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Experimental Study on the Mechanism of Surface Erosion and Deposition in Desert Photovoltaic Power Stations: Postprint

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Abstract

Wind-sand activity induces surface erosion or deposition, affecting the safe operation of photovoltaic (PV) power stations. To elucidate the occurrence mechanism of surface wind erosion in desert PV power stations, this study employs wind tunnel experiments and numerical simulations to analyze the wind velocity flow field characteristics and erosion-accumulation variation patterns of PV panels under varying wind speed conditions ($6 \text{ m} \cdot \text{s}^{-1}$, $8 \text{ m} \cdot \text{s}^{-1}$, $10 \text{ m} \cdot \text{s}^{-1}$) and in both forward and reverse wind directions. The results demonstrate that: (1) PV panels modify near-surface wind velocity and flow field, creating an airflow uplift zone in front of the panel, an airflow acceleration zone beneath the panel, a vortex deceleration zone behind the panel, and an airflow recovery zone at the panel's trailing edge; near-surface wind velocity beneath the panel increases significantly, predisposing the area to scouring, whereas wind velocity behind the panel decreases, predisposing it to accumulation. (2) Under reverse wind direction, the "narrow-channel effect" beneath the PV panel intensifies airflow, resulting in markedly greater wind erosion compared to forward wind, while accumulation behind the panel correlates with vortex deceleration on the leeward side. (3) Wind erosion is most severe beneath panels in edge arrays of PV power stations, while relatively mild beneath panels in interior arrays; with increasing height of PV modules, wind erosion beneath panels diminishes. These research findings can provide a scientific basis for sand hazard prevention and efficient operation of desert PV power stations.

Full Text

Experimental Study on the Mechanism of Surface Erosion and Deposition in Desert Photovoltaic Power Stations

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Abstract

Wind-sand activities cause surface erosion or accumulation, affecting the safe operation of photovoltaic power stations. To elucidate the mechanism of surface wind erosion in desert photovoltaic (PV) power plants, this study analyzed the flow field characteristics and erosion-deposition patterns of PV panels under different wind speeds ($6 \text{ m} \cdot \text{s}^{-1}$, $8 \text{ m} \cdot \text{s}^{-1}$, and $10 \text{ m} \cdot \text{s}^{-1}$) and both wind directions through wind tunnel experiments and numerical simulations. The results revealed that: (1) PV panels alter near-surface wind speed and flow fields, creating four distinct zones: an airflow lifting zone in front of the panel, an airflow acceleration zone beneath the panel, a vortex deceleration zone behind the panel, and a wake recovery zone at the panel tail. Near-surface wind speeds increase significantly beneath the panel, making it prone to scouring, while wind speeds decrease behind the panel, making it prone to deposition. (2) Under reverse wind direction, the “narrow-channel effect” beneath the PV panel intensifies airflow, resulting in significantly greater wind erosion than under normal wind direction, while deposition behind the panel is associated with vortex deceleration on the leeward side. (3) Wind erosion is most severe beneath edge PV arrays, while internal arrays experience relatively light erosion. As PV module height increases, wind erosion beneath the panels decreases. These findings provide a scientific basis for sand hazard prevention and efficient production in desert PV power stations.

Keywords: wind tunnel experiments; numerical simulation; wind erosion intensity; airflow field; photovoltaic power station

Introduction

Against the backdrop of global climate change, the international community is emphasizing carbon dioxide emission reductions while continuously exploring new clean energy sources. Solar energy represents the most promising alternative to fossil fuels for transforming the current energy structure. According to BP' s *Statistical Review of World Energy*, solar energy' s share in renewable power generation has increased annually, rising from [specific values] in [year] to [specific values] in [year]. Photovoltaic power generation costs have gradually decreased, significantly improving economic viability and positioning solar power as a future major energy supplier. Photovoltaic power stations represent one method of solar energy utilization and have attracted global attention. Ground-mounted PV panels require substantial land area, and desert regions offer both vast wastelands and abundant solar resources, making them ideal locations for PV power station construction. Currently, Gulf countries and China are actively promoting this technology, exploring a win-win model that combines photovoltaic power generation with sand control. PV station construction also promotes surface vegetation recovery and facilitates synergistic development with pastoralism.

However, desert areas have sparse vegetation and frequent wind-sand activities that threaten PV station safety. For example, dust accumulation on panels reduces power generation efficiency, strong winds decrease PV support structure stability, and surface wind erosion and sand accumulation affect station infrastructure security. Consequently, surface erosion and deposition hazard prevention in desert PV power stations has become a critical issue requiring urgent solutions in the PV industry development.

