного излучения

**Докт. физ.-мат. наук А. К. Есман[1],
кандидаты физ.-мат. наук, доценты Г. Л. Зыков[1], В. А. Потачиц[1],
канд. техн. наук В. К. Кулешов[1]**

[1]Белорусский национальный технический университет (Минск, Республика Беларусь)

Реферат. Солнечная энергетика является одним из крупнейших секторов мировой электро- и теплоэнергетики. В поисках новых источников энергии ученые и инженеры всего мира все чаще обращают внимание на солнечные

Адрес для переписки	**Address for correspondence**
Есман Александр Константинович	Esman Alexander K.
Белорусский национальный технический университет	Belarusian National Technical University
просп. Независимости, 65,	65 Nezavisimosty Ave.,
220013, г. Минск, Республика Беларусь	220013, Minsk, Republic of Belarus
Тел.: +375 17 331-00-50	Tel.: +375 17 331-00-50
ak_esman@bntu.by	ak_esman@bntu.by

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батареи, которые могут стать подходящей заменой невозобновляемых источников энергии. Вертикально ориентированные солнечные батареи позволят генерировать электроэнергию в течение всего светового дня, что исключает использование дополнительного оборудования. В статье предлагаются 3D модель солнечной батареи с вертикальной ориентацией ее модулей, а также расчет и оценка температурных характеристик и диапазон вариаций КПД, получаемых в условиях как суточных и сезонных изменений температуры окружающей среды, так и изменений плотности мощности концентрированного солнечного излучения, максимальные значения которой были выбраны равными 1; 5 и 10 кВт/м². Построены зависимости максимальных значений температуры солнечной батареи и градиента температуры внутри ее, а также зависимости минимальных, средних и максимальных значений лучистого теплового потока к поверхности солнечной батареи при наличии и отсутствии стабилизации температуры тыльной стороны радиатора от времени суток в серединах января и июля. Как показали расчеты, при концентрации солнечного излучения 10 кВт/м² КПД в июле увеличивается более чем в два раза за счет использования в батарее термоэлектрических преобразователей. Более того, согласно полученным результатам, при вертикальной ориентации солнечных модулей градиенты температуры и, следовательно, суммарный КПД солнечной батареи и время генерации энергии будут больше по сравнению с горизонтальным положением солнечных модулей, что позволит снизить эксплуатационные расходы.

Ключевые слова: солнечная батарея, солнечный модуль, трехмерная модель, COMSOL Multiphysics, теплопередача, стабилизация температуры, градиент температуры, лучистый тепловой поток, коэффициент полезного действия

Introduction

In the next few decades, the Sun may well become a major source of energy. Solar power is the largest sector of the global electric and heat power industry in terms of the amount of annually attracted investment and commissioned capacities. For example, in 2015, the amount of commissioned new capacities of renewable energy sources exceeded the total amount of newly commissioned capacities of coal and gas plants [1]. In 2017, the cost of solar and wind energy was \$0.056 and \$0.014 per kilowatt-hour, respectively. At the same time, the cost of a kilowatt-hour of energy from gas and coal is more than 6 cents [2]. In the search for new energy sources, scientists and engineers from around the world are increasingly focused on solar batteries and electric power plants, which can be a suitable replacement for non-renewable energy sources. Nowadays, the use of solar batteries is increasingly urgent, when oil and gas reserves are gradually running out, and their price is increasing. The use of solar energy is beneficial not only for consumers, but also for the ecology of the planet as a whole.

Usually in the middle of the day, the solar radiation energy converted into electricity exceeds needs. Therefore, it must be stored for future use, which requires additional equipment. Vertical oriented solar batteries will generate electricity throughout the daylight hours. This eliminates the use of the mentioned above equipment [3].

The purpose of this paper is to build a 3D model of the photoelectric converter with vertical orientation of its modules in the simulation software environment and to estimate its main parameters under real operating conditions.

