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Method for Snow Removal from the Surface of a Photovoltaic Array

V. G. Dyskin[a, *], I. A. Yuldoshev[b], and S. Shoguchkorov[c]

[a] Material Science Institute, Academy of Sciences of the Republic of Uzbekistan, Tashkent, 100084 Uzbekistan
[b] Tashkent State Technical University, Tashkent, 100095 Uzbekistan
[c] Physical–Technical Institute SPA Physics–Sun, Academy of Sciences of the Republic of Uzbekistan, Tashkent, 100084 Uzbekistan
**e-mail: dyskin@uzsci.net*

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Abstract—The goal of cleaning snow from the surface of a photovoltaic array (PVA) is relevant for all regions where snow cover is present for several months. In winter, depending on climatic conditions, the amount of energy loss ranges from 10 to 100%. This paper presents the results of measuring the characteristics of the snow cover and the time of cleaning a PVA by a warm air jet, which constitutes a part of a photovoltaic station of 10 kW, located at the training ground of the Tashkent State Technical University. The results of model calculations are in satisfactory agreement with the results of measurements.

Keywords: photovoltaic battery, snow, cleaning time, efficiency, harsh environment

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INTRODUCTION

The prospect of energy shortages in the future stimulates the development and use of alternative energy sources. The sun is an environmentally friendly, practically inexhaustible source of energy. Direct conversion of solar radiation into electrical energy is carried out by photovoltaic arrays (PVAs). The power of the PVA is proportional to the density of the solar radiation flux and depends on the type of semiconductor material of the solar cell, their number, and switching between them. The volume of electricity produced by a photovoltaic station is determined not only by the power, quantity, and quality of the PVA, their switching and orientation relative to the Sun, but also by climatic factors such as daytime temperature and precipitation [1–11].

Photovoltaic stations operate all year round. Atmospheric precipitation, settling on the surface of the PVA, reduces the flow of solar radiation and, accordingly, the amount of electricity generated. In the spring–autumn period of operation, due to a layer of dust on the surface of the PVA, energy losses amount to 50% of the initial power [1–4]. In winter, as a result of snowfall, the PVA surface is covered with a layer of snow, which, like atmospheric precipitation, reduces the amount of electricity generated. Depending on climatic conditions, the value of energy losses ranges from 10 to 100% [5,6]. Therefore, the task of cleaning the PVA surface from snow is relevant for all regions where the snow cover lies for several months. Practically, this is the entire territory of the Russian Federation, Canada, Finland, Norway, the mountainous regions of Central Asia, the Caucasus, etc. [5–8].

Existing methods of snow removal, as in the case of dust pollution, can be conditionally divided into passive and active [2–5]. The passive way of clearing snow is melting and sliding. Passive cleaning lasts from several hours to several days and depends on the air temperature, the amount of solar radiation and the angle of inclination of the PVA. In winter, the angle of inclination of the PVA is chosen so that the snow, thawing, "slides" due to gravity. There is no optimal PVA tilt angle for year-round use, since the Sun illuminates the panel at different angles in summer and winter. In winter, at high latitudes, it is recommended to install the PVA at an angle of 70°. Active methods include cleaning with brushes, vibration, water, etc. During mechanical cleaning, the brush and hard ice crystals scratch the surface of the PVA. During the day, melted snow fills sealant defects, scratches, and corrosion cavities. At night, freezing water increases its volume, resulting in strong tensile stresses that "tear" not only water pipes, but also structural elements of the PVA. Therefore, the life of PVA and photovoltaic stations is reduced. The destructive impact of these factors manifests itself over time. Thus, PVA cleaning from frost and snow is an integral and mandatory part of PVA maintenance.

Cleaning the surface of photovoltaic stations, which include tens to hundreds of thousands of panels, requires the presence of maintenance personnel and technical means. Therefore, the financial costs of cleaning from atmospheric precipitation should be