Scholars have investigated wind fields around PV panels, wind pressure, wind loads, and wind erosion prevention technologies through field observations, wind tunnel experiments, and numerical simulations, exploring erosion-deposition patterns at different positions within PV arrays. Yemenici et al. conducted wind tunnel and numerical simulation studies, finding that PV panel tilt angles and wind direction affect wind erosion, with front-row components experiencing maximum wind pressure and oblique winds creating net negative pressure in main components, while windward array shielding effects remain weak. Huang et al. and Li et al. used numerical simulations to study wind pressure distribution characteristics of multi-row PV panels under different incident wind angles, discovering significant shielding effects between arrays. Other wind tunnel research found differences between single panels and arrays in airflow impact, with PV arrays causing intensified local wind erosion. Yuan et al. conducted field experiments observing wind speed variation characteristics between panels in the Mu Us Sandy Land, analyzing protection benefits and mechanisms of typical wind erosion control measures, and discussing efficient prevention measures and configuration patterns.

The main factors affecting wind erosion in PV power stations include wind di-

rection, wind speed, and PV panel tilt angle, yet few studies have examined wind erosion characteristics of PV panels at different heights. Although scholars have investigated flow field structures around PV panels and proposed protection recommendations for desert PV power stations, they have not deeply analyzed the erosion-deposition mechanisms around panels. Most research has focused on grassland and rooftop PV systems, with relatively few studies on desert PV power stations. Systematic investigation of flow field characteristics around desert PV power stations is necessary to reveal wind erosion mechanisms. This study employs wind tunnel experiments and numerical simulations to investigate and clarify the wind erosion mechanisms in desert PV power stations, propose reasonable prevention recommendations, and provide theoretical foundations for scientific sand hazard prevention in desert PV power stations.

1. Methods

1.1 Wind Tunnel Experiment The experiment was conducted in May at the wind tunnel laboratory of the Mosuowan Desert Research Station, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences. The wind tunnel, designed and constructed by the Aerodynamics Institute of China Aerospace Science and Technology Corporation, is a low-speed, direct-flow blow-type tunnel with a total length of 16.2 m. It consists of a power section, rectification section, experimental section, and diffusion section. The experimental section measures 1.3 m in width and 1.0 m in height, with a side wall diffusion angle of 1.3° and side wall boundary layer thicknesses of 15 cm and 10 cm, respectively. Wind speed is adjustable within the range of $0\text{--}20\text{ m}\cdot\text{s}^{-1}$. During experiments, a constant-temperature hot-wire anemometer measured inlet wind speed, while pitot tubes measured pressures at different heights (30 cm and 50 cm), which were converted to wind speeds.

1.1.1 Model Fabrication The Reynolds number describes turbulence characteristics in fluid motion. When the Reynolds number reaches 2.5×10^5 , fluid action enters a self-simulating region, ensuring motion similarity. For fully developed similarity, the wind tunnel experimental section had an average Reynolds number of 6×10^5 , satisfying turbulence characteristics and aeolian sand flow simulation conditions. Based on geometric similarity theory and Reynolds number similarity principles, combined with field-measured PV panel support heights and panel lengths, a geometric scale ratio of 1:10 was adopted to design and fabricate PV panel models. The model dimensions were $81.0\text{ cm} \times 17.0\text{ cm}$ (length \times width), with the highest point of the PV module 10 cm above ground, the lowest point 6.8 cm above ground, the highest support point 9.1 cm above ground, and the lowest support point 3.2 cm above ground. The spacing between adjacent columns was 10 cm. This model satisfied geometric similarity for wind tunnel experiments.

1.1.2 Measurement Point Layout Wind speeds in the wind tunnel experiment were obtained through a measurement system composed of pitot tubes and

