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Time-Effective Dust Deposition Analysis of PV Modules Based on Finite Element Simulation for Candidate Site Determination

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ABSTRACT For a photovoltaic (PV) power generation system, the shading effect of PV panels caused by dust deposition is extremely unfavorable. The deposition of dust results in a severe reduction of power generation output, since the efficiency of PV panels is affected by the shading irradiance and blocking the cooling. In this study, a numerical simulation method is proposed to model the dust accumulation on PV panels to detect the effects on PV power generation caused by different wind directions and wind speeds. Due to the high accuracy of numerical simulation, and the short calculation cycle, the proposed method provides a certain prediction for the soiling management of PV panels in the wind-sand environment. Through simulations and experiments, the impacts of dust accumulation on the performance of PV panels with different wind directions are studied in detail with the wind speed changing from 4.43 m/s to 6.48 m/s and the dust particle size of 10 μm to 100 μm, which are based on the environment of Liverpool, England in a year. Besides, for PV arrays, the turbulences of the dust distribution around the PV panels are also analyzed. The data collected from experiments and simulations are used to verify the effectiveness of the proposed strategy.

INDEX TERMS Dust deposition, numerical simulation, photovoltaic, power generation.

I. INTRODUCTION

Adopting solar energy is now the mainstream of the renewable energy industry. However, the dust particles affect the PV power generation efficiency seriously. At present, the output power efficiency of PV panel in standard test condition (STC, 1000 W/m^2, 25 °C) is decreased by 18%∼20.2% due to the dust shading [1], [2]. In addition, the dust accumulation also increases the surface temperature that decreases the power generation [3]–[5]. Meanwhile, the relation between the dust deposition and output power efficiency is analyzed to estimate the soiling management of PV modules. The PV power decreased linearly by 1.7% per g/m^2 [6]. Therefore, in order to maintain the PV power generation for a PV array, the frequency of cleaning is three times a month [7], [8]. The soiling management of solar panels not only improves the power generation efficiency, but also protects the PV panel from the hotspot effect. It damages the PV panel, so a reasonable cleaning cycle is necessary, which places great demand on the researches on the dust distribution and deposition on the PV panel surface under different field conditions.

Currently, there are two methods to detect the impact of dust deposition on PV panels: finite element (FE) simulation and experiment. In [9], Wasim. J carried out an experiment in Doha, Qatar (STC, PV tilts 22 °) to compare the dust accumulation in each panel, which includes a two-week observation, a one-month observation, a two-month observation and a six-month observation respectively. From [9], the completely data of dust deposition is from 2 months investigation, which is the suitable exposure period so far, and the dust accumulate 100 mg/m^2/day. In [6], Rohit. P summarized some experiments to collect the data of dust accumulation and transmittance. Because the period of experiments lasts generally between 1 several weeks to and 1 year, which is time-consuming, many other scholars employ FE simulation to discuss the dust deposition and power generation issues.

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It is hard to quickly analyze the dust flow in for a new region where PV farms are going to be constructed. Luke. S in [10] implemented the prediction of particle accumulation by using computational fluid dynamics discrete phase module (CFD-DPM), where the dust particles can be expressed as a spherical model in the simulation. Based on [10], the author in [11] created a 2D model in CFD software to calculate and analyze the impact of dust deposition to PV panels. Therefore, Hao. L introduces the impacts of dust on two-dimensional (2D) PV panel in [11]. Meanwhile, in order to analyze the shielding effect of the front panel on the rear panel, Hao. L also introduces the impacts of dust to on PV array in [12] by using the two-dimensional (2D) based FE analysis, and the accuracy of FE simulation was verified in [13].

Nevertheless, although these previous methods provide some good ideas, some shortcomings still exist. Firstly, the research in [10] only focuses on the effects of particles in the air stream, but does not systematically introduce the applications that are attached or surrounded by particles, especially for the temperature-sensitive objects, such as PV panels. Then, [11] only focused on investigating the influence of dust particle deposit on the PV panels along with a fixed wind direction. Because of the turbulence kinetic energy (TKE), the dust deposition on the surface of PV panel should be non-uniform. Finally, in [12], the same problem occurs when detecting the density of dust accumulation in different parts of each panel in a PV array. However, these studies have only analyzed the situations with the horizontal wind direction and the dust particles distributing around the PV panel, and ignored the relationship between dust motion and PV panels, which is also the limitation of a 2D model. However, the influence of wind direction on sand and dust distribution cannot be neglected. Different horizontal wind directions will cause sand and dust to accumulate on different parts of a PV panel, which stimulates a more actual situation. If dust particles are taken into account, the values in the analytical results can be closer to the actual ones [14]–[16]. Significantly, because of the viscosity and collision of dust particles, the power gets two peak values. When the wind speed is low enough, the viscous force of dust to PV panels is higher than the collision force, and the dust deposition reaches the critical value, which means the cumulative value of dust under this condition does not change. When the wind speed increases significantly, the viscosity of dust to PV panels is less than the collision force, and the dust deposition reaches the critical value, in which case the cumulative mass no longer changes. This change depends on the TKE value. The dust accumulation not only reduces the photoelectric conversion efficiency but also causes the PV panel to generate heat, which accelerates the ageing of PV cells and causes the hot-spot effect. Although the above literature paves the way for studying the dust distribution issue on PV panels, few studies focus on the relationship between the PV dust deposition and power generation by using numerical simulation.

This study proposes to predict the dust deposition concerning different wind directions and wind speeds and obtain a specific relationship between the PV output power and dust deposition by using the 3D model in CFD aiming at a typical district (Liverpool, England). CFD is a powerful software that can be used to calculate and express the physical characteristics of fluid motion including flow and dust distribution and temperature. Firstly, this paper establishes a physical model in CFD. In terms of the setups, they keep in accordance with the real situations. In detail, according to the data from the local meteorological station, the wind speed in Liverpool is from 4.43 m/s to 6.48 m/s yearly. The particle size is from 10-100 μm in the airstream, and the wind direction always shifts. Therefore, following the wind velocity in Liverpool, this study simulates the effects of wind-dust at 0°, 30°, 45°, 60° and 90° wind direction on PV panels. Then, in virtue of the CFD simulation results, the influence of dust on PV panels is further discussed, such as temperature and power generation. Finally, in order to verify the data obtained by using CFD, an experiment is conducted on PV panels. The power efficiencies in different situations of dust accumulation are measured. By analyzing the dust accumulation characteristics under different wind directions and wind speeds, the power efficiency can be derived in these environmental conditions. The significance of the research mainly includes firstly, the analysis cycle has been greatly shortened in comparison with the experimental method. Moreover, during the simulation process, the turbulent energy between the panels is obtained, so that the quantity of dust accumulation of large-scale PV arrays can be predicted. Thirdly, the dust distribution can be observed by changing the wind direction to PV panels, complying with the real conditions.

