Renewable Energy 99 (2016) 654–662

Contents lists available at ScienceDirect

Renewable Energy

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

Performance analysis of vertical-axis-wind-turbine blade with modified trailing edge through computational fluid dynamics

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ARTICLE INFO

Article history:
Received 6 July 2015
Received in revised form
19 July 2016
Accepted 20 July 2016
Available online 27 July 2016

Keywords:
Wind energy
Vertical axis wind turbine
Computational fluid dynamics (CFD)
Trailing edge
Vortex
Power coefficient

ABSTRACT

The design of turbine blades is a critical issue in the performance of vertical-axis wind-turbines (VAWTs). In a previous study, it is discovered that a loss of thrust in VAWT blades with a wave-like leading edge can be attributed primarily to vortex distribution. This finding prompted us to apply the wave-like blade design to the trailing edge rather than the leading edge. In this study, computational fluid dynamics was used to observe the flow field on straight and tubercle blades in order to predict the resulting thrust and power performance. Increasing the amplitude and wavelength of the tubercle was shown to increase the maximum thrust by as much as 2.31% and the power coefficient by 16.4%, compared to a straight blade. Furthermore, the overall and maximum thrust performance of blades with a modified trailing edge was shown to exceed those of blades with a wave-like leading edge, due to a shift in the location of the vortices by the induced flow.

1. Introduction

Small-scale vertical-axis wind-turbines (VAWT) are a popular source of power in urban areas, providing for residential use electricity with low power transmission loss and the ability to generate power regardless of the direction of the wind [1]. Recent studies on VAWTs have included experimental and computational approaches, such as the use of computational fluid dynamics (CFD) for the prediction of aerodynamic characteristics and the performance of turbine blade designs [2–7].

Biadgo et al. [8] performed numerical simulations of VAWTs with NACA0012 type turbine blades. It was shown that, compared to CFD, the results obtained using the analytical double multiple streamtube (DMST) model led to an overestimation of the maximum power coefficient (Cp) under conditions of a low tip speed ratio (TSR). Vassbverg et al. [9] conducted three-dimensional simulations of unsteady, periodic, viscous flows associated with NACA0015 H-type VAWT using the time-spectra RANS (Reynolds-averaged Navier-Stokes equations) method. In an investigation of upwind revolution turbines with several TSRs, Castelli et al. [10] obtained maximum torque values at high angles of attack (AOAs). McLaren et al. [7] studied the aerodynamic performance of a high solidity H-type Darrieus VAWT with a TSR of 1.6 using the URANS (unsteady Reynolds-averaged Navier-Stokes) model. They discovered that a dynamic stall results in vortex shedding and vortex impingement on the source blade. They also discovered that the extraction of flow momentum reduces the amount of power being produced by the downstream blade. An appropriate turbulence model is required for accurate predictions. In simulations of the rotor power of a VAWT, Dobrev and Massouh [2] found that the DES/k-ω model provides better performance for 3-D flow than does the k-ω turbulence model for 2-D or 3-D flow. Lanzafame et al. [5] determined that the transition SST turbulence model is in closer agreement with the experiment data than is the fully turbulent model for the 2D simulation of an H-Darreus VAWT.

Improving the power coefficient of VAWTs can be achieved by increasing the lift-to-drag ratio or delaying the stall angle of attack. With the aim of generating lift, previous studies [11–13] have demonstrated that modifying the leading edge of the airfoil to replicate the shape of waves can improve the transfer of momentum at the boundary layer and affect the vortex structure and circulation around the airfoil. Fish and Battle [14] reported that modifying the leading edge of the airfoil using tubercles can help to maintain lift at high AOAs. Tubercles along the leading edge alter the boundary layer and flow separation, which delays the stall AOA [15]. Miklosovic et al. [16] claimed that modification of the airfoil

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http://dx.doi.org/10.1016/j.renene.2016.07.050