micro-differential pressure transmitters. The system consisted of 12 fine pitot tubes (with heights h above the surface of 0 cm, 3 cm, 5 cm, 8 cm, 10 cm, 15 cm, 20 cm, 30 cm, 40 cm, and 50 cm). Each pitot tube was calibrated before use with a standard pitot tube (Fig. 50 [Figure 50: see original paper]). A total of 12 measurement points were set at the centerline of the PV module model from $1H$ in front to $4H$ behind (where H is the PV module height). Based on field meteorological observation data from desert PV power stations, sand-driving wind events occur most frequently at moderate to strong wind forces, with winds greater than $10\text{--}15\text{ m}\cdot\text{s}^{-1}$ being common and maximum speeds reaching [value] $\text{m}\cdot\text{s}^{-1}$. Preliminary tests revealed that erosion-deposition activities began when wind speeds reached $10\text{--}15\text{ m}\cdot\text{s}^{-1}$. To better simulate erosion patterns under low, medium, and high wind speed gradients, experiments were conducted at three wind speeds: $6\text{ m}\cdot\text{s}^{-1}$, $8\text{ m}\cdot\text{s}^{-1}$, and $10\text{ m}\cdot\text{s}^{-1}$, for both forward and reverse wind directions. Surfer 12.0 software was used to plot vertical flow field cross-sections along the model centerline.

1.2 Numerical Simulation Computational Fluid Dynamics (CFD) is an interdisciplinary field involving mathematics, fluid dynamics, and computer science. This study employed Fluent software for numerical simulation. A three-dimensional model of the PV module was first created: the PV panel dimensions were $81.0\text{ cm} \times 17.0\text{ cm}$, with module heights of 32.8 cm, 40.4 cm, and 48.0 cm. The OpenFOAM file was then used to generate the basic computational domain mesh (Fig. 40 [Figure 40: see original paper]) and refined region meshes, with a refinement level of 10, expansion ratio of 1.3, and maximum thickness of 2.4×10^{-6} . *Mesh quality constraints included a maximum non-orthogonality of 75° , boundary layer count of 6, minimum thickness of 2.4, maximum boundary skewness coefficient of 4.39×10^{-6} , maximum internal skewness coefficient of 6.8, mixed concave angles of 13, and minimum quality of 0.0005. The number of grids for a single PV module was 4.39×10^6 , while the PV array panel*

Steady-state calculations were performed using the k -turbulence model, with walls processed through standard wall functions. Both the PV module model and computational domain walls adopted no-slip boundary conditions, where wall velocity was 0 and gradually increased to mainstream velocity with distance. The velocity field, pressure field, and other variable gradients were very large near the wall, requiring extremely fine computational grids. However, excessive grid numbers consumed computational resources and deteriorated convergence. The finite volume method assumes linear variables at mesh center points, while wall functions use coarser grids to represent variables near walls with nonlinear functions. The SIMPLE algorithm was used for pressure-velocity coupling, with governing equations:

[Equation block with k and ϵ equations]

where S_{ij} is the strain rate tensor; k represents turbulent kinetic energy; ϵ represents turbulent kinetic energy dissipation rate; and R is an additional source term in the k equation representing the effect of mean strain rate on k , expressed as:

[Equation for R]

The simulation inlet adopted logarithmic atmospheric boundary layer conditions, with the outlet set as a pressure outlet and other surfaces as no-slip boundaries. After initialization, calculations proceeded until residuals in x, y, and z velocity directions were less than 10^{-5} and residuals for turbulent kinetic energy and dissipation rate were less than 10^{-3} , indicating convergence.

2. Results

2.1 Wind Tunnel Experiment Results When forward airflow blew toward a single PV module (Fig. 5 [Figure 5: see original paper]), wind speed contours bulged upward in front of the module (position 0-10 cm), indicating increased wind speed and forming a front-plate airflow lifting zone. After airflow passed through the module (position 0-10 cm), wind speed profiles became annular with reduced velocity, indicating a vortex deceleration zone behind the panel. As airflow moved away from the module (position -40 to -120 cm), wind speed gradually increased and eventually recovered to the upwind initial speed, forming a wake recovery zone. When passing through the gap between the module's lower edge and ground (position -5 to 10 cm), definite acceleration occurred.

When reverse airflow blew toward a single PV module (Fig. 5 [Figure 5: see original paper]), airflow passing through the gap between the module's lower edge and ground (position -5 to 20 cm) accelerated due to the "narrow-channel effect," forming an underside airflow acceleration zone. After passing through the module, a large vortex deceleration zone formed on the leeward side (position -5 to -40 cm). As airflow moved away (position -40 to -120 cm), speed gradually recovered. Maximum wind speeds under both wind directions occurred above the PV module, while minimum speeds appeared in the vortex deceleration zone. Wind speed decreased when passing the module and gradually recovered with distance, reaching the upwind initial speed at approximately -4.5 m. As incoming wind speed increased, the vortex deceleration zone behind the model gradually contracted, and the influence range of the PV module on airflow also decreased.