The structure of the rest paper is as follows. Section 2 illustrates the methodology to express the relationship between the dust deposition and output power of PV panels. In the CFD simulation, the wind flow can be set as the boundary condition. Meanwhile, the discrete phase is set as the injecting particles. By changing the wind speeds and directions, the shading and temperature on the surface of a PV panel are analyzed. In Section 3, the data between dust deposition, temperature and output voltage are analyzed. Simulation and experiment results are compared and the uncertainty of simulation is analyzed. Section 4 presents the conclusion.

II. DESIGN OF DUST ACCUMULATION ON PV MODULES

As for PV modules, shading and temperature rise decrease the open-circuit voltage of a PV panel. Therefore, it is necessary to get the local climate information before choosing a location to build a PV station. Using numerical simulation, the data of dust deposition on a PV panel were obtained with respect to different wind speeds and different wind directions in a short time.

Moreover, the accuracy of dust accumulation on the surface of PV panel were validated by experiments. Finally, the relation between the power generation of PV panels and dust accumulation is analyzed with different volumes of dust particles, which was obtained both by the simulation and experiment. On one hand, a reasonable cleaning cycle improves the power generation efficiency. Using CFD simulation can help to plan the solar panel cleaning cycle. On the other hand, the simulation is convenient for helping choose a right place to build a PV station.

A. BOUNDRAY CONDITIONS OF SIMULATION

Initially, a 3D model is established in the CFD simulation environment, where a boundary is set as shown in Figure 1. The distance between the ground and the bottom of PV panel is H. In order to avoid the boundary effect, the distance between the inlet and a PV panel is set as 5H, and the distance between a PV panel and the outlet is 9H. The height of the computation domain is 6H, and the width of the domain is 10H [17]. The PV panel used in the simulation has the volume of 300 × 210×20 mm, which is established as a PV panel (RS PRO). According to [18]–[20], the optimal tilt angle is set as 56° for the solar panel installation with the maximum power generation.

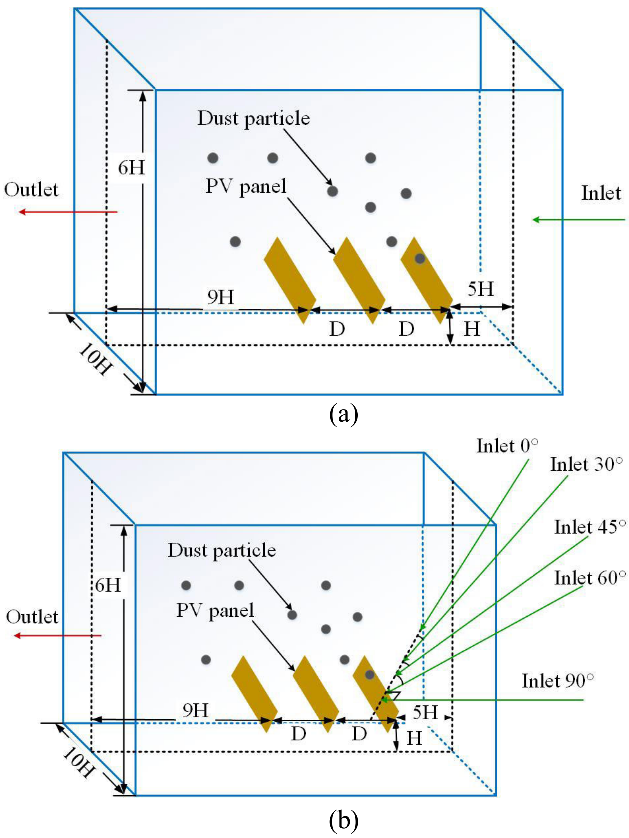


FIGURE 1. Module of computation domain for the case of monsoons. (a) traditional method [18] (b) proposed method.

It is important to analyze the impact of wind direction on PV panels, because the wind direction is uncertain in a year. The physical model is built, which is shown in Figure 1. The previous study only introduces a single wind direction facing the PV panel, which is shown in Figure 1 (a), but it cannot represent the universal cases. On the other hand, the proposed method considers the change of wind directions, which is shown in Figure 1 (b).

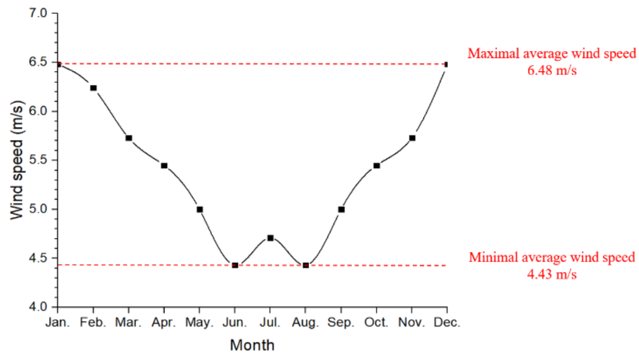


FIGURE 2. Average wind speed in England (www.xcweather.ac.uk).

According to the records from the UK meteorological station, the solar irradiance, wind speeds and wind directions can be obtained in a year. The wind speeds in England dropped from 6.48 m/s to 5.45 m/s from January to March 2019, which is shown in Figure.2 (1 mph = 0.447 m/s). The main wind direction is South-West in this period. Then, from April to September, the wind speeds decreases from 5.45 m/s to 4.43 m/s. In this period, the wind direction is changed to West from South-West. Finally, the wind speeds rise from 5.45 m/s to 6.48 m/s from October to December with the wind direction of South-West. Therefore, the chosen wind speeds for simulation are: 4.43 m/s, 4.71 m/s, 5 m/s, 5.22 m/s, 5.45 m/s, 5.73 m/s, 6 m/s, 6.24 m/s, and 6.48 m/s. Over a year in Liverpool, the most frequently encountered wind direction is from North-West to West. Hence, in the simulation, the incoming wind directions are set as 0°, 30°, 45°, 60° and 90° to the PV panel with respect to the horizontal direction.

