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ILMIY AXBOROTNOMA

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MATHEMATICAL MODEL OF THE SOILING PROCESS OF A PHOTOVOLTAIC MODULE SURFACE

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Abstract. Dust settling on the surface of the photovoltaic module (PVM) forms a film that absorbs part of the solar radiation flux, as a result of which the volume of generated electric energy decreases. An effective method for cleaning the surface of the PVM from contamination should be based on knowledge of the fundamental properties of dust and an understanding of the contamination processes. In this paper, a mathematical model of the contamination of the PVM surface is proposed. It was found that the soiling of the PVM surface depends on the dynamic viscosity and the velocity of the convective air flow. The convective air flow separates dust particles by size. If the convective flow velocity is less than 4 cm/s, then particles with a radius of 50 μm and less do not settle on the surface of the PVM. It is shown that a vertically located PVM retains dust particles with a radius of 50 to 70 μm. The wind speed and direction, the temperature of the PVM, the condition and structure of its surface have a significant impact on contamination.

Keywords: convective flow, dust, efficiency, photovoltaic module, soiling, Van-der-Waals force, viscosity.

Fotoelektrik modul yuzasi ifloslanishi jarayonining matematik modeli

Annotatsiya. Chang fotoelektrik modul (FEM) yuzasida to’planib, quyosh nurlari oqimi ulushini yutadigan plyonka hosil qiladi, natijada hosil bo'ladigan elektr energiyasi miqdori kamayadi. FEM sirtini chang-g’ubordan tozalashning samarali usuli changning fundamental xususiyatlarini bilish va ifloslanish jarayonlarini tushunishga asoslangan bo'lishi kerak. Ushbu ishda FEM yuzasi ifloslanishining matematik modelini taklif etiladi. FEM sirtining ifloslanishi konvektiv havo oqimining dinamik yopishqoqligiga va tezligiga bog'liq ekanligi aniqlandi. Konvektiv havo oqimi chang zarralarini o'lchamiga qarab ajratadi. Agar konvektiv oqim tezligi 4 sm/s dan kam bo'lsa, u holda radiusi 50 mkm va undan kichik bo'lgan zarralar FEM yuzasiga o’tirmaydi. Vertikal ravishda o’rnatilgan FEM radiusi 50 dan 70 mikrongacha bo'lgan chang zarralarini ushlab qolishi ko'rsatib berilgan. Shamolning tezligi va yo'nalishi, FEM harorati, uning yuzasi holati va tuzilishi ifloslanishiga sezilarli ta'sir ko'rsatadi.

Kalit so’zlar: fotoelektrik modul, ifloslanish, konvektiv oqim, qovushqoqlik, samaradorlik, Van-der-Vaals kuchi, chang.

Математическая модель процесса загрязнения поверхности фотоэлектрического модуля

Аннотация. Пыль, оседая на поверхность фотоэлектрического модуля (ФЭМ), образует плёнку, поглощающую часть потока солнечного излучения, вследствие этого уменьшается объём генерируемой электроэнергии. Эффективный способ очистки поверхности ФЭМ от загрязнения должен базироваться на знании фундаментальных свойств пыли и понимании процессов загрязнения. В настоящей работе предлагается математическая модель загрязнения поверхности ФЭМ. Установлено, что загрязнение поверхности ФЭМ зависит от динамической вязкости и скорости конвективного потока воздуха. Конвективный поток воздуха сепарирует частицы пыли по размеру. Если скорость конвективного потока меньше 4 см/с, то частицы радиусом 50 мкм и меньше не осаждаются на поверхность ФЭМ. Показано, что вертикально расположенный ФЭМ удерживает частицы пыли радиусом от 50 до 70 мкм. Значительное влияние на загрязнение оказывает скорость и направление ветра, температура ФЭМ, состояние и структура его поверхности.

Ключевые слова: вязкость, загрязнение, конвективный поток, пыль, сила Ван-дер-Ваальса, фотоэлектрический модуль, эффективность.