2.2 Numerical Simulation Results

2.2.1 Single PV Module Flow Field Simulation Flow field simulations of PV components showed velocity change patterns consistent with wind tunnel experiments. When forward airflow passed over a panel (Fig. 7 [Figure 7: see original paper]), acceleration occurred on the windward side, with maximum wind speed above the panel. After passing through, a vortex deceleration zone formed on the leeward side, while the "narrow-channel effect" beneath the panel created an airflow acceleration zone, with the wake recovery zone located at approximately 0.33 m. As model height increased, wind acceleration in the gap between the panel's lower edge and ground became more pronounced, while the

deceleration zone area on the leeward side gradually contracted and its height increased, indicating that higher panels have reduced influence on the flow field.

When reverse airflow passed over a single PV module (Fig. 7 [Figure 7: see original paper]), airflow through the gap between the panel's lower edge and ground (position 0-3 cm) accelerated due to the "narrow-channel effect," forming an underside acceleration zone. After passing through, a large vortex deceleration zone formed on the leeward side (position -0.75 to 0.25 m). As airflow moved away (position 0.25-1.0 m), speed gradually recovered to the upwind initial speed.

2.2.2 PV Array Flow Field Simulation Regardless of forward wind (Fig. 8 [Figure 8: see original paper]) or reverse wind (Fig. 8 [Figure 8: see original paper]), wind speeds between panels generally showed a decreasing trend, with maximum speed reductions of [value] and a large deceleration zone forming in the wake region. Airflow acceleration existed in the gaps between panel lower edges and ground. The difference was that under forward wind, the deceleration vortex zone range on the leeward side of the first-row panel was significantly larger than under reverse wind. This demonstrates that the PV array flow field is not a simple superposition of single panel flow fields but a complex coupled system. The first-row panel influences the second row, while secondary flows from the second row continue to affect the third row.

As incoming wind speed increased, the vortex deceleration zone range behind the PV array gradually contracted under both wind directions. Compared with single panels, the vortex deceleration zone range on the leeward side of PV arrays was larger. Both forward and reverse winds showed varying degrees of wind speed acceleration in the gaps beneath panels, with the strongest acceleration occurring beneath windward panels.

2.2.3 Surface Shear Stress Simulation for Single PV Module Under constant sand supply, particle size, soil moisture, vegetation cover, and soil compaction conditions, surface shear stress serves as a proxy indicator for ground erosion and deposition, with high shear stress zones typically representing erosion and low shear stress zones representing deposition. From the surface shear stress distribution under forward wind for different panel heights (Fig. 9 [Figure 9: see original paper]), no significant differences existed in shear stress around PV components, with maximum values distributed around support columns. As panel height increased, the low shear stress zone shape on the leeward side changed from teardrop to conical, indicating that panels block airflow and create deposition zones in wake regions.

Under reverse airflow, high shear stress zones were distributed on the leeward side of PV components (Fig. 9 [Figure 9: see original paper]), with shear stress intensity higher than under forward wind. Therefore, reverse wind causes more severe wind erosion damage than forward wind. As PV module height increased,

shear stress intensity gradually decreased, showing a negative correlation between shear stress magnitude and height. Wind erosion was most severe around support columns, consistent in both wind tunnel experiments and numerical simulations (Fig. 9 [Figure 9: see original paper]).

2.2.4 Surface Shear Stress Simulation for PV Array Surface shear stress distribution in PV arrays forms a complex coupled system through interactions between individual components. When forward wind passed through the array (Fig. 10 [Figure 10: see original paper]), surface shear stress on the leeward side of panels gradually weakened and showed a decreasing trend as airflow passed through, significantly different from reverse wind conditions. Under reverse airflow, surface shear stress reduction only occurred at the first-row panel, while shear stress between the latter three rows remained essentially unchanged. Reverse wind had more extensive ground wind erosion area and stronger erosion capacity than forward wind, consistent with single panel erosion patterns. The difference from single panel erosion was that the wind erosion range on the leeward side of the first-row panel in the array was broader than for single components, indicating that PV arrays enhance the wind erosion capacity of individual panels on the ground.

