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Design and numerical investigation of Savonius wind turbine with discharge flow directing capability

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ABSTRACT

Recently, Savonius vertical axis wind turbines due to their capabilities and positive properties have gained a significant attention. The objective of this study is to design and model a Savonius-style vertical axis wind turbine with direct discharge flow capability in order to ventilate buildings. For this purpose, a modeling procedure is defined and validated using available experimental results in literature. In addition, two design modifications, variations in cross-section with respect to the height of rotor and conical shaft in the middle of wind rotor are proposed. The variable cut plane changes the pressure in inner region of rotor and enhances the discharge flow rate. However, this increases the negative torque acting on returning blade thus reducing the power coefficient. The inlet flow to Savonius wind rotor goes along the surface of conical shaft and is diverted to lower pressure in order to improve the discharge flow rate. Results indicate that the twist on Savonius wind rotor reduces the negative torque and improves its performance. According to the results, a twisted Savonius wind turbine with conical shaft is associated with 18% increase in power coefficient and 31% increase in discharge flowrate compared to simple Savonius wind turbine. Also, wind turbine with variable cut plane has a 12% decrease in power coefficient and 5% increase in discharge flow rate compared to simple Savonius wind turbine. Therefore, it can be inferred that twisted wind turbine with conical shaft indicated a proper aerodynamic performance.

1. Introduction

Fossil fuels pollution and their eventual resources depletion, creates an important challenge to reduce the emissions by applying alternative renewable energies. Wind energy has gained a significant attention in developed countries in comparison with other renewable energies, due to their better performance. Advantages such as being clean, having negligible safety issues and sustainable resources make wind energy one of the fastest-growing energy resources of the world.

Wind turbine is one of the most common ways of capturing wind energy for the purpose of producing power. Generally, these turbines are categorized in two types: vertical and horizontal axis turbines. The Savonius wind rotor is a vertical axis wind turbine patented by the Finnish engineer Siguard Savonius in 1925 [1]. It is a drag driven wind turbine. While operating, in certain angular position of the rotor, and while the tip speed ratio is greater than one, the lift force acts on blades [2]. The Savonius wind turbine has several advantages such as low manufacturing cost, good self-starting capability, low noise emission which is suitable for urban areas and low dependency on the wind direction. Many applications can be considered for Savonius turbines including but not limited to pumping water for irrigation, local electricity generation for low demands, heating, ventilation and air-conditioning in buildings and hybrid renewable energy systems [3–7]. Another type of vertical axis wind turbines are H-type rotors which are being widely utilized in several places. The focus of this research study is Savonius type wind turbines, therefore the literature review of H-type rotors is just summarized in Table 1.

Numerous experimental and numerical investigations have been carried out to enhance the performance of the Savonius rotor due to the relatively lower efficiency of this turbine compared with other turbines. The Savonius rotor performance is presented by two aerodynamics coefficients: the power coefficient (C_P) and torque coefficient (C_T). These terms depend on various design parameters

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Nomenclature

C_P	Power coefficient
C_T	Torque coefficient
TSR	Tip speed ratio
d	Chord length of blade (m)
D	Overall diameter (m)
D_e	End plate diameter (m)
e	Overlap distance (m)
H	Height of the blade (m)
ω	Rotating speed of rotor (rpm)
P	The static pressure (pa)
$\rho \vec{g}$	The gravity force (N)
$\bar{\bar{\tau}}$	The stress tensor
μ_T	Eddy viscosity (mm^2/s)
C_{Ts}	Static torque coefficient
T	Dynamic torque (N.m)
ρ	Air density (kg/m^3)
A	Swept area of the turbine (m^2)
V	Velocity of free stream wind (m/s)
R	The radius of turbine (m)
T_s	Static torque (N.m)
$P_{turbine}$	The power produced by the turbine (w)
$P_{availabe}$	The power available in the wind (w)
R^2	Correlation coefficient
α	Twist angle (degree)
H_c	Height of conical shaft (m)
D_c	Conical shaft diameter (m)

Table 1
The literature review for H-type vertical axis wind turbines.