In order to avoid the shading effects among PV panels, the space D between PV panels should be set as a certain value, which is based to the latitude, time angle, etc. The latitude angle (φ) of the winter solstice is (-23.45°), and the corresponding time angle (ω) at 9:00 am is 45°. In this situation, the efficiency of photoelectric conversion is the maximum value in a day. Therefore, according to (1) [11], the distance between two panels is 0.43 m, which is the most suitable distance to make the PV panel absorb the irradiance.

$$D = \frac{\cos A \times H}{\tan[\sin^{(-1)}(\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega)]} \quad (1)$$

where D is the obstruction spacing (m), A is the solar azimuth (°), φ is the latitude (°), δ is the declination (°), H is the PV array height difference (m) and ω is the time angle (°) [12].

The distance between a PV panel and the ground has a great influence on the eddy current of the wind, so it is necessary to establish a realistic model to investigate this effect. Based on the Reynolds number (Re) [17], the Realizable k-3 model is selected. The Realizable k-3 model satisfies the constraint condition of Re. Therefore, the Realizable k-e model corresponds to the real situation, which can simulate the injecting diffusion speed accuracy.

1) DISCRETE PHASE

DPM Model of Lagrange uses the liquid phase as a continuous medium in the calculation and solves the fluid control equations in Euler's coordinate system. The solid sand phase is regarded as a discrete medium in the Lagrangian coordinate system. Solve the sand particle motion equation, and use the iterative calculation to perform the solid-liquid coupling [21]–[23]. Aeolian sand belongs to multiphase flow, in which the particle phase is a discrete phase and the gas phase is continuous.

In the DPM model, since the shapes of dust particles are irregular, it is difficult to analyze the external force in the numerical simulation calculation, such as the collision force and viscus force etc. In this study, a general assumption is made that the particles are spherical, and there are no collisions between the particles, hence no internal energy is generated. Under this assumption, the particles tracking can be expressed by the discrete phase equation. During the period of particle motion in the turbulent field (air flow), the particles are one-way coupling with the air flow. It will generate collision force and adhesion force between each particle. However, the volume fraction of the particles is smaller than 10-6, so the collision force and adhesion force produced by the particles during the particle tracking process is negligible. Due to the particle motion in the non near-wall turbulent flow, the particles are affected by Magnus force, which means the particles in the air flow move and rotate randomly. However, the Magnus force is much smaller than the viscous force. As a result, Magnus effect is neglected in the simulation.

In this model, the continuous phase flow field is first solved, and the discrete phase (dust particles) is added after the calculation results converge, and the discrete phase is set to perform an iterative calculation once every 10 steps of the continuous phase calculation.

The DPM equation can be expressed as follows:

$$\frac{du_p}{dt} = \frac{3}{4}\frac{C_D\rho\left|u_p-u\right|}{\rho_p d_p}(u-u_p)+\frac{g(\rho_p-\rho)}{\rho_p}+F^{\rightarrow} \quad (2)$$

$$\begin{cases} C_D = \frac{24}{Re}(1+0.15Re^{0.687}), & (C_D \leq 1000) \\ C_D = 0.44, & (C_D > 1000) \end{cases} \quad (3)$$

$$Re = {}^{\rho u L}\!/_{\mu} \quad (4)$$

where C_D is the drag coefficient, ρ is the fluid density (kg/m^3), ρ_p is the particle density (kg/m^3), u is the wind velocity (m/s), u_p is the velocity of the particles (m/s), and $F^{\rightarrow}$ is an additional acceleration (force/unit particle mass) term. Re is Reynolds constant, L is the length of fluid field (m), and μ is the viscous force (Pa·s).

Eq. (3) can illustrate the drag force, gravity force, and lift force (Saffman force) of the dust particles in the CFD simulation [10], [13].

2) TURBULENCE MODEL

In the study of two-phase flow, there are two hypothetical methods: the first method is to use the fluid as a continuous medium and the particle group as a discrete system. The second method is to treat the fluid as a continuous medium, the particle group is also regarded as a quasi-continuous medium or quasi-fluid. FLUENT corresponds to a discrete phase model, multiphase flow model (VOF model, mixed model, Euler model). This study chooses the discrete phase model as the simulation model. FLUENT is solving the continuous phase (gas) transport equation while simulating the second phase (solid particles) of the discrete phase in the flow field in Lagrange coordinates. The discrete phase model in FLUENT assumes that the volume fraction of the second phase is generally smaller than 10%, which means the effect of particle-particle interaction and particle volume fraction on the continuous phase is not considered.

Therefore, in the CFD simulation, the air flow, namely the wind-velocity inlet, can be described as a continuous phase. It can be expressed by Navier-Stokes equation [12], which describes the conservation of viscous incompressible fluid momentum as:

$$\rho\frac{du}{dt} = -\nabla p + \rho F + \mu\Delta u \quad (5)$$

where ρ is the fluid density (kg/m^3), u is the wind velocity (m/s), p is the pressure (Pa), F is the external force (N), and μ is the dynamic viscosity coefficient.

The physical structure of the turbulence model consists of large vortices and small eddies, where large-scale vortices are affected by inertia, while small-scale vortices are determined by viscous forces. In the wind-sand two-phase flow, the discrete phase is coupled with it, and the Lagrangian algorithm is used to track the particles in the turbulent flow field.

When the air flow is turbulent, the turbulence model requires an extremely large computer memory and a high computational speed. The realizable k-3 model is able to release the burden of computational memory and achieve high precision.

In the calculation process, the turbulent energy equation from [24], [25] is used to express the motion dynamics of the wind-sand field, and the turbulence intensity decides the wind flow degree.

The turbulent energy equation is:

$$K = \frac{3(uI)^2}{2} \quad (6)$$

where the turbulence intensity I can be described as:

$$I = 0.16Re^{-1/8} \quad (7)$$

where u is the wind velocity (m/s), Re is Reynolds constant. In the assumptions of the model, the two-phase flow model selected is a flow model of gas and solid particles. In this model, the prediction of dust deposition, Collision, friction, and stickiness with solid walls are relatively accurate. This is in line with the situation simulated in this study. The air carries particles with a lower concentration (1.17 kg/m^3) and smaller particle sizes (10 μm to 100 μm). The collision between particles during the movement can be ignored. It is believed that particles and gases have good followability. While achieving better numerical simulation, it guarantees accuracy and saves time.

