

Simulation and Experimental Study of a Novel Heat-Collecting Canopy in a Rotating Wind Energy System (Postprint)

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Abstract

Natural dust devils contain considerable energy, and based on this principle, a novel dust-devil-like rotating wind energy system has been proven capable of forming a stable rotating wind field. The solar collector canopy with pre-swirl guide vanes constitutes the core component of this system, providing the heat source to generate rotating airflow. This paper employs a methodology combining numerical simulation and experimental research, varying the dimensional parameters of the collector canopy model (collector canopy radius, vane incidence angle) and heating temperature difference to simulate and obtain the variation patterns of characteristic wind speed values at the outlet of the rotating wind field under different conditions, thereby selecting an appropriate incidence angle for the collector canopy. Furthermore, through comprehensive analysis of simulation and experimental results with similarity theory, curve relationship diagrams between collector canopy size and characteristic wind speed values under different heating temperatures at this incidence angle are derived, and similar curves conforming to Martian climate conditions are presented, providing important references for rationally predicting the system's structural and operational parameters, as well as for its further application prospects in space.

Full Text

Numerical Simulation and Experimental Study on the Solar-energy-collecting Shed in a New Whirlwind Energy System

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Abstract

Dust devils in nature contain abundant wind energy. A new dust-devil-like whirlwind energy system has been proposed that can generate stable swirling wind fields. A circular solar-energy-collecting shed with pre-rotation vanes serves as the core component, providing heat sources to generate rotational airflow. This paper investigates the effects of geometrical parameters (shed radius and air inflow incident angle) and heating temperature differences on the characteristic wind speeds at the outlet through numerical simulation combined with experimental studies. The optimal incident angle is identified based on the resulting distribution and trends. Furthermore, through comprehensive analysis of simulation and experimental results combined with similarity theory, the relationship between shed dimensions and characteristic wind speeds under different heating temperatures is established for this incident angle. Corresponding curves applicable to Martian climate conditions are also provided, offering important references for rational prediction of system structural and operating parameters and for prospects of further space applications.

Key words: whirlwind energy system; solar-energy-collecting shed; numerical simulation; experimental test; similarity analysis

Introduction

In recent years, the escalating crisis of traditional fossil fuel depletion and environmental pollution has intensified research efforts into various renewable energy technologies, including wind, solar, nuclear, tidal, and geothermal energy. Concurrently, investigations into novel renewable energy utilization technologies have gradually attracted researchers' attention.

Dust devils, a unique natural meteorological phenomenon, provide valuable inspiration. A dust devil is a rotating air mass with a high-temperature, low-pressure core and short lifecycle. Occurring within the atmospheric convective boundary layer, dust devils can reach diameters of tens of meters, with near-surface horizontal velocities of 5 m/s, vertical velocities of 15 m/s, and maximum wind speeds up to 25 m/s near their core, capable of lifting sand and debris, thus containing considerable energy [1-3]. Previous research indicates that dust devil formation results from ground heating of the overlying air, creating an unstable state where a layer of hot air is covered by cold air. Since the entire air layer cannot overturn, small thermal convection cells develop at concentrated updraft locations. Surrounding winds provide angular momentum to these thermal convection cells. As the cells rise, near-surface air converges to fill the void left by the ascending hot air, intensifying angular momentum and forming a dust devil at the center of the cell's base. The necessary conditions for dust devil formation are ground heating and initial environmental vorticity in the air

[4].

It is well known that solar photovoltaic power generation is a widely applied clean energy utilization method, converting solar energy into electricity through solar panels. However, the conversion efficiency is less than 20% [5], and solar panel temperatures can exceed 100°C [6], with most energy wasted as residual heat. Consequently, research on collecting and utilizing this solar waste heat is underway [7,8].

Based on these two considerations and incorporating the concept of generating buoyant jets through low-temperature solar heat collection [9], this paper proposes a novel solar photovoltaic-whirlwind energy utilization system. Grounded in the natural formation mechanism of dust devils, this system artificially satisfies the conditions for generating rotational wind by providing heat sources and initial environmental vorticity, forming a stable rotating thermal buoyant jet (i.e., a rotating wind field) to explore its energy utilization potential. This system can be integrated with solar photovoltaic systems by using the panels as a collecting shed, utilizing their waste heat as the heat source.

1 System Description

The system structure and operation schematic are shown in [Figure 1: see original paper]. A collecting shed device with pre-rotation guide vanes on its inner side provides initial vorticity to the airflow. The shed's upper surface can be arranged with solar panels that deliver conventional photovoltaic power output, while waste heat serves as the heat source to form and maintain the whirlwind. During operation, air inside the shed is heated and moves upward, passing through the pre-rotation guide vanes and exiting as a rotating wind from the central outlet. This flow is essentially a thermal buoyant jet. As airflow exits, external air enters the system, repeating the process to generate a stable rotating wind field.