Introduction. Of the numerous factors affecting the production of electrical energy by photovoltaic (PV) modules in the regions of the Middle East, Africa, Central Asia and some European countries, two main climatic factors can be distinguished: ambient temperature and concentration of solid particles (dust) in the atmosphere [1-3]. Dust, settling on the surface of the PV module, forms a film that absorbs part of the solar radiation flux, thereby reducing the amount of electricity generation. Part of the absorbed solar energy is converted into heat, which increases the temperature of the PV module, as a result, it leads to an additional decrease in efficiency.

This problem is also relevant for Uzbekistan. The energy crisis in the winter of 2023 in Uzbekistan accelerated the process of integration PV plants. A large number of PV stations and PV modules are installed on the roofs of institutions and private homes. However, due to the heavy dustiness of the air in Tashkent, there was no significant increase in electricity.

Search for an effective method (preferably anhydrous or with minimal water consumption!) cleaning the PV modules surface from soiling is a permanent task of modern photovoltaics. An effective way to clean the surface of the PV modules from contamination should be based on knowledge of the fundamental properties of dust and an understanding of soiling processes. However, the fundamental properties of dust are still not completely researched. Investments in science and technology to solve this problem have increased significantly over the past decade, with the main focus on understanding this problem [1].

In this paper, a mathematical model of PV modules surface contamination is proposed.

1. Kinematics of the pv module surface soiling process. The soiling film is formed on the PV module surface during stochastic aerosol sedimentation. An aerosol is a set of solid and liquid particles of a substance dispersed in the air. Aerosol is formed as a result of erosion of the earth's surface, evaporation of water from the surface of fresh and salty reservoirs, and volcanic eruptions [1, 4, 5-7]. The main components of the soil aerosol contain silicon oxides, alumina compounds, carbonates and calcites (Table 1). Most of the aerosols in the atmosphere are created by dust storms. The composition of dust on Earth (in mountains, deserts, semi-deserts, steppes, etc.) is approximately

the same. This statement is based on the weak dependence of the density and refractive index of aerosols on their type (Table 1) [8]. The particle sizes of aerosols and their sedimentation rate can vary in wide range [1, 7]. In the soiling process of PV module surface, several main, dominant processes can be distinguished. Firstly, it is a complex chaotic movement of particles of different masses and shapes in a turbulent air flow, the speed and direction of which is determined not only by the climate of the area where the module is installed, but also by its temperature and the tilt angle of module. Secondly, the particle size and deposition rate distribution depend on the velocity of convective air flow due to the temperature difference between the PV module and the environment, and the inclination and orientation of

Table 1. Main components of dust

Description	Chemical composition	Density, g/cm^3	Refractive index
Dolomite	$CaCO_3$-$MgCO_3$	2,90	1,68
Calcite	$CaCO_3$	2,80	1,65
Gypsum	$CaSO_4$	2,32	1,52
Quartz	SiO_2	2,65	1,55
Silicon oxide	SiO_2	2,20	1,46

PV module relatively to the Earth's surface [1, 6, 7]. Thirdly, the interaction of dust particles with surface depends on the mass and shape of the part, the condition of surface, air temperature, wind speed and direction, etc. In our opinion, the dominant processes are: sedimentation particles on the surface of PV modules and their interaction with the surface, as a result of which they either slide down along the surface of the PV module and/or are fixed on it. The proposed model is based on the following assumptions:

- the complex turbulent motion of air mass (wind) relatively to the Earth's surface is characterized by an average velocity V_w;
- the velocity vector of convective air flow V_c is determined by the temperature gradient and the tilt angle of PV module [6];
- the shape of dust particle is spherical with a radius of $R{\sim}0{,}5\sqrt[3]{m/\rho}$, where m and ρ are the mass and density of particle material.