B. EXPERIMENT SETUP

An experiment is designed to verify the deposition of dust particles on the solar panels in the simulation and the effect of dust deposition on the power generation efficiency of PV panel. The equipment include a fan (SHT-30 portable propeller ventilator), a pipe, a solar panel (RS PRO), thermometer (IP 54), voltmeter, an electronic scale (APTP 452) and sands. The dust particles were sieved under 100 μm by using a 150 mesh sieves.

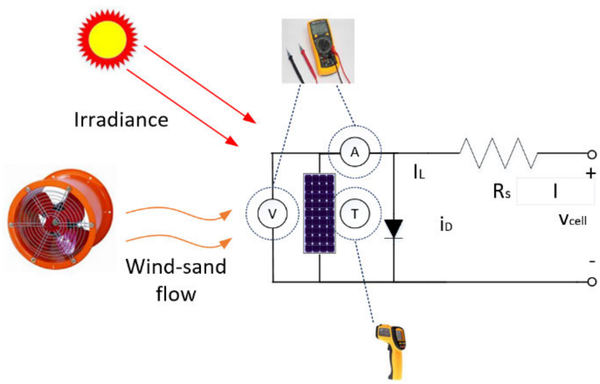


FIGURE 3. Measurement of RS PV panel.

The system configuration of the experiment is shown in Figure 3. PV panels are placed in the courtyard of the four walls, and the walls can serve as the boundaries of the entire area. In this way, PV panels can avoid the interference of the outside wind to the greatest extent. Meanwhile, the natural sunlight and the ambient temperature make the settlement and power generation effect more realistic. The fan as a jet source provides turbulent energy for dust particles. The pipe can be used as a boundary layer to prevent the wind flow from diffusing. Meanwhile, dust particles are injected into the entrance port, so the sand dust moves randomly with the turbulent flow direction to distribute on the PV panel. The thermometer and the voltmeter are used to measure the data when the voltage changes with the temperature.

In [20], the data measured under STC can be used as a reference, such as the surface temperature, dust density, and output power of the PV panel. After measuring the quantity of the dust particles, which are deposited on the PV panel. The relationship between the solar power generation and dust density can be obtained.

In this study, the RS PV panels are used, whose physical size is 300 × 210×20 mm. Technical specifications of the PV panel are shown in Table 1, which are measured under the STC. The optimal tilt angle of the PV panel is also set

TABLE 1. Parameters of PV panel.

Symbol	Parameter	Value
Wp	Peak power	5 W
Vmp	Max. power Voltage	17.5 V
Imp	Max. power Current	0.29 A
Voc	Open Circuit Voltage	22.0 V
Isc	Short Circuit Current	0.32 A

to 56°. There are 36 PV cells in the PV module. The PV power generation efficiency of PV panels was studied by observing the occlusion rate of PV cells by dust particles.

According to the flow equation (8), when the distance between the PV panel and the tuyere increases, the wind speed decreases. The wind velocity at a certain position in the wind field can be described as:

$$v = QA \quad (8)$$

$$Q = \alpha S \quad (9)$$

$$\frac{v_1}{v_0} = \frac{QA_0}{Q_0 A} \quad (10)$$

where A_0 (m^2) and Q_0 (m^3/s)are the airflow at the cross section and the flow rate at the outlet of the air duct, respectively. Meanwhile, A (m^2) and Q (m^3/s) are the airflow at the cross section and the flow rate at a certain distance from the outlet, respectively. α is the turbulence coefficient and S is the distance between the specification place and the tuyere (m).

The dust fluxes can be described as [26]:

$$F_D = aEc\frac{\rho_\alpha}{g}u_*^3(1+\frac{u_{*t}}{u_*})(1-\frac{u_{*t}^2}{u_*^2}) \quad (11)$$

$$u_{*t} = \frac{u_*}{\kappa}In(z/z_0) \quad (12)$$

where E is the erosion factor, α is the sand blasting efficiency, c is the empirical proportionality constant, g is the gravitational acceleration (m/s^2), ρ_α is the air density (kg/m^3), u_* is the friction velocity (m/s) and u_{*t} is the threshold friction velocity (m/s). κ is the empirical constant, which is roughly 0.35 for turbulent flow, and z_0 is the roughness length (m).

TABLE 2. Turbulence coefficient.

Nozzle Type	α	2α
Shrinking	0.066	25°20′
Nozzle	0.071	27°10′
Cylindrical	0.076	29°00′
Tube	0.08	
Axial fan with	0.12	44°30′
air deflector	0.20	68°30

Considering the effect of wind speed on the dust particle motion, and according to (11) and (12), the density of incident particles is set to 0.1 g/s. The turbulence coefficient is shown in Table 2. The turbulence coefficient α and jet diffusion angle

2α are affected by the turbulent intensity. When the turbulent intensity increases, the surrounding medium is driven to increase. In this situation, the turbulence coefficient α is 0.12. The wind speed of the fan used in this experiment is 10 m/s. According to (10), the positions of the PV panel can be calculated to identify the incident wind speed.

Finally, the surface temperature of the PV panel is measured with a thermometer. Meanwhile, the voltage value of the PV panel is detected by a voltmeter. To get an accurate temperature-voltage relationship, the detection of the data is continuously monitored within 30 minutes. Then, repeat the experiment after the PV panel is cooled for 10 minutes.

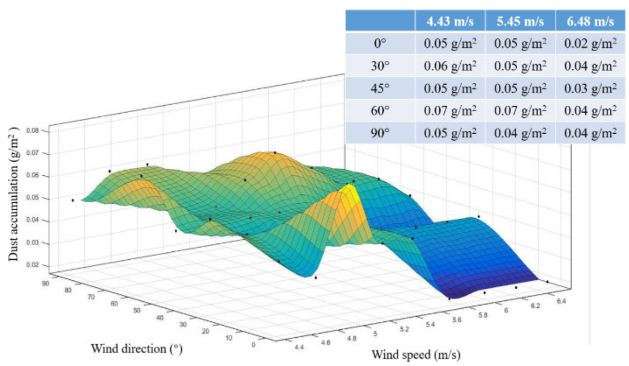
III. RESULTS

In this part, firstly, the dust particles accumulated on the surface of PV panels in different environments were simulated, and the accuracy of dust accumulation was verified by experiments. Then, the change of temperature of the PV panel surface and the occlusion are measured under different dust accumulation conditions. Finally, the power variation of the PV panel is measured.

