Mathematical Modelling and Numerical Simulation for Studying the Trajectory of Dust Particle Approaching Solar Photovoltaic Panel

Published in:
INCOM 2024: Proceedings of 2nd International Conference on Mechanical Engineering

Publication Status:
Published (in print/issue): 05/01/2024

Document Version
Author Accepted version

MATHEMATICAL MODELLING AND NUMERICAL SIMULATION FOR STUDYING THE TRAJECTORY OF DUST PARTICLE APPROACHING SOLAR PHOTOVOLTAIC PANEL

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ABSTRACT

This research aims to investigate the impact of wind velocity on dust particle accumulation on solar panels, a significant factor influencing its efficiency and contribute to increased maintenance costs. The study focuses on analysing the motion of dust particles subjected to various forces, including gravitational force, buoyant force, drag force, wind force, and Van der Waals force. The analytical investigation involves studying particle motion under different wind speeds and directions. The Runge-Kutta method of order four is employed to solve the problem. Interestingly, at low wind speeds (1-2.6 m/s) and wind directions (0°-60°), particles tend to fall to the ground just before reaching the solar panel. However, at higher wind speeds (3.7-5.6 m/s) and similar wind directions, particles exhibit a tendency to fall onto the panel surface. This finding underscores the significance of wind conditions in determining the trajectory of dust particles and their potential impact on solar panel efficiency.

***Keywords:** Dust Simulation, Wind Speed, Runge-Kutta Method, Rupture Distance, Renewable Energy.*

1. INTRODUCTION

As the world increasingly turns its attention towards renewable energy sources to meet growing energy demands, solar photovoltaic systems have emerged as a highly popular choice. These systems harness energy from the sun's radiation, utilizing photovoltaic (PV) modules to directly convert sunlight into electricity. The effectiveness of PV modules is influenced by a combination of geographical factors such as longitude, latitude, sun's position [1], solar intensity, as well as environmental variables including temperature, wind, humidity, pollution, dust, and rainfall. Photovoltaic panels are installed in the outdoors and hence its performance is affected by the outdoor environmental conditions. Dust accumulation is the one of the major factor affecting the performance of solar panels and regular cleaning is required to recover the reflectance loss caused by dust deposition. This results in power losses which lowers the efficiency of the system as well as increases the temperature of panels which leads to decrease in its lifetime.

Researchers have conducted several studies for improving the performance of solar panels based on its material characteristics but little literature is available highlighting the impact of environmental factors affecting dust accumulation on solar panels. Consequently, there is a strong need for a mathematical model to predict, the motion of the dust particle and to determine the conditions that enhance deposition of dust on PV panels. This aspect motivated us for the current study.

Researchers, including Bashir [2], Ali [3], and Ulfat [4], have extensively investigated the performance of solar PV panels across diverse locations. Their studies revealed that the power output of these panels is intricately linked to variables such as solar irradiance, temperature, ambient conditions, day of the year, and the specific type of PV module used.

Sulaiman et al.[5] has conducted an experiment to study the effects of different types of dust accumulation on the PV panels; mud dust and talcum. The motion behaviours and deposition mechanics of dust particles are analysed by the discrete element method by Liu [6].

In this present work, the motion of a single dust particle under the action of various forces has been studied. The impact of wind speed and its direction on the particle's motion has been studied and its trajectory for different wind velocity has been computed.

2. MATHEMATICAL MODEL

Consider a particle P initially at rest at the point P(x_0, y_0) and a neighbouring particle Q at Q(x_1', y_1') (refer Fig.1). The particle is acted on by forces by gravitational force $\overrightarrow{F_g}$ which is acting downwards, and is significant when the particle size is greater than 500 μm [6], the buoyant force $\overrightarrow{F_b}$ acting in upward direction, attractive force Van der Waal force $\overrightarrow{F_a}$ which acts along the line PQ, drag force $\overrightarrow{F_d}$ and the force exerted by wind $\overrightarrow{F_w}$. The particles P and Q are separated by a distance d_o and the line joining P and Q makes an angle θ_p with the horizontal. The wind is assumed to blow from the front side of the panel having a velocity $\vec{u}$ and making an angle θ_v with the positive direction of the x axis. When the particle is at rest and is acted upon by wind moving in the direction θ_v then the drag force $\overrightarrow{F_d}$ acts in the direction of the wind. At any time t, the velocity of the particle be denoted by $\vec{v}$.