2. Kinematics of dust sedimentation. Let's consider the particle motion under the influence of gravity in a counter (convective) of warm air flow. In calm weather, the equation of a particle movement with mass has the form:

$$m\frac{\mathrm{dV}}{\mathrm{dt}} + F_g = F_c + F_a + F_{\mathrm{Ar}}, \qquad (1)$$

V is the velocity, t is the time, F_g is the gravity force, F_a is the force of aerodynamic resistance to the movement of a particle in the air, F_{Ar} is the force of Archimedes; F_c is the force caused by convective flow of air moving vertically upward from the heated surface of PV module at a velocity of V_c. After a while, the motion of the particle becomes uniform:

$$F_g = F_c + F_a + F_{\mathrm{Ar}}, \qquad (2)$$

where

$$F_g = \frac{4\pi R^3}{3}\rho g, \qquad (3)$$

$$F_c = \pi R^2 \frac{\rho_a V_c^2}{2}, \quad (4)$$

$$F_a = 6\pi\vartheta \mathrm{RV}, \quad (5)$$

$$F_{\mathrm{Ar}} = \frac{4\pi R^3}{3}\rho_a g, \quad (6)$$

where g is the acceleration of free fall, ρ_a and ϑ is the density and dynamic viscosity of air. Substituting (3)-(6) into (2), we express from (2) the velocity of uniform motion of a particle:

$$V = \frac{2\mathrm{gR}^2}{9\vartheta}(\rho - \rho_a) - \frac{\rho_a \mathrm{RV}_c^2}{12\vartheta}. \quad (7)$$

Since the dynamic viscosity of the air and the velocity of convective flow increase with increasing temperature, according to (7), the sedimentation rate decreases and finer particles reach the surface of PV modules. If V > 0, then under the influence of gravity, dust is deposited on the surface of the PV module (Fig. 1). If V < 0, the convective air flow prevents dust deposition and the surface of PV module is not soiled. If V ~ 0, then the particle is in a state of unstable equilibrium: The aerodynamic pressure of convective flow balances the force of gravity. Equating (7) to zero, we determine the radius of a particle R_0 "floating" in a convective stream of warm air:

$$R_0 = \frac{3\rho_a V_c^2}{8g(\rho - \rho_a)}. \quad (8)$$

Taking into account (8), formula (7) is represented as:

$$V = \frac{2\mathrm{gR}}{9\vartheta}(\rho - \rho_a)(R - R_0). \quad (9)$$

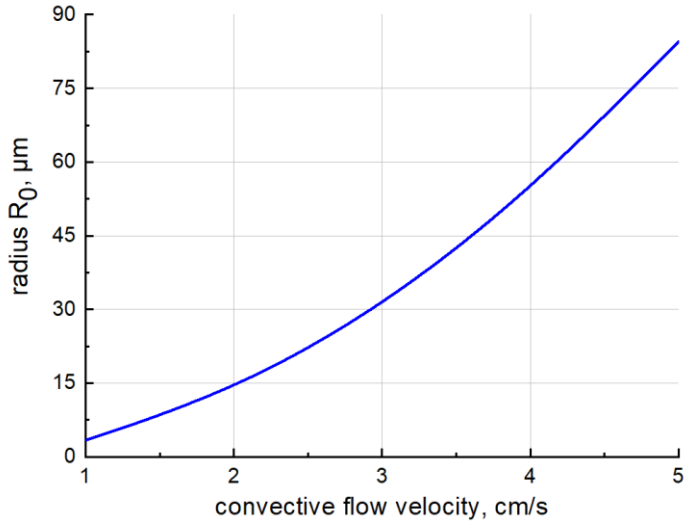

Figure 1. Dependence of the radius R_0 on the velocity of the convective air flow

If the particle radius R is greater than R_0 ($V > 0$), then, under the influence of gravity, dust settles on the surface of PV module (Figs. 1 and 2). If the particle radius R is less than R_0 ($V < 0$), then the convective air flow prevents dust sedimentation, and the surface of PV module is not soiled. Figure 2 shows the results of calculating the sedimentation rate V for a dynamic air viscosity of $1{,}92\times10^{-5}$ Pa s (air temperature 40°C) and air density ρ_a = 1,22 g/sm^3. It can be seen that the convective air flow separates the dust particles by size. For example, at a convective flow velocity $V_c \le 4$ sm/s particles with a radius $R < 50$ microns are not deposited on the PV module surface (sedimentation rate $V < 0$).

The result of a particle collapsing with the surface of a solid body depends on its velocity, the elastic properties of a particle and the surface, and the potential barrier of the surface [7, 8, 9, 10].