Construction of the vertically oriented solar battery

The structure of the proposed solar battery is shown in the Fig. 1 [4].
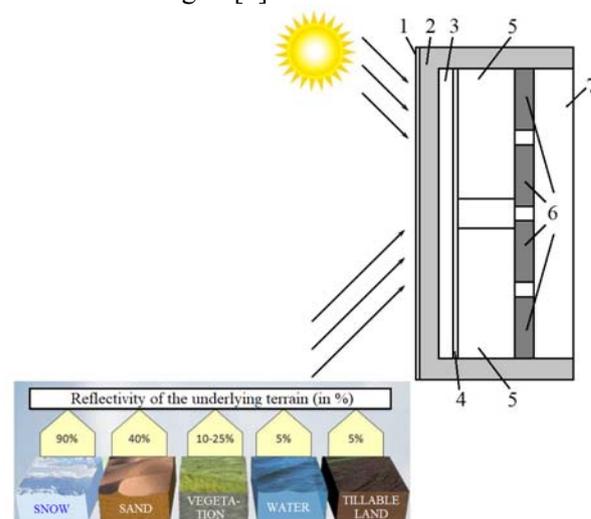
Fig. 1. Structure of the solar battery with vertical orientation of its modules: 1 – silicon oxide nanofilm; 2 – silicate glass case; 3 – sealant, 4 – solar module; 5 – battery of thermal diodes; 6 – battery of thermoelectric converters; 7 – heat sink

The solar battery contains a heat sink 7 with vertical slots thermally connected to the backside

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of a vertically mounted solar module 4 through a battery of thermal diodes 5 and thermoelectric converters (TEC) 6, and the front side of the solar modules 4 mechanically and optically connected to the silicate glass case 2 through sealant 3, the refractive index n of which is selected from the interval:

$$n_{SG} < n < n_{SM}, \qquad (1)$$

where n_{SG} and n_{SM} are the refractive indices of the silicate glass and the solar modules, respectively, and a silicon oxide nanofilm 1 is located on the outer vertical surface of the case 2.

Silicon oxide nanofilm 1 (($x = 100$ nm) $\times$ ($y = 178$ mm) $\times$ ($z = 178$ mm) in size, see Fig. 1) is a silicon oxide nanoparticles film which is fabricated from an industrially produced layer of colloidal solution and is firmly attached to a silicate glass case 2 (($x = 4$ mm) $\times$ ($y = 178$ mm) $\times$ ($z = 178$ mm) in size), while forming a continuous layer of nanoscale tubercles, self-ordered into a structure that does not allow both water droplets and dust particles to stay on it. Sealant 3 is a silicone transparent self-polymerizing adhesive with refractive index n, which is chosen according to expression (1), so that the silicate glass case 2 together with sealant 3 are antireflective coating for solar modules 4 (($x = 0.2$ mm) $\times$ ($y = 178$ mm) $\times$ ($z = 166$ mm) in size) with minimum reflection of the solar radiation. Solar module 4 is a set of standard solar cells (SCs) based on monocrystalline silicon. A battery of thermal diodes 5 consists of cells that perform on the basis of heat pipes and conduct heat in one direction. A battery of thermoelectric converters 6 (each of the converters has dimensions: ($x = 3.8$ mm) $\times$ ($y = 178$ mm) $\times$ ($z = 39.25$ mm)) is a standard battery of Peltier cells. The gap between the TECs is chosen to be 3 mm. The heat sink 7 is made of aluminum alloy D16T.

Operation algorithm
of the vertically oriented solar battery

At first, the SCs of the solar module 4 are mounted vertically, turning their front sides in the south direction. Input solar radiation falls on the silicon oxide nanofilm 1 both directly and after reflection from the flat underlying terrain (e. g., a lake). Passing sequentially through the silicon oxide nanofilm 1, silicate glass case 2 and sealant 3, it reaches the SCs of the solar module 4 and is absorbed in its photosensitive structures. Depen-

ding on the type of the used SCs, the 22 – 15 % of the incoming solar radiation energy is converted into the electric current, and the remaining part of this energy is converted into the heat, which enters to the hot junctions of the battery of thermoelectric converters 6 through a battery of thermal diodes 5. The temperature of the cold junctions of the battery of thermoelectric converters 6 is maintained near the ambient temperature by the heat sink 7 thermally connected to them. As a result, the thermal energy is also converted into electricity in the battery of thermoelectric converters 6. More effective dissipation of heat energy into the environment and thereby the equalization of the heat sink temperature to the ambient temperature is provided by the vertical slots of the heat sink 7. Water particles (rain, fog) on the surface of silicon oxide nanofilm 1 touch it with only a small part of the surface, thereby reducing Van der Waals forces and allowing the surface tension forces to compress them into balls, which easily roll down over the vertical surface, taking particles of dirt, dust, etc. with them.

In the proposed design of the solar battery with vertical orientation of the SCs 4, solar radiation is converted into electrical energy more efficiently both by recycling the heat released by SCs 4 and by the solar radiation concentration by the underlying terrain (Fig. 1). Moreover, the conversion efficiency of the proposed solar battery increases both due to the operation of the battery of TECs 6, as well as during sunsets, because at these times the battery of thermal diodes 5 will maintain the same direction of heat flow. In addition, the considered solar battery with vertical orientation of SCs 4 has the self-cleaning property of the input aperture. This property excludes the cleaning of the device.