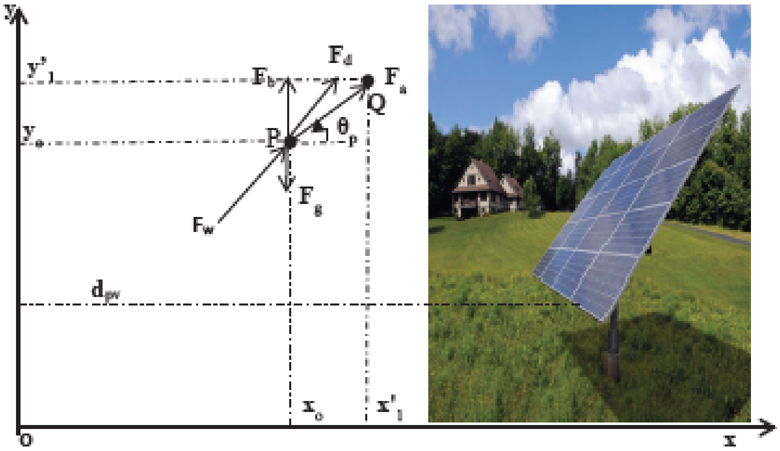

Fig 1: Shows the position of the particle P and Q in front of the PV panel and the forces acting on P.

The equation of motion of the particle P under the action of the forces can be expressed as:

$$m\vec{a} = \overrightarrow{F_g} + \overrightarrow{F_a} + \overrightarrow{F_d} + \overrightarrow{F_b} + \overrightarrow{F_w} \quad (1)$$

The forces depend on the distance of the particle from the panel. Equation (1) can be written depending on the particle's distance from the panel as:

$$m\vec{a} = \begin{cases} \sum_{i=1}^{n} F_i \,;\ d < h_c \\ \sum_{j=1}^{n} F_j \,;\ d > h_c \end{cases} \quad \text{(2a and 2b)}$$

where h_c is rupture distance [7] and F_i denotes the forces acting on the particle P when it is close to the panel and within the rupture distance and Fj denotes the forces acting on the particle P when it is away from the panel. In the present study, the motion of particle when $d > h_c$ is studied. Resolving all the forces acting on the particle P along x and y direction, the equation of motion (2b) reduces to:

$$m\frac{d^2x}{dt^2} = \frac{\rho_{air}(v\cos\theta_v)^2 c_d A}{2} + \frac{A_h r_1 r_2}{6(r_1+r_2)(r\cos\theta_p)^2} + 0.613v^2 A C_d \cos\theta_w \quad (3)$$

$$m\frac{d^2y}{dt^2} = \frac{\rho_{air}(v\sin\theta_v)^2 c_d A}{2} + \frac{A_h r_1 r_2}{6(r_1+r_2)(r\sin\theta_p)^2} - mg + \rho_{air} V g + 0.613v^2 A C_d \sin\theta_w \quad (4)$$

Where,

$$r^2 = (x_0 - x_1' + v_x t)^2 - (y_0 - y_1' + v_y t)^2 \quad (5)$$

$\rho_{air}, \rho_{particle}$ is the air and particle density, c_d is the drag coefficient , A is cross-sectional area, v is the speed of the object relative to the fluid, A_h is the Hamaker constant, r_1 is the radius of particle P, r_2 is the radius of particle Q.

The simultaneous equations (4 & 5) are first reduced to first order differential equations by assuming

$$\frac{d_x}{d_t} = v_x \quad (6)$$

$$\frac{d_y}{d_t} = v_y \quad (7)$$

Therefore, the equations 4 & 5 reduces respectively to

$$\frac{dv_x}{dt} = \frac{1}{m}\left[\frac{\rho_{air}(v\cos\theta_v)^2 c_d A}{2} + \frac{A_h r_1 r_2}{6(r_1+r_2)(r\cos\theta_p)^2} + 0.613v^2 A C_d \cos\theta_w\right] \quad (8)$$

$$\frac{dv_y}{dt} = \frac{1}{m}\left[\frac{\rho_{air}(v\sin\theta_v)^2 c_d A}{2} + \frac{A_h r_1 r_2}{6(r_1+r_2)(r\sin\theta_p)^2} - mg + \rho_{air} V g + 0.613v^2 A C_d \sin\theta_w\right] \quad (9)$$

Apply Runge-Kutta method of order 4 [9] to solve the four simultaneous linear differential equations (6-9).