can delay the stall AOAs by 40%. Johari et al. [17] claimed that the stalling of NACA 63_4-021 airfoils can be nearly eliminated by incorporating a sinusoidal leading edge and used computational methods to demonstrate the benefits of this wave-like design. Using the Spalart-Allmaras model [18] for the simulation of a modified airfoil, Dropkin et al. [19] found that the pressure at the lower surface is distributed in the trough of the sinusoidal leading edge and that this continues to increase lift even at high AOAs. Following the application of the SST transitional turbulence model, Rostamzadeh et al. [20,21] discovered that a delta-shaped vortex near the trailing edge of an airfoil with a wave-like leading edge decreases the pre-stall performance of wings in favor of post-stall performance. Using the 3D panel method, Watts and Fish [22] increased the lift coefficient by 4.8% and decreased the drag coefficient by 11% at pre-stall AOAs through the incorporation of an airfoil with a wave-like leading edge. Using the URANS equations, Patterson et al. [23] demonstrated that an airfoil with tubercles requires a change in the flow field across the re-circulating zone in order to enhance performance. Recently, the wavy-like leading edge applied to the design of wind turbine blade focuses both on the blades of horizontal-axis wind-turbine (HAWT) and VAWT. For HAWT, Bai et al. [24] pointed out that modifying an HAWT blade with a sinusoidal leading edge can increase the power coefficients by 13.3–17.5% at relatively low TSR (TSR = 0.5–3) at a wind speed of 6 m/s. In the simulation carried out by Zhang and Wu [25], an improvement of shaft-torque was found from wavy-like leading-edge wind turbine blades under high wind speed, resulting from the vortex shedding from the tubercles of leading edge. For VAWT, previous study [6] showed that the inclusion of tubercles along the leading edge of the turbine blade decreased the maximum thrust by 5–55% at azimuth angles of 60°–90° due to the effects of vortex distribution. The concentration of inflow at the tubercle forced the vortices to move toward the trailing edge, which formed a low pressure zone at the trailing edge and resulted in a decrease in thrust. The contributions of leading/trailing edge tubercles on turbine blade to HAWTs and VAWTs from literatures are listed in Table 1. This led us to develop a novel modification in which tubercles are applied to the trailing edge of the turbine blade instead of the leading edge.

The CFD analysis of the H-type Darrious VAWT was employed and the simulation results were compared with those obtained using a straight blade as well as a blade with a wave-like leading edge. The simulation results were first validated by comparing the lift and drag coefficients with data obtained in experiments with AOAs between 0° and 40° [26]. Two-dimensional simulations using the *k*-ω turbulence model were also performed, taking into account the effects of the number of cells in the grid as well as the number of time steps in order to improve prediction accuracy. Cases of 2D and 2.5D were also developed for comparison. Finally, the predicted thrust of the modified blade was compared with that of a straight blade.

Table 2
VAWT computational parameters.

Reynolds number	360,000
TSR	1.6
Type	Pressure-based
Time	Transient
Velocity formulation	Absolute
Space	2D/2.5 D model
Viscous model	*k*-ω model (SST)
Fluid	Air
Density	1.225 kg/m^3
Viscosity	1.7894×10^{-5} kg/m·s
Pressure	101,325 Pa
Blade motion type	Mesh motion (rotational)
Relative specification	Absolute
Reference frame	Relative to cell zone
Inlet boundary type	Velocity Inlet
Velocity inlet	13.45 m/s
Outlet boundary type	Pressure outlet
Residual error	1×10^{-4}
Pressure -velocity coupling	SIMPLE scheme
Gradient	Green-gauss node based
Interpolating scheme (momentum)	2nd order upwind
Interpolating scheme (turbulence kinetic energy)	2nd order upwind
Interpolating scheme (specific dissipation rate)	2nd order upwind
Transient formulation	1st order implicit

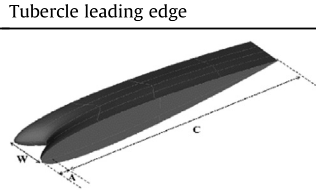
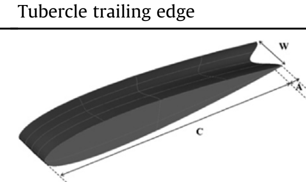
2. Method

2.1. Computational parameters

This study used NACA 0015 to simulate the performance of a VAWT blade by observing the flow field on straight and tubercle blades using the commercial software ANSYS Fluent™.

Table 2 presents the settings used for simulations. For the viscous model, the k-ω SST (Shear-Stress Transport) model, which is a two-equation eddy-viscous turbulence model combining k-ω formulation at the near-wall region with k-ε behavior in the far field, was selected. The SIMPLE (Semi Implicit Method for Pressure Linked Equations) algorithm was used to solve the conservation equations via pressure correction due to its robust iteration for coupling parameters, computational efficiency, and high-order scheme for differentiation. The second-order upwind

Table 1
The contributions of leading/trailing edge tubercles on turbine blade to HAWTs and VAWTs from literatures.

	Tubercle leading edge	Tubercle trailing edge
Geometry		
VAWT		
Aerodynamic observation on the blade surface	Vortex moves from leading edge to trailing edge; low pressure zone occurred at trailing edge	Vortex moves from trailing edge to leading edge; low pressure zone occurred at leading edge
Contribution to VAWT	Decrease in thrust and power coefficient	Increase in thrust and power coefficient
HAWT		
Aerodynamic observation on the blade surface	Localized vortices shedding from the leading edge tubercles forms low pressure region at the leading edge	No literature was found yet
Contribution to HAWT	Aerodynamic performance increases under high wind speed	