A. SIMULATION RESULTS

1) SIMULATION RESULTS OF DUST DEPOSITION

The results display the dust accumulation when the wind flows from different angles in terms of 0°, 30°, 45°, 60° and 90° to the PV panel, as shown in Figure 4. The dust accumulation on the surface of the PV panel is different when the wind speed varies. The table in Figure 4 shows the samples of dust density in minimal, middle and maximal wind speeds in different inject angles. In numerical simulation, FLUENT was used to count the particle weight with zero velocity on the surface of the PV panel. In the test, a simulated wind tunnel is used to perform a blowing experiment to simulate the wind speed and blowing angle under actual conditions. After multiple times (at least 3 times), weight measurement is performed when the weight is no longer increased. The weight includes the dust and PV panel.



	4.43 m/s	5.45 m/s	6.48 m/s
0°	0.05 g/m²	0.05 g/m²	0.02 g/m²
30°	0.06 g/m²	0.05 g/m²	0.04 g/m²
45°	0.05 g/m²	0.05 g/m²	0.03 g/m²
60°	0.07 g/m²	0.07 g/m²	0.04 g/m²
90°	0.05 g/m²	0.04 g/m²	0.04 g/m²

FIGURE 4. Simulation results of dust deposition in various air conditions.

Referring to the trend in Figure 4, it is known that there are two peak values for the quantity of dust deposition. The curve in the Figure 4 shows the values of dust accumulation with different wind inlet angles. The quantity of dust particles accumulate at the first peak value, while the wind speed changes between 4.43 m/s and 5 m/s. During this period, the wind velocity is not high enough, and the viscosity is higher than the collision force between the dust and PV panel. As the wind speed increases, the turbulent energy is greater than the viscous force, and the dust on the surface of the PV panel begins to decrease. Then, the dust particles accumulate at the position with the second peak value, while wind speed changes between 5 m/s and 6 m/s. During this period, the wind velocity is high enough, and the collision force is higher than the viscous force between the dust and PV panels. After that, the quantity of dust on the PV panel surfaces tends to be stable. Moreover, the critical value of dust deposition is not only decided by the wind speed, but also the wind direction. For example, in the first steady time period, the maximum dust deposition at 90° is achieved with the wind speed of 5 m/s. It is obvious at the time of second peak.

According to Figure 4, a set of theoretical principles can be derived to directly observe the dust accumulation of PV panels in England. Influenced by the wind directions, the dust distribution and dust density of PV panels are different. The formula group (12) shows the relationship between the wind speed and the dust accumulation at particular wind directions.

$$\begin{cases} y_{0^\circ} = -0.1315x^5 + 3.6069x^4 - 39.3442x^3 \\ +213.3849x^2 - 575.3697x + 617.0866 \\ y_{30^\circ} = -0.0112x^5 + 0.3276x^4 - 3.7934x^3 \\ +21.8242x^2 - 62.3825x + 70.9352 \\ y_{45^\circ} = -0.0059x^5 + 0.1803x^4 - 2.1471x^3 \\ +12.5746x^2 - 36.2668x + 41.3162 \\ y_{60^\circ} = -0.0262x^5 + 0.7603x^4 - 8.7744x^3 \\ +50.3571x^2 - 143.6585x + 163.9765 \\ y_{90^\circ} = 0.0056x^5 - 0.1875x^4 + 2.4407x^3 \\ -15.4579x^2 + 47.8541x - 58.0582 \end{cases} \tag{13}$$

where x is wind speed (m/s) and y is the density of dust accumulation (g/m^2).

Although in some situations, the quantities of dust deposition are the same, the distribution is various when the wind changes. For example, in Figure 5, the cases with 5 different wind directions and 8 different wind speeds are compared. There are two situations for dust distribution: focus deposition and average deposition. Combined with Figure 4, Figure 5 shows a more visual representation of the cumulative distribution of sand and dust at different wind speeds and wind directions. In figure 5 (a), the dust accumulation on the PV panel with 0° wind inlet, it is focus deposit on a part of panel. Therefore, the irradiance on this part is very week, which is only 600 W/m^2, which is same as figure 5 (d). In addition, figure 5 (b), figure 5 (c) and figure 5 (e) shows the same situation, which is affected by average dust accumulation. In this circumstance, the irradiance is 800 W/m^2.

