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Wind turbine designs for urban applications: A case study of shrouded diffuser casing for turbines

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ABSTRACT

The increased demand for renewable energy and the development of energy independent building designs have motivated significant research into the improvement of wind power technologies that target urban environments. However, the implementation of wind turbines in urban environments is still very limited. There have been some studies analyzing different designs of urban wind turbines either using computational fluid dynamics (CFD), wind tunnel tests or field data for existing or new turbine designs. This paper reviews the state-of-the-art of urban wind energy by examining the various types of urban wind turbine designs, with a view to understand their performance and the synergy between the turbines and the urban environments. It also considers a flanged diffuser shroud mechanism - a fluid machine, mounted on rooftop of buildings used as casing for small wind turbines to improve turbine performance by using mainly CFD. The diffuser shroud mechanism can draw the airflow over buildings utilizing its special features such as, cycloidal curve geometry at the inlet and a vortex generating flange at the outlet, to guide and accelerate the airflow inside. The performance of the fluid machine is optimized parametrically. The mechanism is modeled on a building rooftop in a real test site in Montreal, Canada with real statistical wind data. The CFD result confirms the functionality of the fluid machine to take advantage of the airflow over buildings in complex built-environments for wind power generation.

1. Introduction

Wind energy harnessing technologies are a large part of the renewable energy sector, and as such have been the focus of a great deal of research in the last couple of decades. Developing efficient and cost effective wind turbines for the urban environment is a new area of application that can further reduce dependency on fossil fuels thus reducing greenhouse gas emission. In addition, the ability to provide energy at close proximity to demand, as well as reducing the cost associated with power distribution as a result makes urban wind power a very attractive energy source. The main challenge is integrating wind turbines in complex urban built-environment and building aerodynamics. It is well known that wind power increases with the cube of wind velocity, i.e.

$$P_{wind} = \frac{1}{2}\rho A U^3 \tag{1.1}$$

The velocity and the density of the airflow increases locally in urban areas, as air is forced to navigate around obstacles such as buildings, structures, buses and trains. This creates an opportunity to take advantage of the locally increased density and velocity of the airflow. However, the unavoidable reduction of mean flow due to the increased ground roughness (friction) and the unpredictable - and often changing - direction of air movement, i.e. wind, within urban areas result in a very turbulent flow, which leads to inefficient wind turbines. Therefore, the design of efficient and effective wind turbines, which can operate under these conditions, becomes critical for performance optimization.

2. Overview of urban wind turbines

The application of wind energy such as, use of wind power to sail ships and windmills goes back a long time. Persians started using windmills as early as 900 AD (Manwell et al., 2002). Fig. 1 shows some ancient Persian windmills. These earliest windmills had vertical rotational axis. Horizontal axis wind mills were used in Europe in the middle ages for grinding grains and other mechanical tasks, such as pumping water (Eriksson et al., 2008). Some of the oldest designs of windmills still exist in the Netherlands today. The industrial revolution overshadowed the windmills in Europe while around the same time it became popular in

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Nomenclature

A	Rotor blade swept area (m^2)
A*	Diffuser exit area (m^2)
C_{power}	Power coefficient
Cp	Pressure coefficient
C_s	Roughness constant
C_u	k-ε turbulence model constant
HAWT	Horizontal axis wind turbine
K	Von Karman constant
$K_{S,ABL}$	Equivalent sand-grain roughness height for Atmospheric Boundary Layer
k	Turbulence kinetic energy (m^2/s^2)
Lt	Diffuser axial length (m)
L	Re characteristic length (m)
P_{wind}	Wind power (W)
R	Radius of rotor blades (m)
Re	Reynolds number
TSR(or λ)	Tip speed ratio
U	Wind speed (m/s)
U^*_{ABL}	Atmospheric Boundary Layer friction velocity
ε	Turbulent dissipation (m^2/s^2)
ν	Kinematic viscosity (m^2/s)
ρ	Air density (kg/m^3)
ω	Specific dissipation rate (s^{-1})

the United States for water pumping applications(Abohela et al., 2013a).

Since the very early attempts to generate electricity using wind by Charles Bush in the United States, 1888 (Eriksson et al., 2008), many different types of wind turbines came to existence based on aerodynamic lift and drag principles, the geometric shapes, and the rotational axis. Wind turbines are classified into horizontal axis wind turbines, HAWTs, and vertical axis wind turbines, VAWTs, based on the orientation of their rotating axis. Some examples of commercial urban wind turbines are illustrated in Fig. 2 (a) for HAWTs, and Fig. 2 (b) for VAWTs. The conventional horizontal wind turbines that offer a relatively more proven technology do not outperform VAWT in urban applications mainly due to the increased turbulent flow. Nevertheless, there are more options and technologies available in selecting HAWTs, and they are more economical but the synergy with the building needs to be evaluated. In built environments, wind speed and direction change frequently and the unpredictable turbulence makes it difficult for HAWTs to effectively harness the wind energy. HAWTs function well when the rotors are facing the wind flow. Early wind power generation in urban environment used HAWTs but the past experience has been disappointing.