2.1 Physical Model

The physical model and structural parameters used in our numerical simulation are shown in Figure 2: see original paper. The collecting shed has a certain slope with eight pre-rotation guide vanes embedded on its inner side. According to literature [10], preliminary numerical simulations of sheds with four, six, eight, and twelve vanes under identical structural and initial conditions revealed that while resultant velocities at the outlet were similar, rotational wind speeds for configurations with six or more vanes were significantly higher than those with four vanes, with no notable improvement when increasing from six/eight to twelve vanes. Therefore, we primarily selected six or eight vanes for our study. Regarding vane length, previous results [9,10] indicated that maximum rotational wind speed is achieved when the distance from the vane to the shed center equals half the shed radius, leading to the structure shown in Figure 2: see original paper.

It should be specifically noted that to ensure stable outlet airflow, a cylindrical wall 10 m high was installed at the outlet for flow stabilization. To investigate different incident angles, we also simulated three vane curvatures corresponding to inlet incident angles of 0° , 30° , and 60° , as shown in Figure 2: see original paper.

2.2 Experimental Model and Method

Based on the physical model structure, we manufactured an experimental prototype at 1:100 scale (shed radius of 2 m) with an initial configuration of six vanes, as shown in Figure 3: see original paper. The model was inverted for the experimental setup, shown in Figure 3: see original paper. A temperature-adjustable heating plate was installed at the model bottom, and a cylindrical acrylic wall (radius 10 cm, matching the central outlet dimensions) was placed at the central outlet. Holes were drilled at certain heights on the wall side to insert a hot-wire anemometer, shown in Figure 3: see original paper, for measuring characteristic wind speeds. All experimental apparatus is listed in .

We selected point O at the center of the cylindrical wall' s upper outlet as the characteristic point for vertical upward velocity. Eight measurement points were chosen on two concentric circles located 5 cm above the shed outlet plane (at the cylindrical wall' s lower inlet): points ABCD (radius 8 cm) and EFGH (radius 5 cm), as shown in Figure 3: see original paper, to measure tangential rotational wind speeds at distances of 8 cm and 5 cm from the center. By simulating models with identical structure and initial conditions as in the experiments, we validated the feasibility of our approach and the reliability of the mathematical model.

After completing the experimental system setup and ensuring the surrounding environment was essentially windless, the heating plate was activated with temperature differences of 30 K, 40 K, and 50 K relative to the environment. Measurements began after the wind field stabilized. For the nine measurement points (ABCDEFGHO), each point was recorded for 3 minutes. Using the anemometer' s averaging function, the mean value over 3 minutes was recorded. Each point was measured discontinuously three times, and the final value was taken as the average of these three measurements. The final values for points ABCD were averaged to obtain the mean wind speed on the outer circle, and similarly for points EFGH on the inner circle. The vertical velocity at center point O was measured using the same discontinuous 3-minute averaging procedure.

2.3 Mathematical Model and Case Setup

This study employs the open-source computational fluid dynamics software OpenFOAM with the standard k- two-equation model. All solved variables (velocity, temperature, turbulent kinetic energy, and dissipation rate) are obtained from the general transport equation (1):

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla \cdot (\rho\mathbf{U}\phi) = \nabla \cdot (\Gamma_\phi \nabla \phi) + S_\phi$$

where ρ represents fluid density, \mathbf{U} represents the three-dimensional velocity vector (u, v, w), Γ_ϕ is the diffusion coefficient, and S_ϕ is the source term.

For the computational domain, rectangular meshing was employed with refined grids near the collecting shed region, totaling approximately 22,000 cells. The PIMPLE (PISO+SIMPLE) algorithm was used for pressure-velocity coupling. For numerical discretization, first-order implicit scheme was used for temporal terms, second-order unbounded Gaussian interpolation for gradient and diffusion terms, Gamma scheme for divergence terms, and central-differencing linear interpolation for surface interpolation. Residuals were set to 10^{-8} for pressure and 10^{-6} for other variables.

Boundary conditions were: ambient temperature of 273 K; simplified bottom heating with heating area matching the shed's bottom projection shape; temperature differences of 40 K, 60 K, and 80 K; boundary pressure at one standard atmosphere (10^5 Pa); zero initial velocity at bottom and shed surfaces; and adiabatic shed surfaces.

Cases were configured based on shed radius (2 m, 20 m, and 200 m), inlet incident angle (0° , 30° , and 60°), and heating temperature difference (40 K, 60 K, and 80 K).

2.4 Froude Number Similarity Criterion

For sheds with diameters of hundreds of meters, experimental measurement of generated wind speeds is impractical. Besides numerical simulation, fluid mechanics similarity theory can be used to predict wind speeds for larger-scale sheds based on small-scale model experiments by equating similarity criterion numbers.

The rotating wind at the collecting shed's central outlet is essentially a buoyant jet, governed primarily by buoyancy, inertial, and viscous forces. Based on trial calculations, the rotating wind in this study is turbulent, allowing viscous forces to be neglected. We adopt the Froude number (Fr), the ratio of inertial to buoyant forces, as the similarity criterion, expressed in equation (2):

$$Fr = \frac{u_0^2 \rho_0}{gL(\rho_a - \rho_0)}$$

where u_0 represents the maximum velocity near the central outlet (for simplicity, the maximum wind speed at a certain moment after flow field stabilization is used due to similar flow field characteristics with unchanged shed structure), ρ_0 is the outlet airflow density, g is gravitational acceleration, L is the central outlet diameter, and ρ_a is the ambient air density.

