Renewable Energy 74 (2015) 414–421

Contents lists available at ScienceDirect

Renewable Energy

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

Performance analysis of the airfoil-slat arrangements for hydro and wind turbine applications

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ARTICLE INFO

Article history:
Received 16 January 2014
Accepted 20 August 2014
Available online 7 September 2014

Keywords:
Wind turbine
Hydrokinetic turbine
Hydrofoil-slat arrangement
Towing tank
Tip speed ratio

ABSTRACT

Standard airfoils historically used for wind and hydrokinetic turbines had maximum lift coefficients of around 1.3 at stall angles of attack, which is about 12°. At these conditions, the minimum flow velocities to generate electric power were about 7 m/s and 2 m/s for the wind turbine and the hydrokinetic turbine cases, respectively. In this study, NACA4412-NACA6411 slat–airfoil arrangement was chosen for these two cases in order to investigate the potential performance improvements. Aerodynamic performances of these cases were both numerically and experimentally investigated. The 2D and 3D numerical analysis software were used and the optimum geometric and flow conditions leading to the maximum power coefficient or the maximum lift to drag ratio were obtained. The maximum lift to drag ratio of 24.16 was obtained at the optimum geometric and flow parameters. The maximum power coefficient of 0.506 and the maximum torque were determined at the tip speed ratios of 5.5 and 4.0 respectively. The experimental work conducted in a towing tank gave the power coefficient to be 0.47 which is about %7 lower than the numerical results obtained. Hence, there is reasonable agreement between numerical end experimental values. It may be concluded that slat-hydrofoil or airfoil arrangements may be applied in the design of wind and hydrokinetic turbines for electrical power generation in lower wind velocities (3–4 m/s) and current velocities (about 1 m/s).

1. Introduction

Hydrokinetic turbines represent a class of zero-head hydropower systems, which use the kinetic energy of flowing water without needing dam and head to drive an electric power generator. Hydrokinetic turbines operate on many of the same principles as wind turbines and share similar design philosophies. The most notable difference is that the density of water is about 850 times greater than air density, so the energy in a given flow stream is much greater for a hydrokinetic turbine than for a wind turbine. Average flow velocities for a tidal or river flow, however, tend to be an order of magnitude less than the flow velocities at a good wind site. The net impact is that the Reynolds numbers tend to be in the same range for both wind turbines and hydrokinetic turbines, which allows for much of the same experimental airfoil/hydrofoil data to be used in the design process. Additionally, hydrokinetic turbines can be analyzed and designed using the same incompressible flow techniques used for wind turbines. Unlike wind turbines, however, hydrokinetic turbines must be designed to avoid cavitation [1].

In wind and hydrokinetic turbine design, the optimization of the rotor is very important to maximize the power production and operation in very low hydrokinetic currents. The performance of the rotor can be determined by various parameters including hydrofoil geometry, the number of blades, diameters and also different slat-hydrofoil arrangements.

There are certain research studies in the literature about the effect of slat on the performance of the airfoil. High-lift systems essentially modify the fluid dynamics of wings so as to avoid aircraft stalling and methods have been devised to predict boundary layer separation that causes stalling [2,3]. The optimization of airfoils for high lift is governed by the maximum lift coefficient available from a mono-element airfoil with un-separated flow and the shape of the airfoil can be improved for high-lift situations [4–6]. Leading-edge slats are known to help avoid leading edge separation at low speeds by injection of high-momentum fluid through the gap between the slat and the main airfoil. This injected fluid adds kinetic energy to the boundary layer and hence delays leading-edge separation [7]. Various forms of leading-edge

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http://dx.doi.org/10.1016/j.renene.2014.08.049

devices have been tested, notably the fixed slat [8–10], the retractable slat [11,12] and the Krüger flap [13]. The effectiveness of the leading edge auxiliary airfoil is dependent on its positioning. Same kind of flow behavior can be observed in the flow around double blade airfoils. In the case of using double-blade airfoil, the fluid dynamics governing the flow field eliminates the separation bubble by the injection of the high momentum fluid through the gap between two blades by meaning of the flow control delays the stall up to an angle of attack.

Various studies about the performance of the slat-airfoil configurations and the double blade hydrofoil have been carried out by the members of Baskent University Energy Resource Group [14–17]. Results show that, as outlined other researchers, slat geometry, slat orientation with respect to the main airfoil and other geometric parameters have important effect on the performance of the hydrofoil.

Most of the works conducted on hydrokinetic turbines are the tidal current power systems. Numerical study of the tidal turbine carried out by Jo et al. [18] concerned the performance of horizontal axis tidal current turbine by blade configuration. This paper presents the design procedure for a 300 kW tidal current turbine. They also considered tip losses based on turbine design theory including the blade element theory. The 3D CFD model was applied with the ANSYS CFX program. They have chosen a prototype which has a diameter of 0.5 m for the S814 airfoil shape. At a current flow of 1 m/s the maximum power coefficient was found about 0.51 at a tip speed ratio of 5.0 and the maximum torque was determined about 3.65 N-m at a tip speed ratio of 3.2. Shiono et al. [19] studied the Darrieus type turbine. More works on these tidal current power systems can be found in the literature [20–22].