The VAWTs can also be divided into two categories, lift-based VAWTs, e.g. Darrieus type, and drag-based VAWTs, e.g. Savonius type. These two wind turbines use different principles to capture wind energy. Savonius, is popular because it is reliable and easy to manufacture. The VAWTs rotate about an axis perpendicular to the wind velocity. This characteristic makes them advantageous in environments where wind direction changes frequently and the flow is turbulent. 40 years after Georges Jean Marie Darrieus patented the Darrieus wind turbine, research attention is focused on improving its performance (Macpherson, 1972; Modi et al., 1984; Newman, 1983; Shikha et al., 2005; Tabassum and Probert, 1987; Touryan et al., 1987).

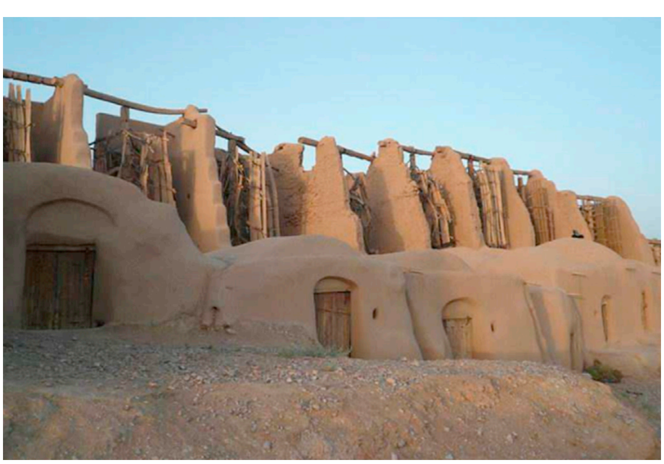

Fig. 1. Persian windmills (D'Ambrosio and Medaglia, 2010).

HAWTs are the most common types of wind turbines. However, recent research shows that the vertical axis wind turbines are better suitable for urban applications. Based on the Wineur Project report (Cace et al., 2007), Table 1 summarizes the advantages and disadvantages of the main types of urban wind turbines.

3. Current urban wind turbine designs

The increasing demand for sustainable building designs and the technological advancement in wind turbine development have created an opportunity for more efficient and realistic wind turbine designs for urban applications. There are many different types of wind turbine designs today, each with a unique performance profile. Designs are driven by various requirements specific to the application and location of the device. Some of the design criteria include size constraints, noise limitations, visual disturbance concerns and low start up wind speeds. Depending on these criteria, one particular wind turbine may be more advantageous in one aspect and less in others. Savonius rotors have proven to be well suited to micro-scaled urban operations due to their simple design and relatively low cut-in wind velocity (Saha et al., 2008). The Darrieus vertical axis wind turbine (VAWT) – see Fig. 3 (a) - is one of the most attractive options for rooftop installation, as it is visually unobtrusive and produces low-level acoustic emissions (Balduzzi et al., 2012).

VAWTs are known to perform well in built environments due to their multidirectional ability in turbulent flow (Elkhoury et al., 2015). Crossflex, a conceptual design of a building-integrated wind turbine using Darrieus VAWT concept was proposed to be integrated to existing buildings (Sharpe and Proven, 2010). The study tentatively validates the advantages of such a design over conventional Darrieus wind turbine in terms of its performance and usability. Further research is needed to develop this concept. A photomontage of such turbines is illustrated in Fig. 3 (b).

4. Challenges of urban wind power generation

There have been major technological advancements in the development of large-scale wind turbines. Wind turbines in rural terrains and wind farms are presently very efficient. However, the small wind turbines used in urban applications are somewhat under researched. The urban built environment has a lot more restrictions for the wind turbine application than open field installations. A number of human factors, such as, clients, the public, legal and statutory bodies are critical in consideration of the urban wind power generation technologies. Most building-mounted wind turbines in urban contexts are conventional HAWTs with rare examples of VAWTs. The inherent design of these turbines, which was originally aimed at operating in open fields, makes them less performant in site-specific applications, such as building rooftop, where wind flow characteristics can be very different (Sharpe