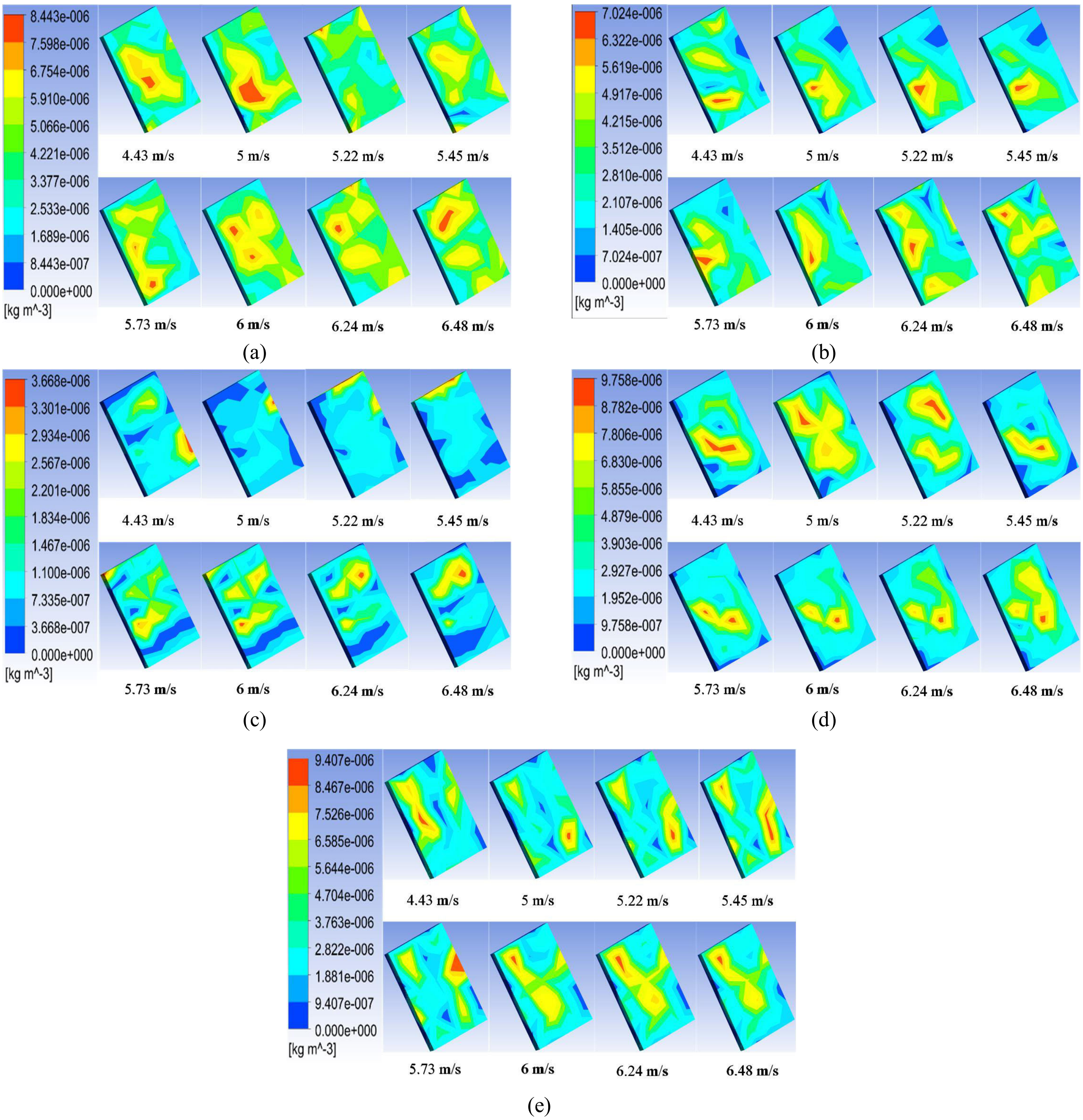


FIGURE 5. Diagram of dust deposition on the PV panel. (a) 0° wind direction (b) 30° wind direction (c) 45° wind direction (d) 60° wind direction (e) 90° wind direction.

The average dust distribution generally only affects the PV power generation, and the concentrated distribution of dust can damage the PV panels. The reason for this is that the dust covering the surface of the PV panel affects the irradiance and blocks heat dissipation. It impacts the power generation efficiency of a PV panel, which will be expressed in the next section.

2) SIMULATION RESULTS OF THE TKE

After analyzing the PV panels, the PV array needs to be briefly analyzed. After all, in the PV array, the front and rear PV panels have an effect, which is important for power generation. In order to figure out the dust particle motion around the PV array, the TKE should be analyzed in the CFD simulation. By analyzing the PV array, the following information

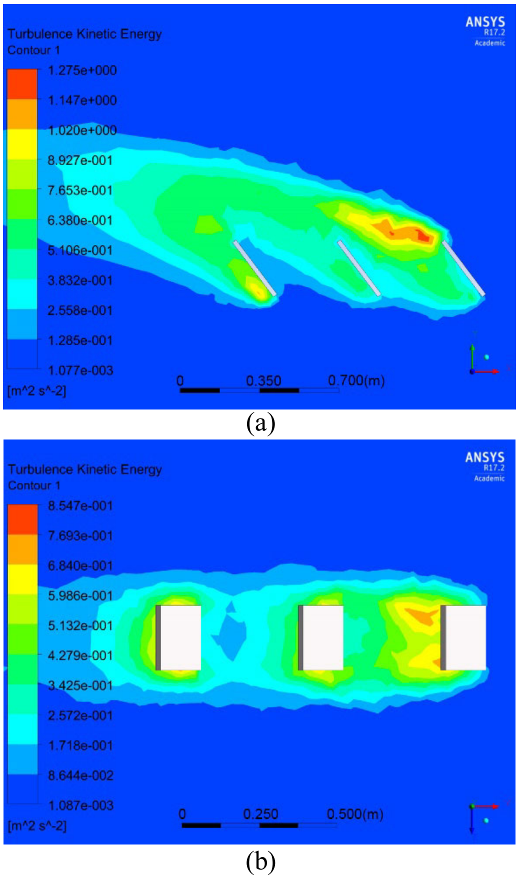


FIGURE 6. The TKE of PV array in CFD. (a) the left view of dust particle deposition of 100 μm dust diameter with 5 m/s wind velocity (b) the top view of dust particle deposition of 100 μm dust diameter on 10 m/s wind velocity.

is derived: the turbulence impact the dust distribution around the PV panels. The TKE is shown in Figure 6.

According to (4), (5) and (6), the TKE is affected by the velocity and turbulence intensity, and the higher the turbulence intensity is, the greater the TKE is. Meanwhile, the turbulence intensity is determined by the Reynolds constant. The larger the Reynolds constant is, the greater the fluid density is, and at this time, the inertia effect is greater than the viscous force. Therefore, the impact of particle to the PV array is related to the wind velocity.

In Figure 6 (a), the TKE distribution of the PV array is uneven, and the turbulent energy between the first panel and the second panel is large, and the upper portion is particularly dense, indicating that the particle concentration here is large. Due to the blockage of the first and second PV panels, the wind speed is decreased when reaching the third panel, so the TKE between the second PV panel and the third PV panel is reduced. Finally, due to the influence of turbulence, a large number of dust accumulate in the back-bottom part of the third panel, and when the wind speed increases, the accumulation amount increases too.

It can be observed from Figure 6 (b) that the front panels decrease the TKE to the rear panels, and it can be seen from the top view that the TKE between the PV panels is not uniform, and as a result, fewer particles accumulate on the rear panels. Thus, the amount of dust accumulated on the surface of the PV panel is different, which is affected by the front panel. However, the non-uniform TKE drives the particles to adhere to a small part of PV panel, and causes high temperature in that part. Therefore, the panel in the middle should be concerned to prevent the hot spot effect.

To sum up, at different wind speeds, the TKE in the PV array is different. Combing with Figure 2 and Figure 5, in the northern area of England, represented by Liverpool, the amount of PV dust deposition is generally small, which is suitable for the construction of PV power stations. The minimal dust deposition cycle is from December to March, and the maximal value is from August to October. Therefore, during August to October, PV panels need to be maintained to avoid hot-spot effects and DC arc shock caused by dust.

