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Structural Risk Evaluation of Solar Panels Under Arid Dune-Modified Wind Flows

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SUMMARY

This study examines how wind flow altered by nearby sand dunes in dry arid desertic environments, affects the aerodynamic loading on ground-mounted solar panels. Experiments were conducted in a blow-type wind tunnel using a scaled solar panel model and a triangular dune placed upwind. Surface pressure measurements were recorded to evaluate the pressure coefficient distribution along the panel. Results showed higher pressure coefficients near the leading edge, especially when the dune was present, due to increased stagnation and modified wind flow patterns. The elevated wind loading indicates a greater structural risk for solar installations in dune-dominated desert terrains. These findings highlight the need to consider dune-panel interaction in the design of solar power plants located in arid regions.

Keywords: *Solar panels, Wind load, Pressure coefficient, Sand dunes, Desert environment, Wind tunnel testing, Aerodynamic interaction.*

1. INTRODUCTION

Renewable energy has proven to be a vital solution to the global warming problem due to less fossil fuel usage and environmental pollution. Solar photovoltaic (PV) being the fastest growing renewable energy technology worldwide, is driven by favorable policy incentives and technological developments (Gagnon et al., 2002; Liu et al., 2015). In India, the National Action Plan on Climate Change (NAPCC) encourages a transition to clean energy by promoting efficient use of energy and requiring renewables to be integrated into the grid. In continuation, sharing knowledge between nations is a need of the hour. The policy targets 100 GW of solar capacity installed in India by 2030. The Renewable Purchase Obligations (RPO) were enhanced to facilitate quicker uptake. This increase in deployments has for instance driven the growing number of solar parks throughout suitable areas of the country (Kumar et al., 2023).

Desert regions are becoming the prime location for solar power projects due to their vast open areas and high solar intensity. In India, Thar Desert is the major site for solar park project. The Thar desert covers about 140,000 km^2, which is approximately 58% of the state's area. Western Rajasthan is classified as a hot arid region with 12 districts receiving less than 250 mm of annual rainfall, compared to overall state average of 587 mm (Singh et al., 2014).The terrain of western Rajasthan, dominated by sand dunes and sand sheets (Bhadra et al., 2019; Kar, 1993). According to Kar (1993), they can reach heights of 15-60 meters. A severe desert environment (strong wind regimes, low precipitation rates, few vegetation types and soils vulnerable to erosion) is one of the leading adverse factors to solar energy construction. Such conditions cause sand movement, dust uplift, and surficial instability that lead to damage of solar panel mounting structures and reduce PV performance by deposition and scratching on panels due to the dust. Under high wind conditions, the PV modules can also get damaged and result in a spike of maintenance costs seen at some site like Bhadla Solar Park. Efforts to mitigate these environmental risks are essential to ensure desert solar facilities remain efficient, durable, and safe in the long term.

2. METHODOLOGY

2.1. Experimental study

The experiments were conducted in a blow-type wind tunnel at the Institute of Technology Jodhpur (IITJ), India. The test section had an initial cross-section of 0.62m wide and 0.6m high with a length of 4 m. The maximum flow velocity at the test section's inlet was 30 m/s. The velocity and turbulence intensity were recorded using a static pitot tube attached to a single-channel manometer. This static-pitot tube is limited to capture wind in one direction only, so there is only the horizontal component of velocity(u). An 8 Port electronic pressure scanner was used to measure the surface pressure distribution. The pressure scanner was connected to the data acquisition system via pressure tubes, and the data was logged using a computer.

A 3D-printed solar panel model with dimensions of 0.2m in width, 0.1 m in chord, and 0.01 m in thickness as shown in Figure 1(a) was used in this study. The total height of the model is 0.1m, and the ground clearance is 0.04m, which is the height reserved for maintenance and air ventilation in the original solar panel. A total of 32 pressure taps were drilled & uniformly distributed on the top half of the panel as shown in Figure 1(a). The vinyl pressure pipe with a diameter of 0.16mm and a length of 1.5m was connected to the pressure tap via small steel pipes. The optimum inclination angle to capture the maximum amount of sunlight is defined as $\alpha = \beta \pm 15^o$, where β is the location's latitude (Yorukoglu and Celik, 2006). In this study, measurements were performed for panel inclinations of 36 °. A sand dune model of triangular shape with a height of 0.15m and a width of 0.24m was used for the interaction study of sand dune and solar panel. This model was placed at a fetch length of 15 times the height of the sand dune as shown in Figure 1(c).

