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

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Abstract

Natural dust devils possess considerable energy, and a novel dust-devil-like rotating wind energy system proposed based on this principle has been proven to generate a stable rotating wind field. The solar thermal collector equipped with pre-swirl guide vanes is the core component that provides the heat source to generate rotating airflow in this system. This study employs a methodology combining numerical simulation and experimental investigation, varying the dimensional parameters of the collector model (collector radius, vane incidence angle) and the heating temperature difference, to simulate and obtain the variation patterns of characteristic wind speed values in the rotating wind field at the outlet under different conditions, and to select an appropriate incidence angle for the collector vanes. Furthermore, through comprehensive analysis integrating simulation and experimental results with similarity theory, curve relationships between collector dimensions and characteristic wind speed values under various heating temperatures are derived for this incidence angle, and analogous curves conforming to Martian climate conditions are presented, providing important references for the rational prediction of the system' s structural and operational parameters, as well as its prospects for further applications in space.

Full Text

Numerical Simulation and Experimental Study on the Solar-Energy-Collecting Shed in a Novel Whirlwind Energy System

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Abstract

Dust devils in nature contain considerable energy, and a novel dust-devil-like whirlwind energy system has been proposed that can generate a stable swirling wind field. The solar-energy-collecting shed with pre-rotation vanes serves as the core component of this system, providing heat to generate rotational airflow. This paper employs numerical simulation combined with experimental methods to investigate how varying the shed’ s dimensional parameters (shed radius and air inflow incident angle) and heating temperature differences affect the characteristic wind speed values at the outlet. Through this analysis, we identify an optimal incident angle for the shed vanes. Furthermore, by comprehensively analyzing simulation and experimental results using similarity theory, we derive the relationship curves between shed dimensions and characteristic wind speed values under different heating temperatures for this optimal incident angle. Additionally, we present corresponding curves for Mars’ climatic conditions, providing an important reference for rationally predicting the system’ s structural and operational parameters and assessing its prospects for space applications.

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

Introduction

In recent years, intensifying fossil energy crises and environmental pollution problems have driven increased research into renewable energy technologies such as wind, solar, nuclear, tidal, and geothermal energy. Concurrently, investigations into novel renewable energy utilization technologies have gradually attracted researchers’ attention. Dust devils, a special meteorological phenomenon in nature, offer valuable inspiration. A dust devil is a rotating air mass with a relatively 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 horizontal velocities up to 5 m/s near the ground, vertical velocities reaching 15 m/s, and maximum wind speeds near the dust devil core attaining 25 m/s, capable of lifting sand and debris and thus containing substantial energy [1-3]. Previous research [4] 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. Simultaneously, ambient wind provides angular momentum to these thermal convection cells. As the heated air rises, near-surface air converges to fill the void created by the ascending hot air, and angular momentum intensifies through this convergence, forming a dust devil at the center of the thermal cell’ s base. The necessary conditions for dust devil formation are ground heating and initial environmental vorticity in the air.

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, during this conversion process, the efficiency of solar panels is less than 20% [5], and 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 actively progressing [7,8]. Based on these considerations and incorporating concepts from previous studies on low-temperature solar collectors generating thermal buoyant jets [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 swirling buoyant jet—i.e., a rotating wind field—to explore the utilization value of this whirlwind energy system. The system can be used in combination with solar photovoltaic systems, with the battery panels serving as the collecting shed to provide heat through their waste heat.

1 System Description

The structure and operation schematic of the system are shown in Figure 1 [Figure 1: see original paper]. The system employs a collecting shed device with pre-rotation vanes on its inner side to provide initial vorticity to the airflow. The shed's upper surface can be arranged with solar panels that perform conventional photovoltaic power output, while waste heat is used to form and maintain the heat source for the whirlwind. During operation, air inside the shed is heated and moves upward. After pre-rotation through the vanes, it exits as a rotating wind from the central outlet. This flow is essentially a thermal buoyant jet. As airflow exits, ambient 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 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 were conducted on sheds with four, six, eight, and twelve vanes under identical structural and initial conditions. The results showed that while the resultant velocity values at the outlet were similar, the rotational wind speed values for six or more vanes were significantly higher than for four vanes, and the rotational wind speed for twelve vanes was not significantly higher than for six or eight vanes. Therefore, we primarily selected six or eight vanes for our study. Regarding vane length, previous research results [9,10] indicate that the maximum rotational wind speed is obtained when the distance from the vane to the shed center is half the shed radius, which is why we adopted the structure shown in Figure 2(a).