3. Discussion

3.1 Limited Effectiveness of “PV Sand Control” in Extreme Arid Regions PV power stations increase surface roughness, significantly affecting near-surface wind speed and altering wind erosion dynamics for soil particles. Soil particle erodibility depends not only on particle size, density, and inter-particle chemical cementation but also on soil temperature, moisture, and vegetation conditions. Due to PV panel shading, the station’s surface albedo is necessarily lower than outside the station, reducing surface temperature and evaporation, which can conserve soil moisture and benefit plant growth. However, research shows that while panel shading reduces surface heat income, it also reduces rainfall reaching the ground, and wind acceleration promotes soil moisture evaporation loss, leading to drier soils, poorer vegetation growth, and more erodible soils beneath panels. Therefore, desert PV power station benefits show significant regional differences, with minimal effects in arid regions. Soils between panels become drier, making surface wind erosion a concern requiring attention.

3.2 Mechanism of Surface Erosion and Deposition in Desert PV Power Stations Scholars have studied erosion-deposition phenomena in desert PV power stations. Tang et al. found through field observations that in the Northern Hemisphere, PV arrays have stronger shelter effects on southerly winds than northerly winds, while the opposite occurs in the Southern Hemisphere. This indicates that reverse airflow causes more severe erosion damage than forward wind, consistent with our wind tunnel results. This study establishes the coupling relationship between surface erosion-deposition and airflow acceleration-

deceleration, identifying vulnerable erosion and deposition zones in PV power stations.

Jia et al. found through field observations that flow fields differ significantly between edge and interior areas of PV power stations. Edge areas have fully developed, typical flow fields with severe wind erosion beneath panels and banded sand accumulation between panels. Edge flow effects also cause sand accumulation on both sides of panels in addition to leeward deposition tails. PV components enhance near-surface wind speeds at station edges, causing severe erosion, while interior areas experience reduced overall flow velocity and lighter surface erosion. Our simulations also found strong wind-sand activity beneath the windward first-row array, where surface sand particles are more easily removed, providing sand sources for downwind areas. As sand material transports into the station interior, deposition readily occurs. This study also found that increasing PV module height gradually reduces surface wind erosion because the blocking and downward compression effects of PV arrays on surface airflow diminish.

Surface erosion and deposition in desert PV power stations result from multiple environmental factors. Besides wind speed, wind direction, and panel height, other factors include: (1) microtopographic features in desert areas, such as dunes and depressions, which affect wind speed, direction, and airflow distribution; (2) surface soil properties including particle size, moisture content, and cohesion, which critically influence wind erosion and sand accumulation processes—loose, dry sand is more easily entrained and redeposited; (3) vegetation plays an important role in sand fixation and erosion reduction, with vegetation type, coverage, and growing season significantly affecting surface erosion-deposition; and (4) PV power station construction and maintenance alter original surface characteristics and ecosystems, affecting erosion-deposition processes, as construction and vehicle activities destroy soil structure, making it loose and erodible.

To ensure safe operation of desert PV power stations in arid regions, comprehensive prevention measures should be implemented. First, increasing PV module height as much as conditions permit can effectively reduce ground wind erosion risk, benefit vegetation growth beneath panels, and mitigate power generation efficiency reduction caused by plant shading. Second, integrated biological and mechanical sand control measures should be deployed in windward edge areas prone to erosion and sand burial. Finally, surface drifting sand should be stabilized outside the PV power station to reduce sand inflow into the station. Besides conventional straw checkerboards, sand fixation measures such as gravel or clay coverage and chemical sand fixation agents can be adapted to local conditions.

4. Conclusions

Through wind tunnel experiments and numerical simulations, this study investigated near-surface flow fields and surface erosion-deposition characteristics of

PV panels under forward/reverse wind directions and different wind speeds, yielding the following main conclusions:

- (1) Significant spatial heterogeneity exists in surface erosion-deposition intensity in desert PV power stations. Erosion-deposition is most severe beneath edge PV arrays on the windward side, while internal arrays experience relatively light wind erosion. In arid and extremely arid desert PV power stations, surface erosion-deposition hazards require attention.
- (2) PV components have a downward-guiding compression and acceleration effect on surface airflow, increasing ground shear stress and causing surface wind erosion. Reverse vortex deceleration formed in front of or behind panels causes wind-sand accumulation. Reverse airflow intensifies surface erosion-deposition hazards in PV power stations. Increasing PV panel height reduces the disturbance of PV components on surface airflow, decreasing surface erosion-deposition hazards.
- (3) The “PV sand control” effect shows obvious regional differences, with minimal effects in extremely arid regions. The soil between panels becomes drier, and surface wind erosion issues require attention.

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