The hydrofoil-slat arrangements, considered to be the high performance blades, can be used in wind and hydrokinetic turbines applications. This study considers the performance analysis of the hydrofoil-slat arrangements, NACA4412-NACA6411. The analyses were carried out numerically and experimentally. The 2D simulations for acquiring optimum orientation of hydrofoil-slat which gives maximum lift to drag ratio and 3D CFD simulations for observing power, pressure and turbulence distributions were conducted on the systems and the experimental works were carried out in the towing tank.

2. Mathematical modeling and geometric parameters

In the hydrodynamic model, the blade–element momentum theory which is a combination of two different theories, namely the conservation of momentum theory and the blade element theory is used [23]. Conservation of momentum theory refers to a control volume analysis of the forces at the rotor plane based on the conservation of linear and angular momentum. Conservation of momentum states that the loss of pressure or momentum through the rotor plane, which occurs as the fluid passes through the rotor plane, is caused by work done on the turbine blades by the moving fluid. The conservation of momentum theory then allows calculation of the induced velocities in the axial and tangential directions from the momentum lost by the moving fluid. A flow field, characterized by the axial and angular induced velocities, is used to define the local flow conditions at the rotor hydrofoils. Blade-element theory is an analysis of forces which assumes that the blades can be divided into many smaller elements which act independently of surrounding elements. Given the local flow conditions and the blade geometry, the hydrodynamic forces on these blade elements can be calculated. Blade-element theory then sums these elemental forces along the span of the blade to calculate the total forces and moments exerted on the turbine.

3. Two dimensional analyses

The 2D analyses were conducted on the system with using GAMBIT – FLUENT program to acquire optimum geometric parameters of hydrofoil-slat arrangement which gives maximum lift to drag ratio leading the maximum performance or efficiency. Detailed analyses were made using the FLUENT code with steady conditions including Spalart–Allmaras, k-ε turbulent model. AUTO CAD and PROENGINEER were used for the modeling. No-slip boundary conditions were used at blade and domain surfaces. The grid used for the airfoil-slat hydrofoil is generated by the program GAMBIT FLUENT. Grid sizes giving the grid-independent results were selected and the total number of cells is adopted as approximately 45,000 nodes. The 2D analyses were also conducted on the standard NACA4412 hydrofoil for comparisons. Geometric definitions of the hydrofoil-slat arrangement were shown in Fig. 1 and grid structure of with and without slat arrangements were illustrated in Fig. 2.

The variations of the geometric parameters in the analyses were chosen to be as $0.125 < h/c_1 < 0185$, $0.36 < c_1/c_2 < 0.71$, angle of attack, $0^\circ < \alpha < 38^\circ$, slat angle, $18^\circ < \delta < 37^\circ$ (Plus and minus). In 2D analyses Spalart–Allmaras turbulent model was used and the values of C_L and C_D were obtained in chosen intervals. The hydrodynamic performances of hydrofoil with and without slat arrangements, NACA4412-NACA6411 and NACA4412 were presented in Table 1 and Table 2. The optimum geometric parameters of hydrofoil-slat arrangements, leading the maximum values of the C_L/C_D were obtained to be as $c_1/c_2 = 0.394$, $h/c_1 = 0.273$, $\delta = 16^\circ$ and $\alpha = 10^\circ$ at the Reynolds number ($Re = Uc_2/\nu$) of 3.02×10^5. Comparing Tables 1 and 2, for the hydrofoil with slat arrangement, the optimum angle of attack at which C_L/C_D has maximum value of 24.11 is about $\alpha = 10^\circ$ while hydrofoils without slat gives the maximum values of C_L/C_D 21.51 at the angle of attack, 6°. Thus the design parameters of this hydrofoil-slat arrangement, NACA4412-NACA6411, are $\alpha = 10^\circ$, $C_L = 1.559$, $C_D = 0.064$ and $C_L/C_D = 24.11$.

The hydrofoil-slat arrangement has a maximum lift coefficient of 2.788 at a stall angle of attack of 24°, while the standard hydrofoil has a maximum lift coefficient of 1.45 at a stall angle of attack, 16°. Pressure distributions on the surfaces of the hydrofoil-slat arrangement are presented in Fig. 3. As seen the slat has very important effect on the pressure distributions. The hydrodynamic performances of the various hydrofoil-slat arrangements, NACA2415-NACA22, NACA2415-NACA97 and standard hydrofoil, NACA2415 were given in detail by Yavuz and Koc [15].

The geometry of the blade 0.6 m in diameter, shown in Fig. 4, can be obtained from the optimum geometric and flow parameters determined. The chord line and twist angle along the blade can be obtained from the formulas [23];

$$c = \left(\frac{8\pi r}{BC_L}\right)(1 - \cos\varphi)$$

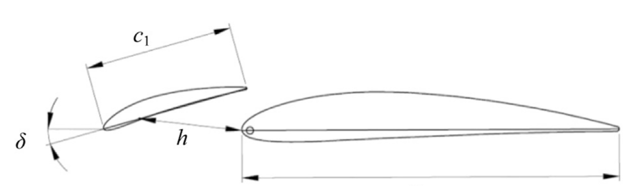

Fig. 1. Geometry of hydrofoil with leading edge slat.