Computer simulation

For the development and implement of the solar battery, we used the COMSOL Multiphysics [5–8]. The temperature characteristics and range of efficiency variations were calculated in the presence and absence of temperature stabilization of the backside of the heat sink 7. Diurnal and seasonal variations of both the ambient temperature and solar radiation power density with maximum values of 1, 5 and 10 kW/m^2 were taken into account in the simulation for the geographic coordinates of Minsk (Fig. 2).

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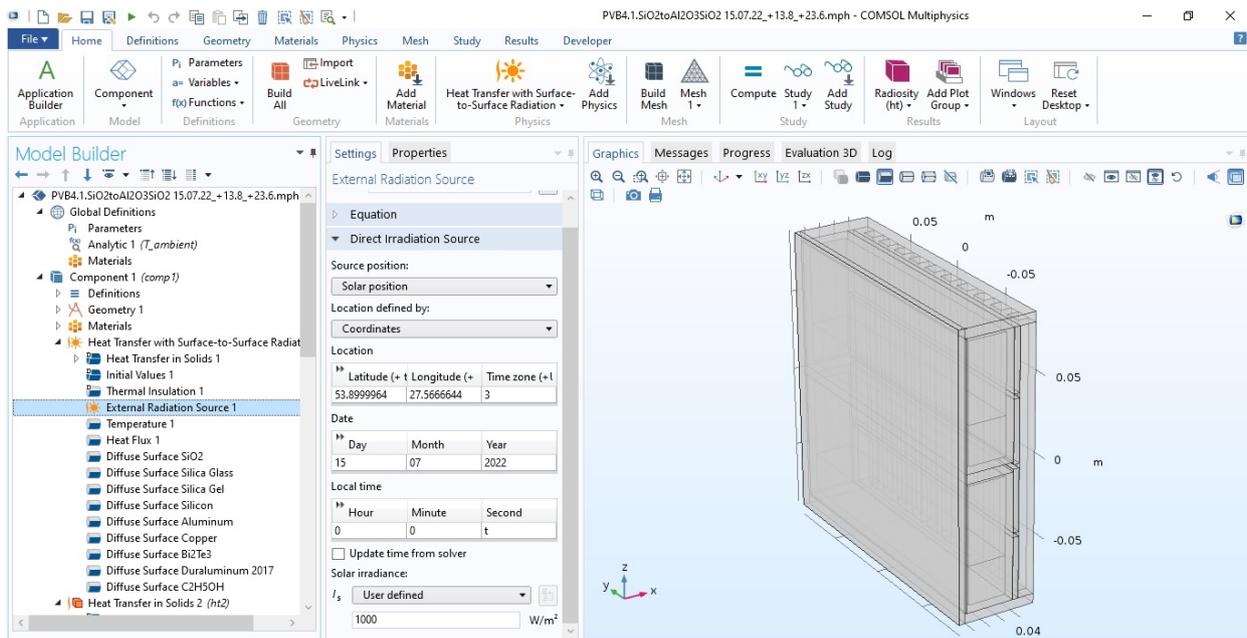Science and Technique. V. 22, No 5 (2023)

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Fig. 2. Screenshot of the COMSOL Multiphysics setup window using the Solar Position option

The diurnal variation curve is close to a sinusoidal distribution around the average air temperature:

$$T_{amb}(t) = T_{av} + \Delta T \cos\left(2\pi \frac{t-14}{24}\right),$$

where T_{av} and ΔT are the average temperature and half diurnal temperature variation, respectively; t is the time in hours.

The solar battery with vertical orientation of the SCs was divided into finite elements (Fig. 3).
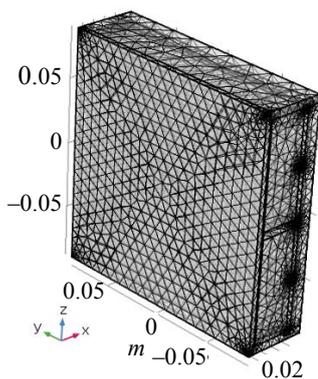

Fig. 3. Screenshot of the grid construction of the solar battery in the COMSOL Multiphysics software