B. EXPERIMENT RESULTS

1) ACCURACY OF SIMULATION

The particle densities from the simulation and experiment results are shown in Figure 7. Compared to the simulation results with the experimental results, it is found that the two groups of data witness very similar trend. According to analyze the diagram in Figure 7 when the wind speed varies in a year, the errors between experiment and simulation are not totally same in each wind direction. From 0 ° to 90 ° wind inlet, the average error is 0.5%, 0.4%, 0.2%, 0.2% and 0.3% respectively. As a result, the actual dust deposition value can be predicted by using (13) in England area. Therefore, since the finite element simulation results are highly accurate, the simulation data can be used to predict the real situation of local PV power generation.

$$\begin{cases} y_{0^\circ} = (-0.1315x^5 + 3.6069x^4 - 39.3442x^3 \\ +213.3849x^2 - 575.3697x + 617.0866)(1 \pm 0.5\%) \\ y_{30^\circ} = (-0.0112x^5 + 0.3276x^4 - 3.7934x^3 \\ +21.8242x^2 - 62.3825x + 70.9352)(1 \pm 0.4\%) \\ y_{45^\circ} = (-0.0059x^5 + 0.1803x^4 - 2.1471x^3 \\ +12.5746x^2 - 36.2668x + 41.3162)(1 \pm 0.2\%) \\ y_{60^\circ} = (-0.0262x^5 + 0.7603x^4 - 8.7744x^3 \\ +50.3571x^2 - 143.6585x + 163.9765)(1 \pm 0.2\%) \\ y_{90^\circ} = (0.0056x^5 - 0.1875x^4 + 2.4407x^3 \\ -15.4579x^2 + 47.8541x - 58.0582)(1 \pm 0.3\%) \end{cases} \quad (14)$$

where x is wind speed (m/s) and y is the density of dust accumulation (g/m^2).

According Figure 7, the first two batches of experiments carried out at a low airflow angle, the dust particles carried by the airflow were less constrained on the surface of the solar panel, and the sedimentary motion of the particles was more cluttered, resulting in relatively large data changes in the experiment and a large deviation in the simulated results.

To conclude, after verification, the dust is related to the wind speed, and a lower wind speed, results in a lower