It should be specifically noted that to ensure stable outlet airflow, a cylindrical wall 10 m high was installed at the outlet to stabilize the flow. To investigate the effects of different incident angles, we also simulated three different vane curvatures corresponding to air inflow incident angles of 0°, 30°, and 60°, as shown in Figure 2(b).

2.2 Experimental Model and Methods

Based on the physical model structure of the collecting shed, we manufactured a scaled-down physical model at 1:100 scale (shed radius of 2 m) for experimental use, as shown in Figure 3 Figure 3: see original paper. The model was inverted, and the experimental platform was set up as shown in Figure 3(b). A temperature-adjustable heating plate was installed at the model bottom for heating. A cylindrical wall made of organic glass (radius 10 cm, consistent with the central outlet dimensions) was placed at the central outlet. Holes were drilled at certain heights on the wall’ s side to insert the hot-wire anemometer shown in Figure 3(c) for measuring characteristic point wind speed values. All experimental apparatus is listed in Table 1 .

We selected point O at the center of the cylindrical wall’ s upper outlet as the characteristic point for vertical upward velocity. We also selected measurement points ABCD (radius 8 cm) and EFGH (radius 5 cm) on two concentric circles located 5 cm above the shed outlet plane (the lower inlet of the cylindrical wall), as shown in Figure 3(d), to measure tangential rotational wind speed values at distances of 8 cm and 5 cm from the center. By simulating models with identical structures and initial conditions as in the experiments, we verified the feasibility of the approach and the reliability of the mathematical model.

Table 1 Experimental Apparatus

Apparatus	Function	Specifications
Cylindrical induced wall	Stabilize airflow for measurement	Radius 10 cm, height 50 cm
ED330L Temperature controller	Control heating plate temperature	Precision ±1°C
TM902C Thermocouple	Measure heating plate surface temperature	Range -50-1300°C
TSI9515 Anemometer	Measure central outlet wind speed	Precision ±5% of reading, resolution 0.01 m/s, operating temperature -18-93°C

2.3 Mathematical Model and Case Setup

This study employs the open-source computational fluid dynamics software OpenFOAM for simulation, using the standard k- two-equation model. All variables to be solved (velocity, temperature, turbulent kinetic energy, and dissipation rate) are solved by 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 the density of the calculated fluid, $\mathbf{U}$ 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, we employed rectangular grid division with refined grids near the collecting shed region, totaling approximately 22,000 cells. The PIMPLE (PISO+SIMPLE) algorithm was used to handle pressure-velocity coupling. For numerical discretization, a first-order implicit scheme was used for the time term, second-order unbounded Gaussian interpolation for gradient and diffusion terms, the Gamma scheme for divergence terms, and central-difference linear interpolation for surface interpolation. Residuals were set to 10^{-8} for pressure and 10^{-6} for other variables.

Boundary conditions were set as follows: ambient environment temperature of 273 K, heating condition simplified as bottom surface heating with the same shape and dimensions as the shed’ s bottom projection, providing temperature differences of 40 K, 60 K, and 80 K, boundary pressure at one standard atmosphere (10^5 Pa), initial velocity of 0 at both bottom and shed surfaces, and adiabatic shed surface.

Cases were set up according to collecting shed radius (2 m, 20 m, and 200 m), air inflow incident angle (0°, 30°, and 60°), and heating temperature difference settings (40 K, 60 K, and 80 K).

2.4 Froude Number Similarity Criterion

For collecting sheds with diameters of hundreds of meters, it is difficult to experimentally measure the generated wind speed values. In addition to numerical simulation, similarity theory in fluid mechanics can be used to predict wind speed values produced by proportionally larger sheds of the same structure based on experimental values from small-scale models, by equating similarity criterion numbers for similar flows.

The rotating wind at the collecting shed’ s central outlet is essentially a buoyant jet, primarily determined by buoyancy, inertial, and viscous forces. Based on trial calculations, the rotating wind in this study is turbulent, so viscous forces can be neglected. We adopt the Froude number (Fr), the ratio of inertial to buoyant forces, as the similarity criterion, as shown 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 value at a certain moment after flow field stabilization is used here since the shed structure remains unchanged and flow field characteristics are similar), 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 of different scales are similar, their Fr numbers must be equal. Accordingly, the relationship between the characteristic velocity ratio δu and characteristic size ratio δL for flows at two different scales should satisfy equation (3):

$$\delta u = (\delta L)^{1/2}$$

Thus, characteristic velocity values and characteristic size values satisfy a certain exponential relationship. This paper uses the same pre-rotation incident angle for the collecting shed while only changing its scale (radius of 2 m, 20 m, and 200 m). Based on experimental and simulation values for the 2 m radius condition and simulation values for the 20 m and 200 m conditions, we can obtain the relationship between collecting shed radius and total wind speed values under certain conditions.