If two buoyant jets at different scales are dynamically similar, their Fr numbers must be equal. Consequently, the ratio of characteristic velocities δu and characteristic dimensions δL between two flows at different scales should satisfy equation (3):

$$\delta u = \sqrt{\delta L}$$

Thus, characteristic velocity and characteristic dimension follow a specific exponential relationship. This paper examines sheds with the same pre-rotation incident angle but different scales (radii of 2 m, 20 m, and 200 m). Using experimental and simulation data for the 2 m radius case and simulation data for the 20 m and 200 m cases, the relationship between shed radius and generated total wind speed can be established under certain conditions.

3.2 Outlet Wind Field and Influencing Factors

After achieving computational stability, we focused on the velocity field distribution near the central cylindrical guide wall outlet. Since our objective is to utilize the total kinetic energy of the outlet wind field, the velocity distribution in the resultant velocity field is of greater significance. Figure 5: see original paper shows the resultant velocity field distribution obtained from the model in Figure 2: see original paper. The cut-in wind speed for typical low-speed wind turbines is 3 m/s [11], and all velocities within the dashed box exceed 3 m/s, confirming that the system can generate sufficient wind speeds to drive low-speed turbines. Figure 5: see original paper shows the tangential velocity vector field on the A-A cross-section at the guide wall outlet, demonstrating that inlet airflow, after pre-rotation through the guide vanes, forms a swirling upward rotating wind field at the central guide wall outlet.

As discussed in Section 2.1, we have already obtained the effects of vane number and length on the wind field. For this 200 m radius shed model, we further simulated different inlet incident angles (0° , 30° , and 60°) to obtain rotational wind speeds U_z and resultant velocities U_{mag} at characteristic points, with trends shown in [Figure 6: see original paper].

Wind speed increases with heating temperature difference. Smaller inlet incident angles (greater vane curvature) provide more sufficient pre-rotation, resulting in higher tangential rotational wind speeds. Conversely, the resultant velocity shows an opposite trend due to velocity losses from excessive pre-rotation. While higher resultant velocities are desired, sufficient airflow rotation effectively increases wind energy density. Among the three angle groups, although 60° yields the maximum resultant velocity, its rotational wind speed is too low. Comparing 0° and 30° , while 0° produces slightly higher rotational wind speed, the values are very close, and 30° yields a slightly higher resultant velocity, meaning greater outlet total kinetic energy at similar energy densities. Therefore, 30° is the more suitable inlet incident angle among these three options.

3.3 Preliminary Application Prospects Analysis

For shed radii of 2 m, 20 m, and 200 m, combining similarity criterion analysis with simulation results and following the analytical method in reference [12], we generated the curves shown in Figure 7: see original paper. These curves delineate, for given pre-rotation vane incident angles and collecting shed heating temperature difference ranges, the shed size ranges capable of generating maximum wind speeds above 3 m/s. This provides technical references for selecting optimal structural and operating parameters for this type of collecting shed.

Furthermore, with advancing space exploration and manufacturing technologies, this energy system shows promise for future implementation on Mars. Mars' s characteristics make it more suitable for this system than Earth: greater available space for constructing and installing collecting sheds, desert surface regions with low specific heat sand/rock, and a thinner atmosphere resulting in much larger diurnal temperature variations that can generate stronger rotating winds. The system also offers advantages for Mars: humans could live inside the vane structure, and with existing solar collection conditions supplemented by temperature/humidity control and air generation devices, habitable conditions could be created inside the vane structure. Moreover, both the rotating wind energy from the shed' s central outlet and the electricity from solar panels could directly serve as energy sources for human inhabitants.

Using Martian meteorological conditions (temperature, pressure, atmospheric density, etc.) as initial conditions and following the same methodology used for Figure 7: see original paper, we obtained the collecting shed diameter-maximum wind speed curves for Mars shown in Figure 7: see original paper. These curves enable determination of appropriate shed diameter ranges for usable wind speeds once the cut-in wind speed for Mars-suitable turbines is established.

4 Conclusions

Through numerical simulation and experimental analysis, this study investigated the structural parameters of the collecting shed—the core component in a novel whirlwind energy system—yielding the following conclusions:

- 1) By providing heat sources and inlet pre-rotation, stable upward rotating wind fields can be formed at the collecting shed outlet. When the shed reaches certain dimensions, the generated wind field is sufficient to drive low-speed wind turbines.
- 2) Increased heating temperature difference enhances wind speed in the rotating wind field. For pre-rotation angle, smaller inlet incident angles (greater vane curvature) provide more sufficient pre-rotation that increases rotational wind speed (tangential velocity), while the resultant velocity shows the opposite trend. For this system, heating temperature should be maximized and an appropriate vane inlet incident angle selected—neither too large nor too small.

- 3) The size ranges of collecting sheds that generate usable wind speeds have been determined for both Earth and Mars environments across certain heating temperature difference ranges, providing a preliminary assessment of application prospects.

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