3. RESULTS AND DISCUSSION

In the current research study, the site chosen is Amity University Haryana, Gurugram (28.46°N, 77.03°E) having a hot semi-arid climate. Dust particles are spherical in shape and uniform in diameter. The list of parameters used for performing the numerical simulation are: radius of P and Q is 0.01m, density of particle 1400 kg/m^3 (Liu [2019]), density of air 1.29 kg/m^3, C_d= 0.5, A_h=8.45 × 10^{-20}J [8], wind velocity1-6m/s,$d_o = 3 \times 10^{-10}$ nm [7], distance of the bottom of panel from y axis 5m, θ_v=0-60°, $\beta = 30^0$, $\theta_p = 30°$, $m = 5.86 \times 10^{-3} kg$, height of front side of solar panel from the ground 3ft and length of panel is 197.6 cm. The simultaneous equations (6-9) is solved using RK4 method by varying the wind speed keeping the wind angle θ_v constant. Again, it is solved by varying the angle θ_v at which wind hits the particle while keeping the magnitude constant. It is observed that when the wind speed is 1-1.7 m/s and direction of wind is $0^\circ - 10°$ the dust particle falls on the ground at a distance of approximately 3.4m from the origin as shown in fig 2 and 3. The particle falls at a distance of approximately 3.2 m as the direction of wind changes from $20^\circ - 60^\circ$. It is observed that the particle does not reach the panel and falls before it.

When wind speed is 2.6- 3.7 m/s and direction of wind is 0° the dust particle falls to the ground at a distance of 4.61m. As the wind direction is increased from $10^\circ - 60^\circ$, the particle travels a distance of 4.6m before falling to the ground.

When the particle moves with a speed from 4.4-5.1 m/s, it is observed that the particle reaches the panel and tends to fall on the panel at varying height along the length of the panel for all values of wind direction, 0° *to* 60° and average distance travelled by the particle in this case is 5.9 m. When the particle moves with a higher speed of 5.6 m/s, it is observed that particle reaches the panel and tends to fall on the panel for all wind direction and average distance travelled by the particle is 6.34 m.

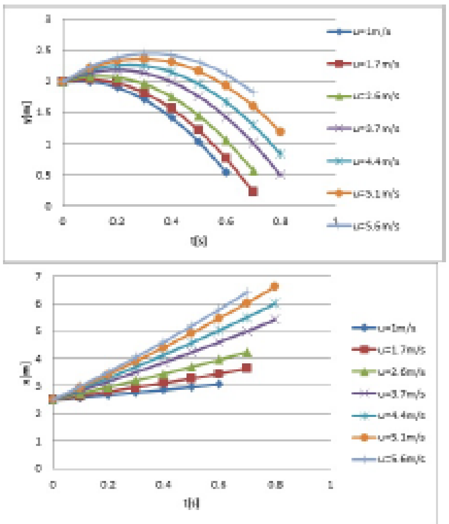

Fig. 2: Height(y) and distance(x) of the particle as a function of time for different wind speed but fixed θ_v=30°.

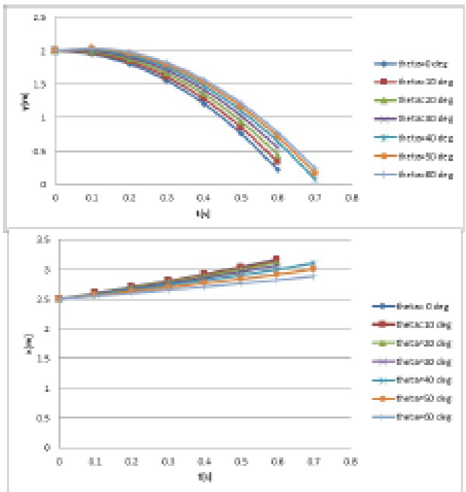

Fig 3: Motion of the particle for constant wind speed=1 m/s and different wind direction.

