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ORIGINAL ARTICLE

Geometrical optimization of a swirling Savonius wind turbine using an open jet wind tunnel

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Abstract It has been suggested that waste heats or naturally available heat sources can be utilized to produce swirling flow by a design similar to that of split channels which is currently used to initiate fire whirls in laboratories. The new design combines the conventional Savonius wind turbine and split channel mechanisms. Previous computational and preliminary experimental works indicate a performance improvement in the new design (named as swirling Savonius turbine) compared to the conventional Savonius design. In this study, wind tunnel experiments have been carried out to optimize the swirling Savonius turbine geometry in terms of maximum power coefficient by considering several design parameters. The results indicate that the blade overlap ratio, hot air inlet diameter and the condition of the top end plate have significant influence on power and torque coefficients, while a larger aspect ratio and closed top end plate have some favourable effects on the performance. The optimum configuration has been tested in four different wind velocities to determine its influence on the performance, and power coefficients were found to be higher in high wind velocities. The performance comparison of optimum configuration with conventional Savonius rotor showed an increase of 24.12% in the coefficient of power.

1. Introduction

Being an energy source of low impact on the environment, low effects on health, and negligible safety issues, the demand for wind power has been increasing exponentially in recent years [1]. Moreover, wind energy is abundantly available in the Earth's atmosphere, can be locally converted, and can thus help in reducing our reliance on fossil fuels. Until now, Horizontal Axis Wind Turbines (HAWTs) have played a primary role in response to this demand. The HAWTs can provide large power outputs, but it needs greater wind velocities and often generates low-frequency noise that can be harmful. In contrast, Vertical Axis Wind Turbines (VAWTs) are free from these environmental problems, resulting in the recent expansion of their use in urban environments. Savonius turbine is known as the most quiet wind power source among the wind turbines because the blades run at a speed of the same order as the wind velocity e.g. tip speed ratio $\gamma \approx 1$ [2]. Therefore, it can be employed to generate on-site electricity in city

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Nomenclature

C_P	coefficient of power
C_T	coefficient of torque
d	hot air inlet diameter (m)
d_w	nylon wire diameter (m)
D	diameter of rotor (m)
D_{ep}	end plate diameter (m)
D_{sh}	shaft diameter of rotor (m)
e	blade overlap distance (m)
H	height of rotor (m)
ID	inside diameter of blade pipe (m)
OD	outside diameter of blade pipe (m)
P	mechanical power (W)
Re	$(=\frac{UD}{\upsilon})$ Reynolds number
S	spring balance reading (N)
T	rotor torque (Nm)
U	wind velocity (m/s)
W	dead weight of dynamometer (N)

Greek letters

β	$(=\frac{e}{ID})$ blade overlap ratio
γ	tip speed ratio
ε	relative uncertainty
θ	blade tip extension angle (deg)
υ	kinematic viscosity (m^2/s)
ρ	air density (kg/m^3)
ω	angular velocity (rad/s)

Subscripts

ep	end plate
P	power
sh	rotor shaft
T	torque
w	wire

environments. The turbine also easily starts to rotate at low wind speeds because the differential drag on the two blades produces the torque. This allows the turbine to rotate not only at the top of high-rise buildings but also at street level in a city. As there are no severe restrictions on blade material, the manufacturing process is easy to realize on-site using on-site materials [3].

On the downside, Savonius turbines are widely considered as drag-driven devices [4]. The power extraction efficiency (power coefficient, C_p) from the wind is typically less than half of the efficiency of HAWTs and there are a number of geometrical parameters that affect this efficiency. Among the geometrical parameters of conventional Savonius rotors, the optimum overlap ratio value has been found as 0.15 by Fujisawa [5] in an experimental study, and Akwa et al. [6] in a numerical investigation. Open jet wind tunnel experiments at this value of overlap ratio and an aspect ratio of 1.0 have been reported to have a maximum power coefficient of 17.3% by Fujisawa and Gotoh [7] and 17% by Kamoji et al. [8]. This value corresponds to only one-third of maximum ideal power coefficient of 59.3% (Betz's limit). However, it has been observed that, at low angles of attack, the lift force also contributes to the overall torque generation [6,9,10]. Thus, it can be concluded that the Savonius rotor is a combination of a drag-driven and a lift-driven machine. Therefore, it can go beyond the limit of power coefficient of purely drag-driven devices which is 8% [11].

Continual efforts are being made to improve the coefficient of power either by examining the effects of various design parameters, by incorporating additional features, or by modifying the shape of conventional Savonius rotors. The number of rotor blades has significant effect on Savonius rotor performance [12]. Wind tunnel experiments show that the three blade rotor is inferior to the two blade rotor, while the performance of two stage rotor is superior to the single stage rotor [13,14]. Kamoji et al. [15] in an experimental study concluded that, double-step and three-step rotors are slightly superior to the corresponding single-step rotor in self-starting, but lower for both torque and power characteristics. Further investigation on the single stage and three stage rotors in an open jet wind tunnel by Hayashi et al. [16] concluded that the static and dynamic torque variations in one revolution of three stage rotor are positive and smoother in comparison with the single stage Savonius rotor but that the aerodynamic coefficients of three stage rotors were much smaller than single stage rotors.

An Investigation on modified Savonius rotors was reported by Modi and Fernando [10] to have a maximum power coefficient of around 32% based on closed jet wind tunnel testing. Menet [17] proposed a modification of Savonius rotor using three geometrical parameters which has maximum values of static torque much higher than conventional rotor. Kamoji et al. [18] examined the influence of the end plates and the central shaft on a single stage modified Savonius rotor and found that the power coefficient rose up to 21% with the best combination. Mahmoud et al. [19] confirmed higher coefficient of power when end plates were used. Experiments on twisted Savonius rotor showed better performance than conventional semicircular rotor, but sensitive to Reynolds number [1,13]. Saha and Rajkumar [20] confirmed that the twisted blades in the vertical direction provide a better performance (13.99%) than conventional cylindrical blades (11.04%) at low air speeds. Reupke and Probert [21] performed dynamic-torque tests for Savonius wind rotor with hinged blades to improve the performance of the rotor. Roy and Saha [22] conducted wind tunnel experiments on a newly built two-bladed turbine and compared its performance with semi-circular, semi-elliptic, Benesh and Bach type bladed turbines that demonstrate a gain of 34.8% in maximum power coefficient compared to the conventional bladed Savonius turbine.

Another area of improvement presented by Ushiyama et al. [23] is the introduction of wind collection equipment to the space around Savonius wind turbines. Surrounding the turbine with a guide box succeeded in raising the power coefficient by up to 123% for two-blade and 150% for three-blade models relative to the original models reported by Irabu and Roy [24]. Mohamed et al. [25] placed an obstacle plate in front of

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