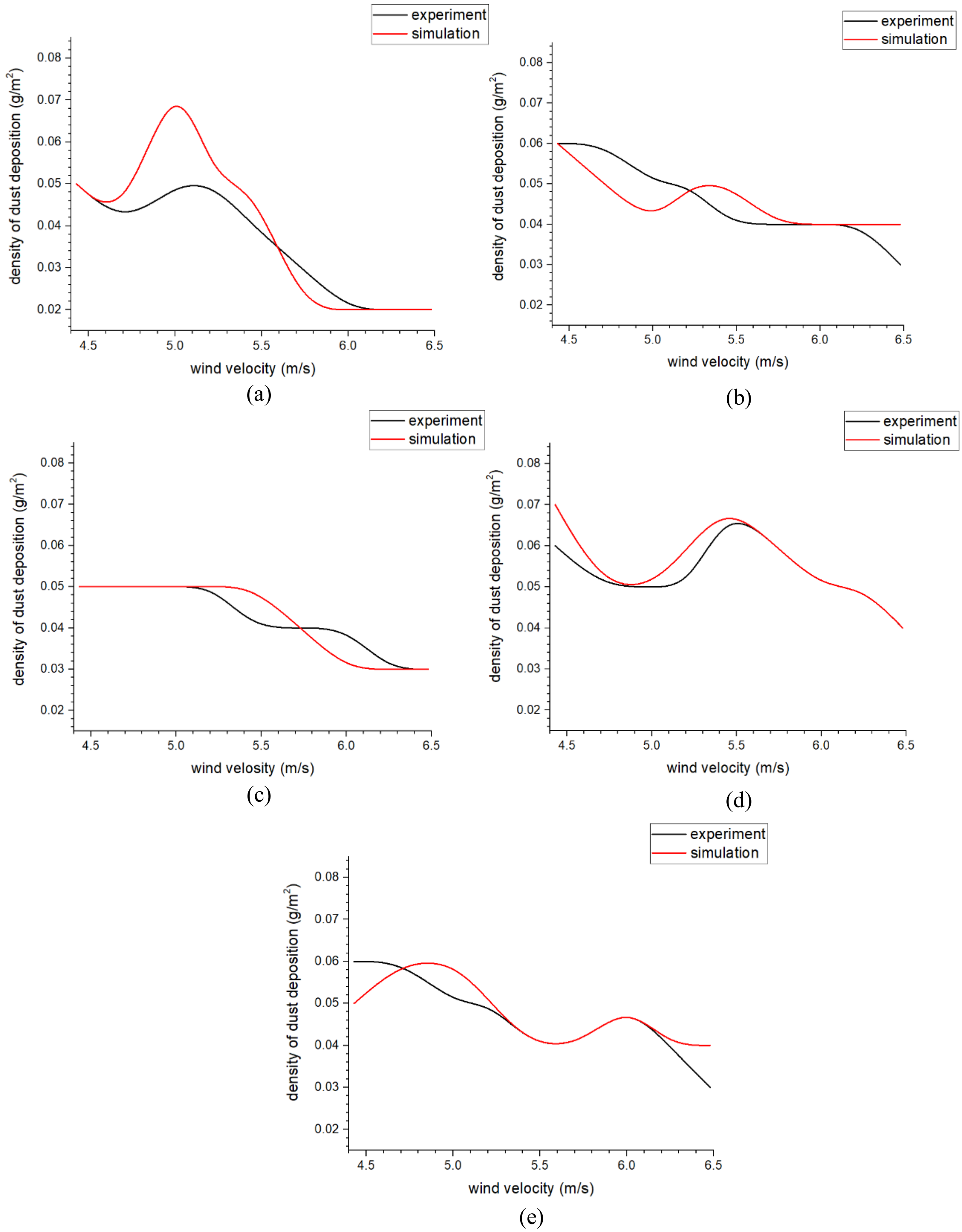


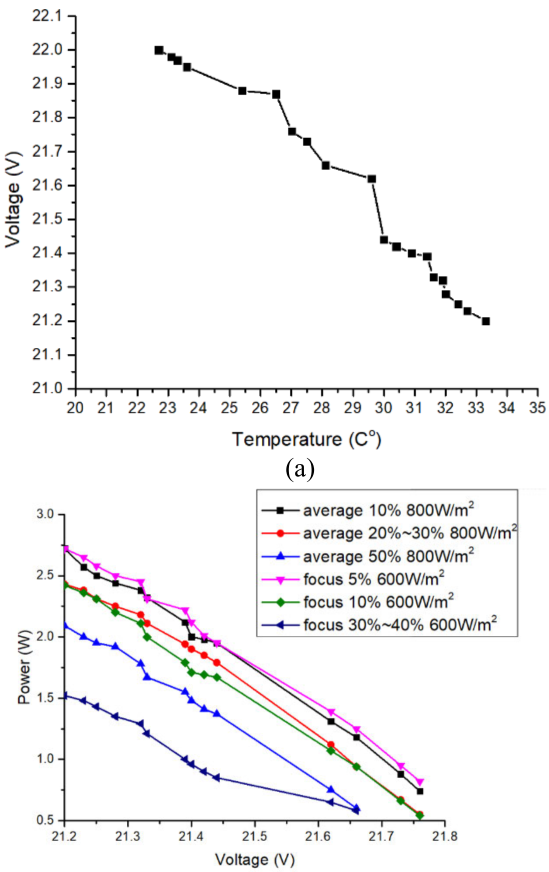
FIGURE 7. Comparison of experiment value and simulation value of dust deposition. (a) 0° wind direction (b) 30° wind direction (c) 45° wind direction (d) 60° wind direction (e) 90° wind direction.

dust density. In addition, due to the high accuracy of simulation results, the situation of dust deposition in a region can be detected by using CFD simulation.

2) IMPACTS OF DUST DEPOSITION ON TEMPERATURE AND OUTPUT OF PV PANELS

Since the dust accumulation of PV panels in a region can be obtained through simulation. This section will analyze the impact of sand and dust accumulation on temperature and PV power generation efficiency. It can determine whether a place is suitable for building a PV station.

The comparison between a clean PV panel and a dusty PV panel with 100 μm dust particles at the wind speed of 5 m/s when the wind flows vertically (90°) to the surfaces of the PV panels. The maximum surface temperature of the cleaning PV panel is 28.1 °C in Liverpool over one day, and the maximum surface temperature of the dusty PV panel is 32.6 °C in the same condition. Since the material of the PV panel is polysilicon, it is very sensitive to temperature changes. Therefore, the dust covering the surface of the PV panel prevents the heat of the panel from being released, and cannot be transmitted outward, so that the temperature gets higher.



(b)

FIGURE 8. **Measured data (a) temperature-voltage curve (b) P-V curve.**

From Figure 8 (a), it can be seen that the panel surface temperature has a great influence on the output voltage of the PV panel. When the surface temperature of the PV panel reaches 33.2 °C, it does not increase further. The dust covering the surface of the PV panel not only blocks the irradiation, but also blocks the heat dissipation that affects the power generation efficiency. Therefore, when the dust accumulates on the PV panel, the output voltage of the PV panel decreases. In addition, when the temperature rises, the forbidden bandwidth of the solar cell becomes narrower, so the open-circuit voltage decreases. Because the bandgap is narrow, more electrons can transit from the valence band to the conduction band, the short circuit current increases and the temperature affects the open-circuit voltage. The impact on the short-circuit current is small, so the overall temperature rises and the battery power drops. Then, the output power at a certain temperature is obtained when the dust accumulates in different situations.

From Figure 8 (b), there are two situations for dust accumulation: almost average accumulation and focusing on a part of a PV panel. Considering the factors of shading and temperature rise, the PV power generation decreases by 46%∼70% in different environmental conditions. When the dust deposition focuses on a part of a PV module, the irradiance of the shading part is roughly 600 W/m2. Because of the quantity of the dust particles on the PV panel, there are three situations:

(a) There is 0.02 g/m^2 dust shading on 1 PV cell, and 1 cell occupies 5% of a module.
(b) There is 0.04 g/m^2 dust shading on 4 PV cells, and 4 cells occupy 10% of a module.
(c) There is 0.05 g/m^2 to 0.08 g/m^2 dust shading on 14 PV cells, and 14 cells occupy 30%∼40% of a module.

When the dust deposits averagely on a PV module, the irradiance of the shading part is 800 W/m^2 approximately. There are also three situations on dust accumulation:

(a) There is 0.02 g/m^2 dust shading on 4 PV cells, and 4 cells occupy 10% of a module.
(b) There is 0.04 g/m^2 dust shading on 9 PV cells, and 9 cells occupy 20%∼30% of a module.
(c) There is 0.05 g/m^2 to 0.08 g/m^2 dust shading on 18 PV cells, and 18 cells occupy 50% of a module.

To sum up, the dust deposition affects PV power generation efficiency. The thicker the dust is, the lower the output voltage is, because the temperature of PV panel rises sharply within 5 minutes. In addition, due to the impacts of dust deposition to PV power generation, the selection of PV station should be concerned while the region has large quantity of dust accumulation. If a station is chosen in a large dusty place, it will invest many resources in cleanings, such as cost and labor.

IV. CONCLUSION

The deposition of dust particles on PV panels was studied by CFD simulation and further verified by an experiment in this study, which is based on the weather of Liverpool, England. The wind field was predicted by the Realizable k-e turbulence model, and the DPM model of turbulent particle diffusion was used to simulate the dust deposition behavior. As long as the boundary conditions of local situation are set, the corresponding environmental conditions can be obtained. Meanwhile, calculations are made in advance to predict the local suitability for building PV power plants.

Due to the influence of the monsoon, the most dust accumulation is from March to August. According to the experiment, the essence of dust effect on the efficiency of PV power generation affects the temperature of the surface of PV panel. Dust particles impact the PV panels, and they also increase the temperatures of PV panels. After the measurement process, it was found that the output power of the PV panel is decreased from 46%∼70%, due to dust accumulation and surface temperature of PV panel change. Therefore, according to the dust shading and the surface temperature of PV panel change, the relationship between dust deposition and PV power generation can be obtained. As a result, the output power in a certain area can be predicted. Meanwhile, in the PV array, there is an influence among the panels, resulting in uneven coverage of dust.

In summary, the numerical simulation method can accurately predict the dust accumulation on the PV panel and the distribution of the approximate dust pattern, which provides guidelines for the solar panel dust removal in the wind-sand environment. Meanwhile, based on the significant influence of the solar panel temperature on the output efficiency, how to effectively reduce the temperature in the local micro-environment of the solar panel will be the focus of the next step.

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