Analysis of the results

While in operation of the solar battery with vertical orientation of the SCs under conditions of ambient temperature variation and solar radiation exposure, there is uneven heating of both its surface and internal layers. The maximum power density was 1 kW/m². Stabilization of the heat sink backside temperature at (T_{amb} + 4°C), where T_{amb} – ambient temperature, leads to a decrease of battery temperature by 5.5 °C in January and by 3.8 °C in July during daylight hours (Fig. 4). As can be seen from Fig. 4, the temperature stabilization reduces the operating temperature range of the solar battery from 18.5 °C (from –6 °C to +12.5 °C, see Fig. 4a, curve 3) to 9.3 °C (from –2 to +7.3 °C, see Fig. 4a, curve 2) in January and lowers its maximum temperature values from +36.8 to +33 °C in July (Fig. 4b, curves 2′ and 3′). The radiative heat flux to the solar battery surface versus the time of day is shown in Fig. 5. Calculations have shown that in the middle of January the radiative heat flux to the solar battery surface reaches maximum values of 1.6 kW/m² at about 13 o'clock (Fig. 5a, curve 3), and in the middle of July its maximum values of 1.46 and 1.57 kW/m² are reached at about 8 o'clock and at a half past 18 o'clock, correspondingly (Fig. 5b, curves 2, 2′, 3 and 3′). In this case, the radiative heat flux is lower during the day time. This is due to the fact that the temperature of all battery cells equalizes and the temperature gradient becomes smaller by mid-day in the middle of July. The temperature stabilization of the heat sink backside has no significant effect on the radiative heat flux both in January and July (Fig. 5).
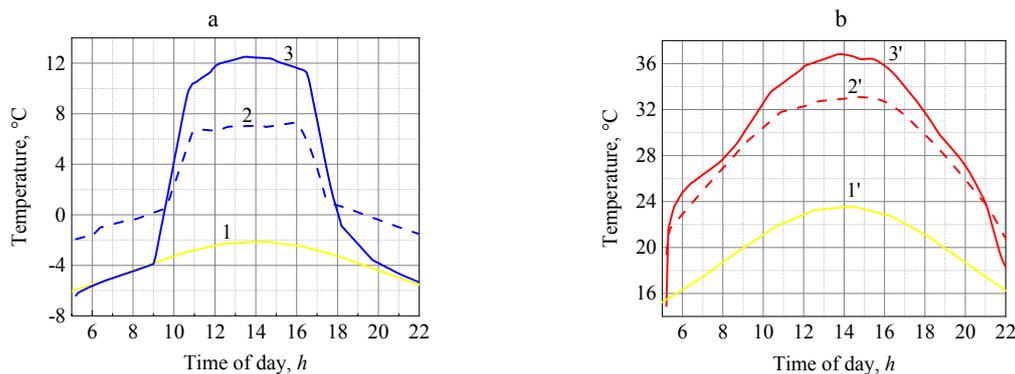
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Fig. 4. The average ambient temperature (curves 1 and 1′) and the maximum temperature of the solar battery with (curves 2 and 2′) and without (curves 3 and 3′) the temperature stabilization of the heat sink backside versus the time of day in the middle of: a – January; b – July
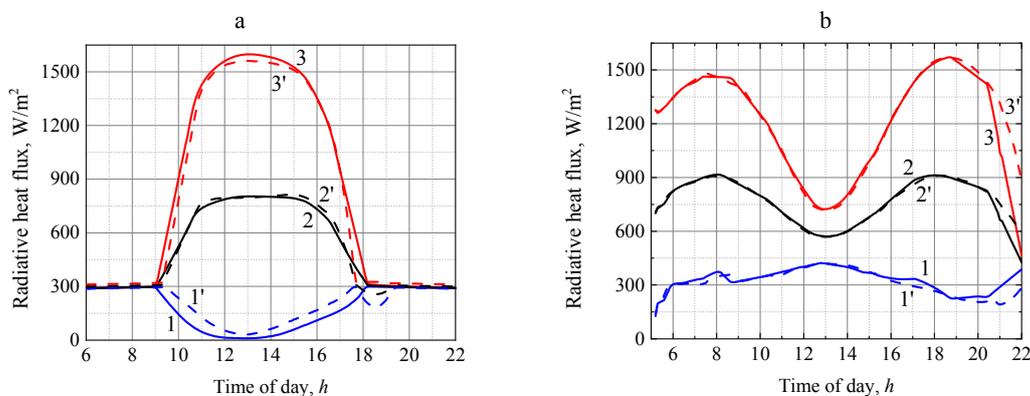

Fig. 5. The minimum (curves 1 and 1′), average (curves 2 and 2′) and maximum (curves 3 and 3′) values of the radiative heat flux to the surface of the solar battery with (curves 1, 2 and 3) and without (curves 1′, 2′ and 3′) the temperature stabilization of the heat sink backside versus the time of day in the middle of: a – January; b – July