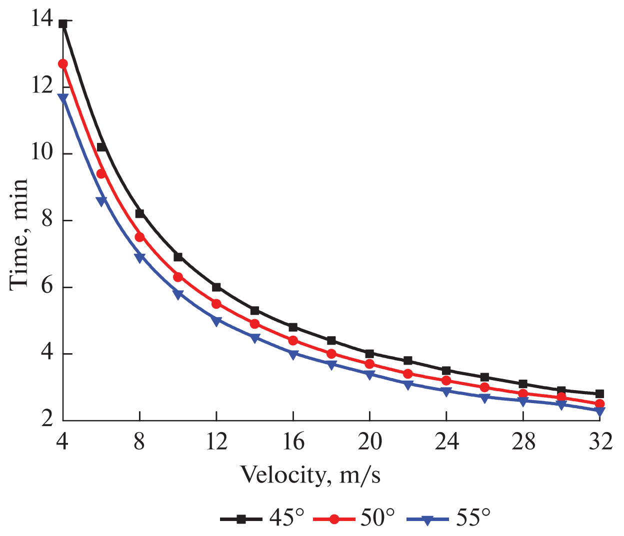

Fig. 1. Dependence of the PVA surface cleaning time on the temperature and velocity of the heat flux jet.

included in the cost of electricity already at the design stage of a photovoltaic plant. As criteria for the effectiveness of a particular cleaning method, you can choose the cost and time of cleaning. The smallest value of these parameters characterizes the optimal (effective) cleaning method. In the spring–autumn period of operation of a high-capacity photovoltaic plant, large volumes of technical (purified) water are required for cleaning. To reduce the consumption of water for cleaning, an anhydrous method for cleaning the surface of the PVA using a directed air flow was proposed. Experiments have confirmed its effectiveness [2, 3, 9, 10]. Obviously, this method can also be used in winter to clear the PVA of snow.

The measurement of the cleaning time of the PVA of a photovoltaic plant with a capacity of 10 kW with a jet of warm air was carried out at the training ground of the Taskent State Technical University. The measurements are compared with the results of model calculations.

MODEL

Under the influence of solar radiation and the flow of warm air, the process of snow melting begins. The time during which the outer boundary of the snow cover reaches the PVA surface is determined by the solution of the Stefan–Neumann problem [11]. The solution of the Stefan–Neumann problem is complicated by the fact that the snow cover is a dynamic system consisting of two phases (ice crystals, air) or three phases (ice crystals, water, and air containing water vapor), whose optical, thermodynamic characteristics, and concentration of phases depend on external conditions [12, 13]. However, a useful estimation of the melting time for practical purposes can be obtained without solving the Stefan–Neumann problem.

PVA covered with snow is a system consisting of two equal-sized plates of different thickness, located at an angle to the horizon. The upper plate with thickness h is the snow cover, the lower plate is the PVA. The temperature of the boundary snow cover on the PVA is taken equal to zero. The temperature difference between the snow cover boundaries is equal to ΔT. An increase in snow cover temperature by ΔT and its transformation into water occurs due to the energy of solar radiation and convective heat transfer. Expressing the mass of snow in terms of volume and density, we write the law of conservation of energy:

$$fh\rho(H + C\Delta T) = \tau(\xi E + \alpha t), \tag{1}$$

where E is the solar radiation flux density; $\xi = 0.05$ is the coefficient of absorption of solar radiation by snow; $H = 333$ kJ/kg, $C = 2120$ J/(kg °C), $\rho = 917$ kg/m^3 is the melting enthalpy, specific heat capacity, and density of ice; f is the volume concentration of ice in the snow cover; α is the coefficient of convective heat transfer; t is the temperature of the air flow; τ is the PVA cleaning time. From (1), two formulas useful for practical purposes can be derived:

$$\tau = \frac{f\rho h(H + C\Delta T)}{\xi E + \alpha t} \tag{2}$$

and volume concentration of ice:

$$f = \frac{\tau(\xi E + \alpha t)}{\rho h(H + C\Delta T)}. \tag{3}$$

The maximum time of snow melting on the PVA surface can be estimated from formula (2) if we put $\alpha = 0$, which corresponds to passive cleaning. The cleaning time in cloudy weather is estimated by formula (2), if we take $\xi \sim 0$. If the air flow temperature is less than 100°C, then the coefficient of convective heat transfer is calculated by formula [14]:

$$\alpha = 0.032\frac{\gamma}{L}\left(V\frac{L}{\nu}\right)^{0.8}, \tag{4}$$

where $L = 0.1$ m is the distance from the nozzle of the hair dryer to the PVA; γ, ν are the coefficients of thermal conductivity and kinematic viscosity of air, depending on air temperature [14–16]. Calculation by formula (2) is shown in Fig. 1. The initial data for the calculation are taken from reference books [15, 16]. It can be seen that the temperature of the air jet has little effect on the cleaning time of the PVA surface. As the jet velocity increases, the cleaning time decreases and remains almost unchanged for $V > 28$ m/s.