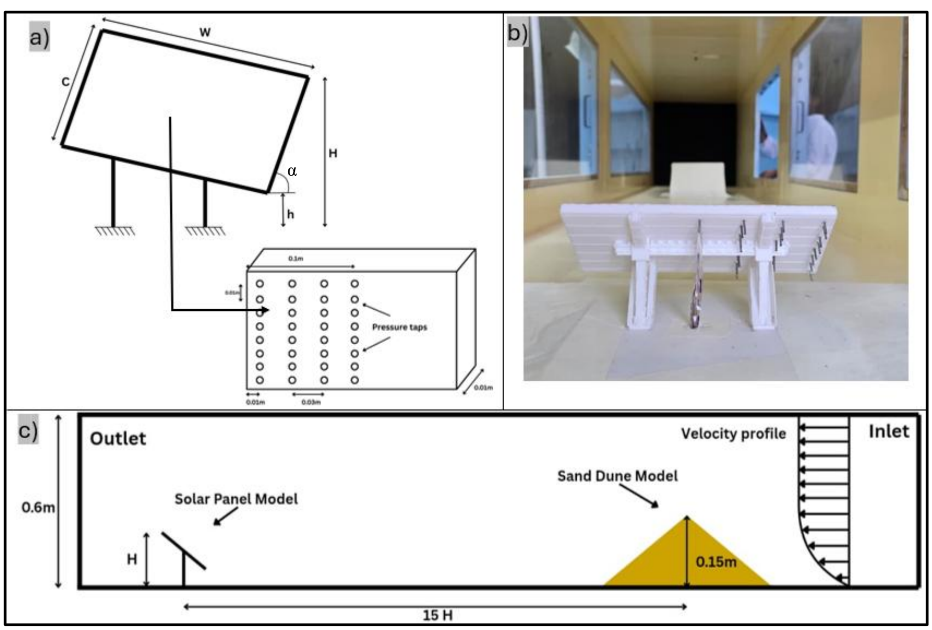

Figure 1: a) Solar panel model with pressure tap details, b) Picture of Wind Tunnel test section at IIT Jodhpur, c) Schematic view of wind tunnel setup

The ground-mounted SPs are low-height structures located within the lower 10m of an atmospheric boundary layer. The wind velocity profile in the atmospheric boundary layer was described using

a power-law equation.

$$\frac{u}{U} = \frac{z^{\frac{1}{\alpha}}}{zg} \tag{1}$$

where u and U are mean velocities along height z and reference height zg, respectively, and 1/α is taken as 0.13, which is the exponent for the arid region of sand dunes (White 1996). The model were scaled to 1:10 of actual size of solar panel in thar desert and the blockage ratio is maintained to less than 10%.The pressure was recorded using a pressure scanner and was expressed in terms of pressure coefficient (Cp) which was calculated using equation as:

$$Cp(t) = \frac{Pi(t)}{0.5\ \rho\, U^2} \tag{2}$$

where Pi is the pressure at the measuring point, ρ is the air density, i is the pressure tap number, and U is the mean velocity at the reference height.

3. RESULTS & DISCUSSION

The experiments were conducted for two configurations: a solar panel without sand dune interaction and a solar panel with sand dune interaction. The pressure distribution on the panel surface was analyzed based on the measured surface pressure data. Figure 2 shows the pressure coefficients (Cp) on the mid-plane of the panel for both configurations. In the plot, LE refers to the leading edge (the lower end of the panel), and TE refers to the trailing edge (the upper end of the panel).

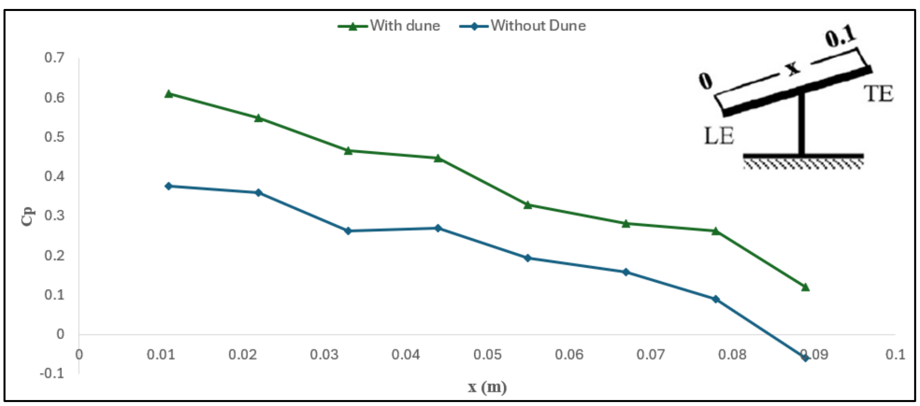

Figure 2: Graph represents the Cp variation for both the configurations

It is observed that the highest mean Cp values were found along the panel's leading edge, where the incoming wind directly impacts the surface. As the flow expanded over the panel and approached the trailing edge, these values gradually decreased for both cases as the flow accelerated (Yemenici & Aksoy 2021). The Cp values are comparatively higher when the panel interacts with the sand dune, indicating an increased wind pressure on the panel due to the presence of the dune. When Cp is larger, the wind pressure on the panel increases substantially when it located in the dune-wake, as depicted in Figure 3. This has an impact on the acceleration of the flow from the leading edge to the trailing edge and may initiate a more severe separated flows occurrence causing structure fatigue. As such, sand dunes present around ground-installed solar structures can largely strengthen the risk of wind-induced structure failure, and nonconsideration of the dune effects may indicate that less attention is paid to safety measures in designing solar parks.

4. CONCLUSION

The experiments in this study demonstrate that the dune field has a significant impact on wind loading on solar panels. The airflow slows down for an upward dune and stagnates near the leading edge, causing the pressure coefficients to increase compared to panels placed on flat terrain. As the flow continues upward toward the trailing edge, the pressure gradually reduces due to accelerated motion over the inclined surface. These results necessitate that solar installations in desert environments are more vulnerable to wind-induced forces when dune formations are nearby, and overlooking this factor during design may compromise the structural safety of the mounting systems.

In order to further expand the results of this study, experiments are extended possibly using different fetch distance between panel and dune in order to simulate more accurate field conditions. Additionally, a numerical simulation using ANSYS ICEM and CFD analysis will be carried out to validate the experimental results and provide deeper insight into flow separation, turbulence behavior, and pressure distribution. The combined insights from both experimental and computational studies will support the development of improved design guidelines for securing solar panels in the harsh wind conditions typical of desert regions.

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