No.	Reference	Topic
1	Chong et al. [8]	Utilization of adaptive neuro-fuzzy methodology for the purpose of estimating the wind turbine rotational speed.
2	Zuo et al. [9]	Investigating the wake effect of a H-type vertical axis wind turbine on the downstream turbine using numerical simulations.
3	Li et al. [10]	Experimental investigation of the effect of flow field and aerodynamic forces on the turbine
4	Li et al. [11]	Experimental and numerical investigation of the aerodynamic loads on a two bladed vertical axis wind turbine
5	Li et al. [12]	Experimental and numerical investigation of the flow field on a two bladed vertical axis wind turbine
6	Li et al. [13]	Investigating the influence of number of blades on the aerodynamic forces of a vertical axis wind turbine

such as tip speed ratio (TSR), the aspect ratio (height of blade to diameter of blade), the overlap ratio, number of blades, the impact of end plates on aerodynamic performance, the rotor twist angle and cross-section profile [14]. Several researchers investigated these parameters to improve the aerodynamic performance of Savonius turbine [15–19]. Kianfar et al. [20] studied the effect of blade curve on the power coefficient of Savonius wind rotor by means of numerical simulation and compared it with wind tunnel tested results. Saha et al. [21] assessed the aerodynamic performance of single-, two-, and three-stage Savonius rotor systems. Both semicircular and twisted blades have been used in their investigations. Mahmoud et al. [22] compared different geometries of Savonius wind turbine to determine the most effective operation parameters. They reported that two-blade rotor is more efficient than three and four-blades and the rotor with end plates has a higher efficiency. Also, double stage rotors without overlap ratio have a higher performance. Moreover, Rashidi et al. [23] studied the effect of blade number on three different scaled-down helical Savonius vertical axis wind turbines systems performance. Driss et al. [24] studied the incidence angle effect on the aerodynamic structure of an incurved Savonius wind rotor. In this study, the numerical model was based on the Navier-Stokes equations in conjunction with the standard k-ε turbulence model. Soo Jeon et al. [25] experimentally studied the effects of the end plates with various shapes and sizes on the aerodynamic performance of helical Savonius wind turbines. Their results indicated that by increasing the end plate area ratio up to 1.0, the power coefficient and its tip speed ratio also will increase.

Augmentation techniques can be used to improve the performance of Savonius wind rotor. Accordingly, several significant efforts have been done on numerical and experimental investigations to achieve an optimized geometry. Tartuferi et al. [26] enhanced the Savonius wind rotor aerodynamic performance with two approaches which was based on developing innovative airfoil-shaped blades. Altan and Atilgan [27] designed a curtain to increase the performance of the Savonius wind rotor and experimental and numerical analysis was carried out on the static rotor performance equipped with this curtain. In addition, they introduced a new curtaining arrangement to improve the Savonius wind turbine performance. This curtain arrangement prevents the negative torque which is opposite to the direction of rotation [28,29]. During the rotation of the rotor, this negative torque constantly acts on the returning blade, in the flow direction. Twist of the Savonius wind turbine is one of the practical solutions to overcome this problem [30]. Saha and Rajkumar [31] investigated the feasibility of twisted bladed Savonius rotor for power generation. Their Experimental results indicated that the twisted bladed rotor shows a better smooth running, self-starting ability and higher efficiency compared to the conventional rotor. Kamoji et al. [32] tested a helical Savonius rotor with a twist of 90° in an open jet wind tunnel to measure the coefficient of static torque, coefficient of torque and coefficient of power. The results indicated that the helical Savonius rotor has a positive static torque coefficient at all the rotor angles. Driss et al. [33] carried out the numerical investigations to study the bucket design effect on the turbulent flow around unconventional Savonius wind rotors which results indicated that the bucket design has a direct effect on the local characteristics.

Many researchers obtained innovative geometries to provide an effective wind rotor with high capabilities [34–36]. Roy and Saha [37] designed a novel developed two-bladed Savonius-style wind turbine which evolved from a series of experiments on different types of blades. Their investigation demonstrated a maximum power coefficient of 34.8%. Shaheen et al. [38] studied the development of a multi-turbine cluster for construction of efficient Savonius wind turbine farms and performed numerical investigations on a single Savonius wind turbine, clusters of two turbines in parallel and oblique positions, and triangular clusters of three wind turbines. Mohamad et al. [39] studied a considerably