J. Wind Eng. Ind. Aerodyn. 156 (2016) 1–13

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/indaer

CFD based synergistic analysis of wind turbines for roof mounted integration

P. Larin [a], M. Paraschivoiu [a,*], C. Aygun [b]

[a] Concordia University, Quebec, Canada
[b] Gaza University, Ankara, Turkey

ARTICLE INFO

Article history:
Received 23 March 2016
Received in revised form
24 June 2016
Accepted 25 June 2016

Keywords:
Savonius wind turbine
Cup type turbine
Buildings
Efficiency
Power coefficient
Computational fluid dynamics

ABSTRACT

The increasing global demand for energy and environmental concerns have provoked a shift from exhaustible, fossil fuel based energy to renewable energy sources. It is clear that wind energy will play an important role in satisfying our current and future energy demands. In this paper, a horizontal configuration of a Savonius wind turbine is proposed to be mounted on the upstream edge of a building, in such a way that its low performance is improved by taking advantage of the flow acceleration generated by the edge of the building. The importance of integrated simulations which include both the building and the turbine is shown and it is also demonstrated that the individual calculations of the flow around the building and the turbine individually cannot be superposed. Following the validation of our methodology with experimental data, we calculate the performance of the Savonius wind turbines placed in the vicinity of the edge of the building top. The position, blade number, and circumferential length are then investigated when the turbine is mounted on a building. The objective is to better understand wind turbine behavior for low speed urban environments. The flow fields of conventional Savonius and cup type turbines are solved using Computational Fluid Dynamics (CFD) in 3D domains. The optimal configuration shows an improvement in the power coefficient from 0.043 to 0.24, representing an improvement of 450%. The improvement also demonstrates that although cup type blades show very poor performance in free stream flow, they perform well in the right environment.

1. Introduction

It is a well-known fact that diminishing global fossil fuel reserves combined with mounting environmental concerns require the modern world to focus on the development of ecologically compatible and renewable energy resources (Paraschivoiu, 2002). Furthermore, it is known that there is a strong worldwide reluctance to building new nuclear power plants to mitigate the growing energy deficiency, mostly due to perceived safety and environmental concerns.

From an environmental perspective, wind energy is a clean, emission free source of electrical power. Over the life cycle of a wind turbine, only a small amount of greenhouse gases (GHGs) are associated with the manufacturing and processing of raw materials. During the energy generating stage of a wind turbine's life, no GHGs are produced. Wind turbine farms have become the norm in term of wind energy production but the efficiency of each turbine does suffer from interaction effects due to the close longitudinal as well as the lateral separation distance between turbines (McTavish et al., 2015).

This paper focuses on distributed energy production in particular in urban environments. For such locations Savonius Vertical Axis Wind Turbines (VAWTs) offer an interesting alternative because these turbines can start at low wind speeds and in highly turbulent flows. In the late 1920s, S.J. Savonius, a Finnish engineer, developed a vertical axis wind turbine which he patented in 1927. The conventional Savonius wind turbine is a drag based device with cup like blades in an S shape (Savonius, 1931). The shape is obtained by cutting a cylinder and sliding the half cylinders along the cutting plane creating an S shaped turbine with a slight overlap. The shape can be seen in Fig. 1.

In comparison with other VAWT, such as Darrieus or Gyro Mill type, or Horizontal Axis Wind Turbines (HAWT), the Savonius turbine presents a low power coefficient (C_p), around 0.15 as reported in Sukanta and Ujiwal (2013). Nevertheless, they remain attractive due to their self-starting capabilities at low wind speed, simplicity, low cost, and their independence relative to wind direction. The self-starting capability and independence relative to wind direction make VAWTs particularly attractive in urban environments. A review of the performance of Savonius wind turbines is presented by Akwa et al. (2012). They stated that the

* Corresponding author.

http://dx.doi.org/10.1016/j.jweia.2016.06.007
0167-6105/

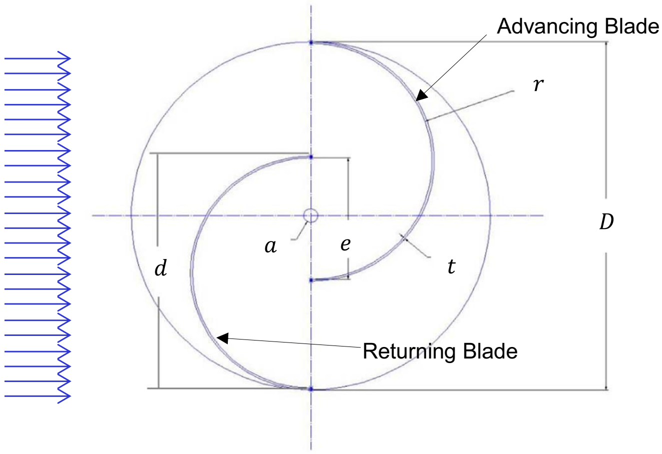

Fig. 1. Conventional Savonius geometry.

application of Savonius turbines for obtaining useful energy from wind is an alternative to the use of conventional wind turbines. Also, VAWTs are more easily maintained due to their smaller size and the fact that the alternator and gearbox can be placed on the ground.