When a particle collapses with a surface, a part of the energy is lost to its deformation. If, after the collapse, a particle's velocity is insufficient to overcome the potential barrier, then it remains on it. In the case of an elastic collision, the velocity V_m required to overcome a potential barrier is determined by the formula [7, 10]:

$$V_m = \left[\frac{G}{4\pi\rho R^2 H_0}\right]^{\frac{1}{2}}, \qquad (10)$$

where G is the Hamaker constant, and H_0 is the equilibrium distance between the particle and the surface (~30-40 nm). The values of the Hamaker constants for a number of materials are given in [7, 10, 11].

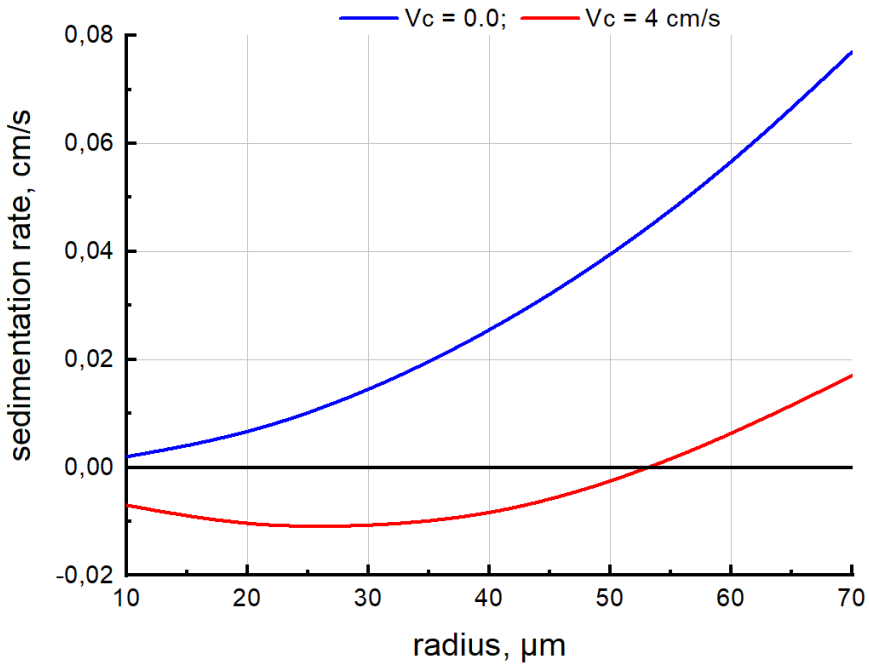

Figure 2. Dependence of the sedimentation rate on the radius R of a particle

If a dust particle is "captured" by a surface, then it is affected by a frictional force, the Van der Waals force F_w (we assume that the particle and the surface are not charged). For a system the spherical particle–flat surface, the Van der Waals force has the form [12]:

$$F_w = \frac{\mathrm{GR}}{6H_0^2}. \qquad (11)$$

To increase the efficiency, the PV module is oriented at an angle θ to the Earth's surface. In this case, the PV module can be considered as an inclined plane (Fig. 3) on which the particle is located.

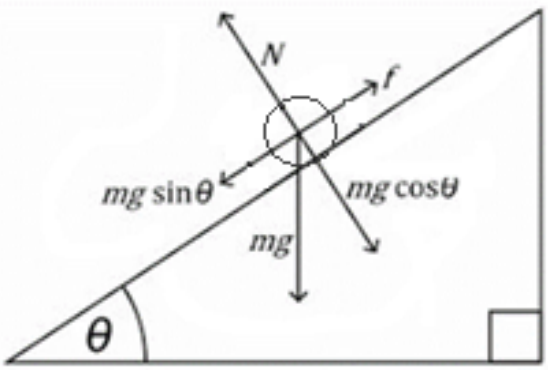

Figure 3. Forces acting on a particle on an inclined plane

In calm weather, the equilibrium condition of a particle on the PV modu surface has the form (Amont–Coulomb formula):

$$\mathrm{mg} \cdot \sin\theta = \mu \cdot (\mathrm{mg}\cos\theta + F_w), \qquad (12)$$

where μ is the coefficient of sliding friction ($0 \le \mu \le 1$). From (12), we express the R_{ip} radius at which the dust particle on PV module surface is in unstable equilibrium:

$$R_{\mathrm{ip}} = \sqrt{\frac{\mu G}{8\pi\rho g \mathrm{H}_0^2(\sin\theta - \mu\cos\theta)}}. \qquad (13)$$

For the tilt angles of PV module $\theta < 45°$ ($\mathrm{tg}\theta < \mu$), the sliding friction force is greater than the component of gravity directed along the surface of PV module: the particle is in a state of equilibrium.

