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# Effect analysis on power coefficient enhancement of a convective wind energy collecting device in the expressway

Wenyu Hu[a,b], Jiaqiang E[a,b,c,*], Yuanwang Deng[a,b,c,*], Lijun Li[d], Dandan Han[a,b], Xiaohuan Zhao[a,b], Zhiqing Zhang[a,b], Qingguo Peng[a,b]

[a] *State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China*
[b] *College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China*
[c] *Institute of New Energy and Energy-saving & Emission-reduction Technology, Hunan University, Changsha 410082, China*
[d] *College of Electrical and Mechanical Engineering, Central South University of Forestry and Technology University, Changsha 410082, China*

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ABSTRACT

The purpose of this paper is to study the equipment parameters of expressway convective wind energy collection devices and determine the optimal structural parameters by numerical methods. Firstly, the characteristics of convection wind energy and flow field on the expressway are analyzed and the principle of wind energy utilization is determined. Based on traditional resistance wind turbines, two different blades of the device are designed and developed. Some structural parameters (such as blade height and the number of blades) of the device are discussed based on the flow field characteristics. Secondly, the device is numerically simulated using Star CCM+ software, and the optimal structural parameters are determined based on the power coefficient. Thirdly, the proposed numerical analysis method is verified and indirect verification is used to determine the most suitable turbulence model and grid independence based on the similarity principle. Based on the above research results, the experimental verification is used to determine the high reliability of the simulation model. Finally, the simulation results between the Rectangular turbine and the Savonius turbine are compared and obtained. The results show that the device is useful for the wind energy usage, wind energy conversion and the wind resistance reduction of the opposite vehicle. At the same time, when the inlet wind speed is 15 m/s, the tip speed ratio (TSR) is 1.4, the device is rectangular turbine (RT), the height of blade is 1.55 m, the number of blades is 4, and the maximum power coefficient $C_p$ is 0.363.

## 1. Introduction

With the development of the times, the expressway has become the most important mode of transportation in people's daily life. With the increase of vehicle ownership, the popularization of driver's license and the acceleration of life pace, more and more vehicles run on the expressway. The average speed of vehicles on the highway is 100 km/h. Because of the closed structure of the highway, the vehicle cannot be turned around, which formed a high-speed convection traffic [1]. High-speed cars will make the air around them move quickly, thus this form high-speed convection wind energy [2]. If this energy can be collected and used to solve the problem of dust pollution and tail gas pollution caused by large traffic flow on the expressway, the driving environment of the freeway can be effectively improved and the peripheral pollution can be reduced [3]. The extra power was delivered to nearby service station. This wind energy can greatly improve power supply of service stations of expressway [4]. A smart energy management system was created to make this energy into Grid [5]. Similarly, the theory of convection wind energy also could be used at subway, and the energy may deliver to subway station [6]. Moreover, because the wind energy generated during the driving of the vehicle is the work done by the vehicle to overcome the wind resistance, this part of the work is also a part of the energy generated by the engine using the fuel [7]. Therefore, collecting and utilizing this energy are also indirectly energy savings and emission reduction [8]. Finally, due to the effect of the reaction force of the collecting device, wind energy on one side of the expressway could be passed through the device to the other side, and the same direction as the other side of the vehicle [9]. Wind resistance will be reduced effectively, and the dynamics and economy of the vehicle will be enhanced indirectly [10].

Wind energy is one of the cleanest and pollution-free renewable energies [11]. With the development of wind power, a variety of wind power plants were now available [12]. For example, wind power devices with Megawatt level [13] were used in mountainous region and

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* Corresponding authors at: State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China.
*E-mail addresses:* ejiaqiang@hnu.edu.cn (J. E), dengyuanwangt@hnu.edu.cn (Y. Deng).

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**Nomenclature**

| | |
|---|---|
| $C_p$ | output power coefficient |
| $C_T$ | torque coefficient |
| $D$ | diameter of rotor, m |
| $D_1$ | cap diameter of experimental modal, m |
| $D_e$ | diameter of experimental modal, m |
| $d$ | diameter of blade of experimental modal, m |
| $e$ | overlapping distance of experimental modal, m |
| $G_b$ | turbulent kinetic energy due to buoyancy |
| $G_k$ | turbulent kinetic energy generated by velocity gradient |
| $H$ | height of blade, m |
| $H_1$ | height of experimental modal, m |
| $H$ | height of blade from the ground, m |
| $I$ | number of blades |
| $k$ | turbulent kinetic energy |
| $n$ | number of experiments |
| $\bar{p}$ | static pressure, N |
| $R$ | arc radius, m |
| $r$ | displacement vector, m |
| RT | rectangular turbine |
| $S_\varepsilon$ | hypothetical source term |
| $S_1$ | distance of the blades from the center of the circle, m |
| ST | Savonius turbine |
| $S_{u_i}$ | Centrifugal Coriolis force, N |
| $t$ | time, s |
| $T$ | rotational moment, N·m |
| TSR | tip speed ratio |
| $u$ | velocity of the fluid in the flow field, m/s |
| $u_j$ | velocity component |
| VAWTs | vertical axis wind turbines |
| $x_i$ | $x$, $y$ and $z$ directions when $i = x, y, z$ respectively |
| $x_j$ | $x$, $y$ and $z$ directions when $j = x, y, z$ respectively |
| $Y_M$ | effect on the overall dissipation rate of the expansion in a compressible turbulent flow |