The tip speed ratio (TSR) of the turbine is defined by the following equation.

$$\mathrm{TSR} = \frac{\omega R}{U} \tag{1}$$

where ω is the angular velocity of the turbine, R is the radius of the turbine, and U is the free stream velocity.

The coefficients of moment and power are defined by the following equations.

$$C_m = Moment\ Coefficient = \frac{M}{\frac{1}{2}\rho U^2 AR} = \frac{M}{\rho U^2 HR^2} \tag{2}$$

and

$$C_p = Power\ Coefficient = \frac{M}{\frac{1}{2}\rho U^3 A} = \frac{P}{\rho U^3 RH} = C_m * \mathrm{TSR} \tag{3}$$

where P is mechanical power, H is the height of the turbine, M is the moment created by the wind about the axis of rotation, A is the swept area, and ρ is the density of the fluid.

The TSR, C_m, and C_p are dimensionless parameters that take incoming wind speed and size of the turbine into consideration such that turbines of different sizes and turbines in different wind conditions can be compared.

A comparison of the experimental results obtained by different research groups is presented in Sukanta and Ujiwal (2013). For experiments using a single stage conventional Savonius turbine with no external geometries to increase power, the average C_p reaches 0.167. More recently, numerical simulations to predict wind turbines' behavior have become more reliable due to larger computational power (Naghib Zadeh et al., 2014). For that reason, CFD simulations of Savonius VAWTs would be beneficial in the optimization of their designs and to analyze their interaction with buildings.

As scientific attention is now also considering energy generation under special conditions such as in low wind or water current speeds, in urban areas, or in shallow tidal basins, many new turbine configurations are reported and investigated. Altan and Atilgan designed a curtain to increase the low performance of a Savonius wind turbine with a vertical axis and they analyzed the effect of this curtain experimentally and numerically. It was found that a considerable increase is acquired in the absolute values of static torque with longer curtain dimensions (Altan and Atilgan, 2008), pointing out that Savonius turbines appear to be particularly promising for the conditions of low speeds and urban areas, but suffers from poor performance efficiency. Mohamed et al. (2011) proposed a considerably improved design to improve the output power of a Savonius turbine as well as to obtain better self-starting characteristics. An obstacle shielding the returning blade of the turbine is used and its orientation is optimized. In a separate study, they additionally optimized the blade shape to further improve the output power and the self-starting capability of the turbine in the presence of the obstacle plate. They reported a maximum increase of the power coefficient by almost 40% (Mohamed et al., 2011), compared to a standard Savonius turbine.

The investigation of flow around buildings and the influence of building shape have been studied to better understand how buildings can affect flow. Abohela et al. showed the effect of roof shape on the flow (Abohela et al., 2011). They concluded that for all investigated roof shapes, there is an acceleration of flow, but the lowest position a turbine should be placed is 30% of the building height above the building, and for a building with a flat roof, the turbine should be placed 35% to 50% of the building height above the building (Abohela et al., 2011). They also claimed that a roof mounted turbine has the potential to produce 56% more power than a free stream turbine. One of the primary novelties in this study is that the building and turbine are included in the same simulation whereas the simulations in the previously mentioned literature does not include the turbine on the roof. To obtain more accurate predictions of the potential improvements in power, the turbine and the building must be included in the simulation as the turbine can significantly change the flow characteristics around the building both upstream and downstream.

The choice of turbulence models in CFD simulations of wind turbines is an important parameter to consider. Many research groups have investigated the differences between the results obtained with different turbulence models, but the conclusions vary largely. Song et al. (2015) presented that the realizable $k-\epsilon$ turbulence model obtained the closest results to experimental data. This was the chosen model for Mohamed and Thevenin (2010) and Mohamed et al. (2011) as well as for Zhou and Rempfer (2013). Yaakob et al. used the standard $k-\epsilon$ model for their simulation in Yaakob et al. (2012) along with Altan and Atilgan (2010). Several different turbulence models such as the Spalart-Allmaras (SA), standard $k-\epsilon$, realizable $k-\epsilon$, Re-Normalization Group (RNG) $k-\epsilon$, and $k-\omega$ were compared by Rogowski and Maronski (2015). They found that the SA turbulence model was satisfactory for the purposes of their work. Akwa and da Silva (2012) used a more computationally expensive model, the $k-\omega$ *Shear Stress Transport* (SST) turbulence model, similar to Kacprzak et al. (2013), and Sagol et al. (2012). Furthermore, Dobrev and Massouh (2006) presented results for simulations run using the $k-\omega$, $k-\omega$ SST, and hybrid *Detached Eddy Simulation* (DES)/$k-\omega$ SST, and showed that the DES/$k-\omega$ SST was the most appropriate and used said model again in Dobrev and Massouh (2012). The different conclusions found in literature concerning the most accurate model for simulation of drag based turbines show that the choice of turbulence model is slightly case dependent. Hence, it is concluded that the choice of turbulence model and wall function should be further investigated for the specific conditions studied in this paper. Due to significant time and computational resource investments required for hybrid models, such as the DES/$k-\omega$ SST, or higher accuracy models, such as Large Eddy Simulation (LES), known to obtain reliable results, only one and two equations models are investigated.

In our study, the rotation axis of a Savonius turbine is tilted horizontally and placed at different locations on the building to identify the location that provides the best performance. Cup type