Fig. 6 shows the diurnal changes in the temperature gradient inside the solar battery under conditions of the solar irradiation exposure with the maximum power density of $1\,kW/m^2$ in January (curves 1 and 1′) and July (curves 2 and 2′). As follows from the graphs (Fig. 6), the maximum temperature gradient values of, respectively, 0.4×10^5 and 0.48×10^5 K/m are reached inside the solar battery with and without the temperature stabilization of the heat sink backside at about 11 o'clock in the middle of January. In the middle of July, the maximum temperature gradient values of 1.14×10^5 and 1.17×10^5 K/m are reached inside the solar battery with and without the temperature stabilization of the heat sink backside at about at about 7 o'clock. This is due to the thermophysical properties of the TECs of solar battery and the temperature difference on their surfaces under conditions of changing ambient temperature. In July, the maximum values of the temperature gradient are about 35–40 % higher than in January (Fig. 6). Temperature stabilization of the heat sink backside increases the temperature gradient by about 20 % in the middle of January and by about 2.7 % in the middle of July. Due to the fact

that the daylight hours in July are longer than in January, the total energy gain, obtained throughout the day in July, is greater than in January due to the presence of TEC in the solar battery.

Achieved maximum temperature gradients (Fig. 6) between the internal and external surfaces of TECs of the solar battery under solar radiation exposure lead to the fact that the potential difference generated between these electrodes also reaches maximum values in the morning and in the middle of day in January and in July. This leads to an increase in the efficiency of the device as a whole.

For solar batteries with monocrystalline silicon modules with an efficiency of 22 % at 25 °C, the temperature coefficient of power reduction was –0.25 %/°C, when these batteries are illuminated by a radiation flux of 1400 W/m^2 with a spectrum close to the solar spectrum [9].

Therefore, in the middle of the day in January, the solar battery will work with maximum efficiency, while in July at its temperature of 36 °C, solar battery without a concentration of solar insolation will work with an efficiency of 19.3 % and 20.3 %, correspondingly, in the absence and

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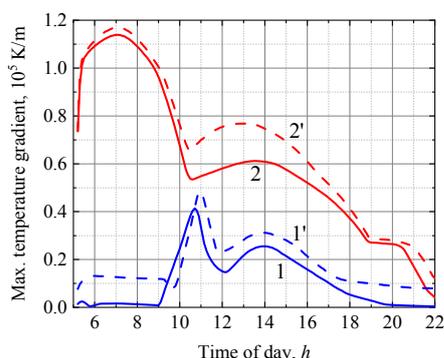presence of thermal stabilization of the heat sink backside.

Fig. 6. The maximum temperature gradient inside the solar battery with (curves 1′ and 2′) and without (curves 1 and 2) the temperature stabilization of the heat sink backside versus the time of day in the middle of January (curves 1 and 1′) and July (curves 2 and 2′)

Moreover, in summer morning (until about 7 a. m.) and in summer evening (after about 10 p. m.) solar batteries work with an efficiency of 22 %, when they have not yet warmed or have already cooled down (Fig. 4).

The temperature of the solar battery with the temperature stabilization of the heat sink backside under solar radiation exposure with the maximum power density of 10 kW/m^2 is 68.6 and 96.4 °C in the middle of January and July, respectively. In this case, the efficiency of the solar battery is 11.1 and 4.2 % in the middle of January and July, respectively. Developed low-temperature TECs for the temperature range of 30–300 °C have an efficiency of 5.3 % [10], so when using them without a concentration of solar insolation, the total efficiency of the device in July will be more than 23 %, and in January will be less than 26 %. The efficiency of the device under a solar concentration of 10 Suns will reach values of 9.3 % and 15.8 % in July and January, respectively. The total efficiency values are obtained taking into account that the heat flux is calculated by considering the current level of photogeneration.

CONCLUSION

The proposed solar battery with vertical orientation of the solar cells was developed in the COMSOL Multiphysics software. The temperature characteristics was calculated under conditions of diurnal and seasonal changes of the ambient temperature and the solar power density, the maximum values of which chosen to be 1; 5 and 10 kW/m^2. According to the calculations, the efficiency of the solar battery under exposure of solar radiation with maximum of the considered concentrations in July increases by more

than 2 times due to the use of the TECs in the battery. Moreover, according to the results, the temperature gradients and, consequently, the total efficiency of the solar battery and the time of energy generation will be greater in the case of vertical orientation of the solar cells as compared with to the its horizontal orientation, such as on the roof [7, 8].

Using the vertical orientation of the solar cells in addition to the optimization of the energy generation levels during the day will reduce the operating costs associated with cleaning the solar batteries and replacing them after external effects.

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