*Greek letters*

| | |
|---|---|
| $\varepsilon$ | dissipation rate of turbulent kinetic energy; |
| $\lambda$ | tip speed ratio |
| $\mu$ | viscosity, Pa s |
| $\mu_t$ | turbulent viscosity |
| $\rho$ | density of the air, kg/m$^3$ |
| $\sigma_k$ | constant for the standard k-Epsilon model |
| $\overline{\tau_{ij}}$ | stress tensor |
| $\Omega$ | rotational angular velocity of the blade, rad/s |
| $\bar{\Omega}_{ij}$ | time-averaged rotational tensor |
| $\omega_k$ | relative angular velocity of coordinate system |

street lights of the wind power [14] were used in campus and road. In commonly wind turbines, Darrieus is lift wind turbines, and Savonius is resistance wind turbines [15]. Under the natural wind, there has been a lot of research on the vertical axis wind turbines (VAWTs). For Darrieus, Rezaeiha et al. [16] studied the relationship between the diameter and the roughness of the shaft and turbine speed, which increase the power coefficient as much as possible. Afterwards, Rezaeiha et al. [17] found that the elevation angle can increase the power coefficient by 6.6%, and accurate CFD simulations of different tip speed ratio (TSR) and firmness were also made by Rezaeiha et al [18], providing guidelines for follow-up studies. Wang et al. [19] studied the blade may be automatically modified, which may inhibit the flow separation blade surface. Nidal et al. [20] studied a foldable and re-mounted wind turbine, and verified the numerical analyses by the experimental data. For Savonius, the earliest use is in hydroelectric power [21]. Because of the similarities between hydraulic and wind power and its simple structure, Savonius rotor had application in wind power generation [22]. There are many similarities between them. Golecha et al. [23] studied the influence of the baffles on *S*-type hydroturbine, and determined its optimal position. Elbatran et al. [24] studied a nozzle pipe hydroturbine, the principle is similar to the baffles, which can improve the speed of low flow area, and enhanced the power coefficient. Tahani et al. [25] studied the wind turbine which owns flow conductivity. In addition to studying flow conductivity, there are researches that change the shape of the rotors. For instance, Sharma et al. [26] used multiple quarter-leaves to increase the power coefficient. Moreover, Sharma et al. [27] also added concentric multiple micro-blades to the basic structure to improve performance. Kumar et al. [28] found that the Savonius fluid-powered turbines have the maximum power coefficient at a twist angle of 12.5°. After then this team [29] subsequently confirmed that when the blade radian is 150° and the blade shape factor is 0.6, the turbine power coefficient is 0.426. Tian et al. [30] improved the optimization procedure for different concavo-convex surfaces and developed the blade shape with strong tip eddy and reclaimed flow. Tartuferi et al. [31] proposed a new type of airfoil blade shape, and conducted experiments to verify that its power coefficient improved significantly. In addition to the study of shapes, Li et al. [32] researched the influence of the number of blades on the aerodynamic force of the vertical axis wind turbine, and concluded that the power coefficient decreased with the increase of the number of blades. Frikha et al. [33] studied multi-stage Savonius rotors, and concluded that the dynamic torque coefficient and power coefficient increase with the number of stages. And Driss et al. [34] studied unconventional leaves and draws the best efficiency for blades with an angle of 130°. Besides above-mentioned research, there were also studies of air flow factors. Team of Driss [35] also studied incident angle of wind and found maximum turbulent kinetic energy at 45° and 90° respectively. Roy et al. [36] studied clogging factor in wind tunnel experiments and found that the blocking effect of the open test part is almost negligible. Driss et al. [37] researched a small incurved Savonius wind rotor and improved Savonius rotor design. Zhang et al. [38] developed a novel wake energy reuse method and optimized the layout of Savonius turbines. After the basic research, there was much follow-up research. Sarma et al. [39] compared the differences between hydraulic machines and wind turbines at low speeds and found the reason for the improvement in performance. Koy et al. [40] did the unsteady analyses of wind turbine momentary forces and moments. Wen et al. [41] studied the process of ring induction heating and greatly reduced the temperature inhomogeneity by changing the start and end positions of heating. There were many research on the Savonius working conditions have been studied. Goodarzi et al. [42] found energy-saving effect using *S* wind turbines in the vicinity of radiators of naturally ventilated and dry cooling towers. Lee et al. [43] studied the effect of wind direction on S wind turbine on the roof of a building and determined the better direction. Goh et al. [44] determined the best performing wind speed by dragging and dropping the wind turbine on the roof of a building. There were different methods for *S*-type wind turbines simulation, for example, Ferrari et al. [45] simulated the *S*-type wind turbine using the open source OpenFOAM, Ducoin et al. [46] used the open source Nek5000 to simulate the *S*-type wind turbine, and Chong et al. [47]