EXPERIMENTAL

To determine the cleaning time using a warm air flow, several PVAs with a power of 270 W were selected (Fig. 2). PVA dimensions were 1.65 × 0.99 m^2. The

Fig. 2. Photovoltaic station at the polygon of the Tashkent State Technical University. February 2021: (a) before the experiment; (b) during the experiment; and (c) fractal structure of the snow cover.

measurements lasted for 4 h (Fig. 3) in calm weather. Air and snow temperatures were measured with laboratory thermometers. DS18B20 temperature sensors were attached to the PVA surface from the back side with a thin adhesive tape. The PVA temperature was recorded by an electronic measuring unit connected to a computer. The total (direct + diffusely reflected) flux of solar radiation was measured using a Solar Power meter Di-LOGSL101. The velocity of the warm air jet was measured with a UNI-T, UT363 MINI digital anemometer.

The source of the jet of warm air was a hair dryer with a power of 3 kW. A velocity of 15 m/s and air jet temperature of 45°C were preliminarily measured. The solar radiation flux was measured every 20 min. The average value of the total solar radiation during the experiment was 952.3 ± 48.6 W/m^2.

RESULTS AND DISCUSSION

Examination of the snow cover showed that snow is a dry porous (fractal) system consisting of ice and air crystals (Fig. 2). All PVAs at the test site were covered with the same layer of snow. The average snow cover thickness was 7 ± 1.0 cm. Figure 3 shows the results of measuring the PVA temperature. The air temperature during the experiment remained constant at 4°C. During cleaning and drying, the PVA temperature increased by 1°. This means that the hot air of the hair dryer does not heat up the PVA and there is no need to be afraid of a violation of the battery tightness due to uneven heating of its surface. The temperature difference between PVA and air in Fig. 3 is explained by the fact that the PVA is heated by the thermal radiation of the Earth and solar radiation, scattered by the atmosphere, diffusely reflected by the Earth and the environment. This effect can be taken into account by add-

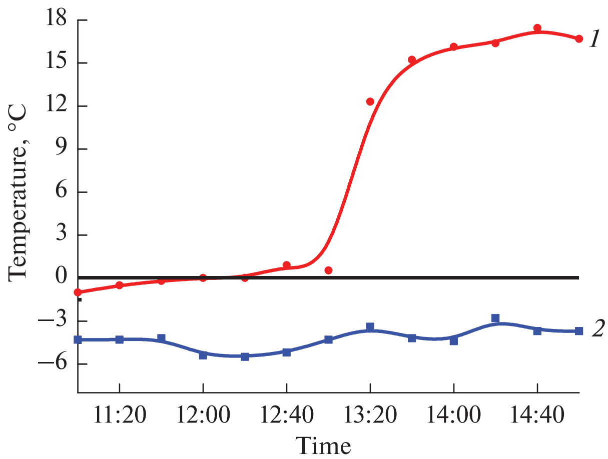

Fig. 3. Change in PVA temperature (*1*) and air temperature (*2*) during the experiment.

ing one more term to the right side of (1). The snow lying on the PVA was thawed from top to bottom. It was assumed that the melt water formed during the thawing process would "heat" and "wet" the lower layers, which would speed up the cleaning process and reduce energy consumption. The average time of thawing the surface of one PVA with a hair dryer was 14.0 min. By halving the nozzle area, we increased the air jet velocity to 20.0 m/s, and the PVA cleaning time was 12.0 min.

The model has been tested. For this, using the cleaning time, according to (3), the volume concentration of ice in the snow cover was determined as $f = 8.5\%$. Substituting this value into formula (2), we determined the cleaning time of the PVA at a heat flow rate of 20.0–11.1 m/(s min). Comparing these times, we can conclude that the model satisfactorily describes the process of PVA cleaning with a jet of warm air. To prevent melt water from remaining in the defects of the sealant, the PVA surface was dried for another 4–6 min.

CONCLUSIONS

• Cleaning the PVA surface from snow with an air flow is technically easy to implement.

• In this experiment, the flow of warm air did not have a destructive effect on the surface of the PVA.

• The model satisfactorily describes cleaning by a stream of warm air.

• Comparison of experimental results with calculations allows us to recommend a model for estimating the cleaning time.

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CONFLICT OF INTEREST

The authors declare that they do not have a conflict of interest.

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