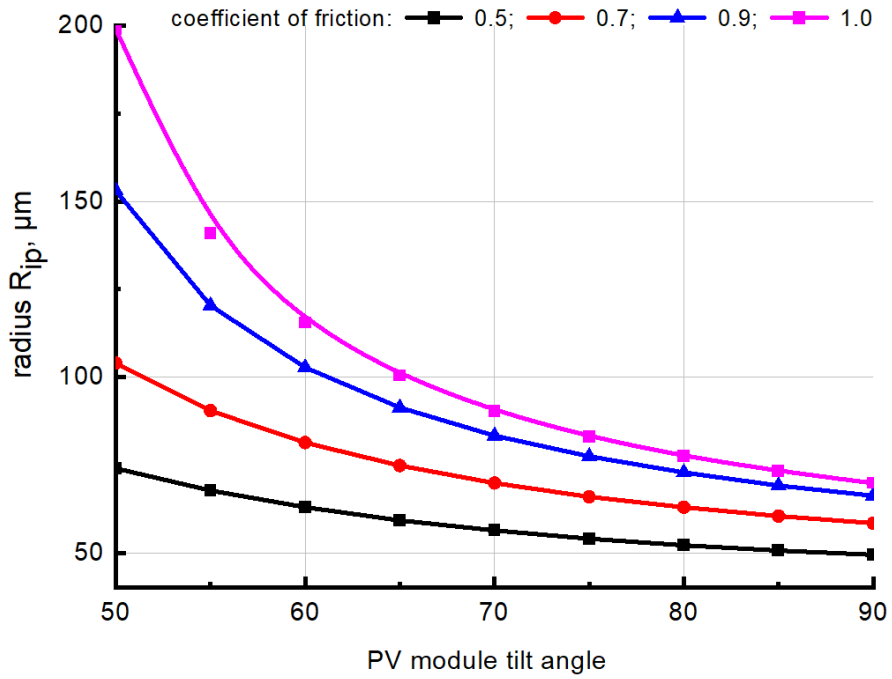

Figure 4. Dependence of the R_{ip} radius on the tilt angle of PV module for different coefficients of friction

If the tilt angle of module $\theta > 45°$, then the sliding friction force is less than the component of gravity directed along the surface of PV module. The particle is in a state of unstable equilibrium and can slide along the surface of PV module. As the angle of inclination of PV module increases, the sliding friction force decreases, and the dust particle is held on the surface by the Van der Waals force

(Fig. 3). The results of calculating the R_{ip} dependence on the angle of inclination of PV module and several coefficients of sliding friction are shown in Fig. 4. It can be seen that the particle radius depends on the angle of inclination and the coefficient of friction. Particles with a smaller radius are captured on the surface of PV module due to the forces of molecular interaction. With an increase in the coefficient of friction and a decrease in the angle of inclination, particles with a radius $R > R_{ip}$, are retained, and the surface of PV module is soiled. Even for the vertical arrangement of PV module ($\theta = 90°$) the surface of PV module retains dust particles with a radius of 50 to 70 microns (Fig. 4).

Conclusions. Based on the obtained results, the following conclusions can be drawn:

- convective air flow separates dust particles by size: thus, at a convective flow velocity $V_c \leq 4$ sm/s, particles with a radius $R < 50$ microns are not deposited on the surface of PV module;
- the radius of particle held by the adhesion forces depends on the tilt angle of PV module;
- A vertically positioned PV module ($\theta = 90$) holds dust particles with a radius of 50 to 70 microns;
- The wind speed and direction, the temperature of PV module, the condition and structure of PV module surface have a significant impact on soiling.

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