3.2 Outlet Flow Field and Influencing Factors

After the calculation process reaches stability, we focus on the velocity field distribution near the central cylindrical induced wall outlet. In our research, we aim to utilize the total kinetic energy of the outlet wind field, making the velocity distribution in the resultant velocity field more significant. Figure 5 Figure 5: see original paper shows the resultant velocity field distribution obtained from the model in Figure 2(a). The cut-in wind speed for general low-speed wind turbines is 3 m/s [11], and the resultant velocity values within the dashed box all exceed 3 m/s, again demonstrating that the system can generate wind speeds sufficient to drive low-speed wind turbines. Figure 5(b) shows the tangential velocity vector field on the A-A cross-section at the induced wall outlet, i.e., the rotational velocity vector field, proving that the inlet airflow, after pre-rotation through the guide vanes, forms a swirling upward rotating wind at the central induced wall outlet.

Figure 6 [Figure 6: see original paper] shows the variation trend of generated velocity with heating temperature difference under different incident angles. Wind speed values increase with increasing heating temperature difference. Larger vane curvature corresponds to smaller inlet incident angles but provides more sufficient pre-rotation, resulting in higher tangential rotational wind speed values. For resultant velocity values, due to velocity losses from sufficient pre-rotation, the variation trend is opposite to that of rotational wind speed values. We require higher resultant velocity values, but sufficient airflow rotation can effectively increase wind energy density. Among the three groups, while the 60° case yields the maximum resultant velocity value, its rotational wind speed value is too small. Comparing 30° and 0°, although the 0° case has slightly higher rotational wind speed, the values are very close, while the 30° case has a slightly higher resultant velocity value than the 0° case. This conclusion indicates that with approximately equal energy density, the 30° case provides higher resultant velocity (i.e., greater total kinetic energy at the outlet), making 30° the more suitable inlet incident angle among these three angles.

3.3 Preliminary Application Prospects Analysis

When the collecting shed radius is 2 m, 20 m, and 200 m, combined with similarity criterion analysis and simulation values at these scales and referencing the analysis method in literature [12], this paper plots the curves shown in Figure 7 Figure 7: see original paper. The significance of these curves lies in defining, after determining the pre-rotation vane incident angle and collecting shed heating temperature difference range, the size range of collecting sheds that can generate maximum wind speeds above 3 m/s, providing technical reference for future selection of structural and operational parameters for this type of collecting shed.

Meanwhile, with humanity' s exploration of space and advancements in manufacturing technology, this energy system is expected to be realized on Mars in the future. Mars' characteristics make it more suitable for this system' s operation than Earth. First, Mars has larger space for manufacturing and installing collecting sheds. Second, Mars' surface is primarily desert with low specific heat of sand and stone, and its thin atmosphere results in much larger day-night temperature differences than Earth, enabling greater rotating winds from larger temperature differences. This system also demonstrates advantages on Mars: humans could live inside the vane region, and with existing solar collection conditions plus temperature-humidity control and air generation devices, habitable conditions could be obtained inside the vanes. Furthermore, the rotating wind energy from the collecting shed' s central outlet and the electricity from solar panels could directly serve as energy sources for humans living inside the vane region.

Using Mars' meteorological conditions (temperature, pressure, atmospheric density, etc.) as initial conditions and following the method used to obtain the curves in Figure 7(a), we derived the collecting shed diameter-maximum wind speed curves for Mars shown in Figure 7(b). The significance of these curves is that after confirming the suitable cut-in wind speed for Mars-adapted wind turbines, the corresponding collecting shed diameter size range for usable wind speeds can be determined.

4 Conclusions

This paper investigates the structural parameters of the collecting shed—the core component in a novel whirlwind energy system—through numerical simulation and experimental analysis, yielding the following conclusions:

1) By providing heat sources and inlet pre-rotation, a stable upward rotating

wind field can be formed at the collecting shed outlet, and when the collecting shed reaches a certain scale, the generated wind field is sufficient to drive low-speed wind turbines.

2) Increasing the heating temperature difference can improve wind speed values in the rotating wind field. For pre-rotation angles, smaller inlet incident angles (greater vane curvature) provide more sufficient pre-rotation that increases rotational wind speed values (tangential velocity), while the variation pattern of resultant wind speed values is opposite. For this system, heating temperature should be maximized as much as possible, and an appropriate vane inlet incident angle should be selected—neither too large nor too small.

3) The size ranges of collecting sheds that generate usable wind speeds under Earth and Mars environments for certain heating temperature difference ranges were obtained, providing a preliminary assessment of the system' s application prospects.

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Note: Figure translations are in progress. See original paper for figures.