Table 1: Trajectory of the dust particle

Wind speed, m/s	θ_v degree	$\overline{a} \pm \sigma$	$\overline{b} \pm \sigma$	$\overline{c} \pm \sigma$
1-1.7	0-10	-2.28 ± 0.04	11.09 ± 0.26	-3.22 ± 4.51
	20-40	-3.19 ± 0.47	16.07 ± 2.46	-7.82 ± 12.11
	50-60	-7.39 ± 1.83	37.62 ± 9.31	-45.83 ± 11.82
2.6-3.7	0	-0.38 ± 0.14	1.79 ± 0.66	-0.07 ± 0.80
	10-40	-0.49 ± 0.05	2.77 ± 0.42	-1.85 ± 0.71
	50-60	-1.28 ± 0.31	7.56 ± 1.74	-8.83 ± 2.42
4.4-5.1	0-20	-0.16 ± 0.00	0.90 ± 0.14	0.77 ± 0.33
	30-60	-0.35 ± 0.16	2.64 ± 1.16	-2.38 ± 1.91
5.6	0-10	-0.11 ± 0.00	0.55 ± 0.07	1.29 ± 0.18
	20-40	-0.14 ± 0.03	1.20 ± 0.32	0.50 ± 0.40
	50-60	-0.32 ± 0.08	2.86 ± 0.63	-3.08 ± 1.06

Using least square method, the trajectory of the particle P is obtained by fitting a second degree polynomial $y = ax^2 + bx + c$ to the calculated value of (x,y) obtained using RK4 method.

The curves fit the data well with coefficient of determination, R^2= 0.99 for all wind speed and direction. Clustering has been done based on the path traced by the particle under different wind speed and direction and is tabulated in Table

1.Avergae values of the parameters a, b and c for each cluster and its standard deviation is presented in Table 1 to understand the nature of the curve traced by the particle under varying wind speed and direction θ_v.

It is observed that for wind speed from 1-5.6 m/s and wind direction $0^\circ - 10^\circ$, the particle has a downward motion from the start of its motion. For lower wind speed 1-2.6 m/s the particle always have a downward motion. For wind speed 3.7 m/s and direction $40^\circ - 60^\circ$, the particle initially moves upwards for 0.3 s and then attends its maxima at 3.23 m and then starts moving downwards and falls at a distance of 4.5 m from the origin. The particle does not reach to the panel. Similar is the case when wind speed is 4.4- 5.6 m/s and direction is $20^\circ - 30^\circ$.

When the wind speed is varying between 4.4-5.6 m/s and wind direction θ_v is $30^\circ - 60^\circ$ the particle moves upwards for a longer time approximately equal to 0.4s and attains maxima at around 3.86 m and then it starts moving downwards and falls on the middle of the panel at an average distance of 6.22 m from the origin. When the wind speed is varying between 5.1-5.6 m/s and wind direction θ_v is $40^\circ - 60^\circ$ the particle travels a longer distance similar to the above case and moves in the upward direction for a longer time (0.5s) and attains its maxima at 4.18 m and starts moving in downward direction faster than the above cases and strikes the panel at the top end approximately at a distance of 6.4m from the origin. The wind speed 4.4-5.6 m/s and wind direction 30-60° is found to be the critical wind velocity which may cause dust deposition on the panel.

The results obtained are compared with those reported by Dagher [10] for dust simulation performed at Cairo. They reported that for dust particle of size 150μm, 2m/s wind speed is found to be critical. For particle size of 1-10 μm, dust deposition was found to be very low. A wind speed on 9-11.5 m/s was reported to be critical for particle of size 1 μm. Tt suggests that both wind speed and particle size plays important role is dust deposition.

In the present study, a particle of 0.01m is considered for study and it has been observed that wind speed of 4.4-5.6m/s and wind direction 30-60° is found to be critical.

4. CONCLUSIONS

The major inferences from the study done are:

- Study identified critical wind velocity which may result into dust deposition on the panel for a given particle size.
- Trajectory of the particle is found to be parabolic for all chosen wind velocity.
- Distance travelled and flight time of the particle also depends on wind speed and direction.

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