Renewable Energy 76 (2015) 234–241

Contents lists available at ScienceDirect

Renewable Energy

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

Numerical characterization of a preliminary portable micro-hydrokinetic turbine rotor design

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ARTICLE INFO

Article history:
Received 22 February 2014
Accepted 12 November 2014
Available online

Keywords:
Micro-hydrokinetic
Portable turbine
Turbulence
CFD

ABSTRACT

Portable micro-hydrokinetic turbines are designed and characterized using computational fluid dynamics (CFD) simulations. The two equation $k-\omega$ shear-stress transport (SST) turbulence model is employed to predict quasi steady flow structures for a wide range of tip-speed ratios. Seven input design parameters selected *a priori* are used to create preliminary turbine rotor designs by using a hydraulic design methodology. Various blade designs are characterized and compared in terms of torque and thrust over a range of operating conditions. Performance characteristics of two, three, and four blade designs are shown to be similar. The results indicate that a maximum power coefficient of 0.43 with a 73.7% efficiency relative to Betz limit is achieved. The portable hydrokinetic turbines, designed and characterized here, do not require large civil structures, making this technology an attractive alternative to conventional hydropower.

1. Introduction

Conventional hydropower produces nearly 80 GW of energy annually in the United States, amounting to approximately half of the nation's renewable energy capacity [1]. However, conventional hydropower requires large capital investments, especially in civil structures such as dams, and can have negative consequences on the local aquatic environment. Marine and hydrokinetic (MHK) technology does not require these civil structures, thus offering an advantage over conventional hydropower.

Hydrokinetic technology encompasses a broad range of systems from horizontal and vertical axis turbines to oscillating hydrofoils. The common theme between these types of machines is that they rely on hydrodynamic principles to convert flowing water into mechanical rotational energy, which in turn drives an electrical generator. These technologies are not as mature as conventional hydropower systems in terms of design and implementation; however, it is estimated that there is 1381 TWh/yr of untapped for power generation in the continental United States for MHK technologies [2]. Hydrokinetic turbines can make use of the previously unexploited potential power generation of these rivers.

Micro-hydro refers to projects that generate between 0.5 kW and 100 kW of power, which is the amount of power typically required by a single family home or a small business [3]. Small hydrokinetic systems fall within this micro-hydro category and offer portability. These characteristics are especially desirable in temporary encampment situations such as military field operations. A photovoltaic battery system called the Ground Renewable Expeditionary Energy System, or GREENS, has been developed for use by the U.S. Marine Corps to produce 300 W of continuous power to run these encampments [4]. However, when sunlight is not available, a secondary source of energy is needed to power necessary equipment. A micro-hydrokinetic system could potentially interface with this system to provide the required power.

Hydrokinetic turbines are a popular research topic, with engineers investigating multiple configurations. Batten et al. [5–7] used a blade element methodology (BEM) approach for horizontal axis tidal turbines. They validated their method using a scaled model in a cavitation tunnel, and concluded that their BEM model agreed with their experiments. Mukherji et al. [8] compared BEM with CFD for a horizontal axis hydrokinetic turbine, and determined the effect of solidity, angle of attack, and number of blades on power generation. Myer and Bahaj [9] conducted experiments on a horizontal axis turbine and concluded that the blade twist distribution, centrifugal force at the surface of the blade, lift and drag performance, and rotor yaw angle affect the stall delay of the hydrofoil

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http://dx.doi.org/10.1016/j.renene.2014.11.032
0960-1481/

Nomenclature

Full scripts

C	coefficient
c	chord length, m
D	diameter, m
e	error, %
F	blending function
GCI	Grid Convergence Index, %
k	turbulent kinetic energy, J/kg
L	length scale, m
m	meridional length, m
N	number of cells
p	pressure, Pa
$\tilde{p}$	normalized pressure
P	power, W
r	refinement factor
R	radius of rotor tip, m
S	mean rate-of-strain tensor, rad/s
s	blade spacing, m
t	time, s
b	thickness, m
T	thrust, N
U	velocity, m/s
$\tilde{U}$	normalized velocity
Z	quantity

Greek symbols

α, β, σ	closure coefficients
β	relative angle, °
Δ	change in variable
ε	permutation symbol
θ	wrap angle, °
μ	dynamic viscosity, Pa-s
ν	kinematic viscosity, m^2/s
ξ	local tip-speed ratio
ρ	density, kg/m^3
σ	solidity
φ	dummy variable
ψ	stagger angle, °
ω	angular velocity, rad/s
Ω	specific dissipation rate, rad/s
$\tilde{\omega}$	normalized vorticity

Superscripts

*	denotes a closure coefficient
′	denotes the blade angle

Subscripts

a	absolute
B	blades
ext	extrapolated
H	hydraulic
h	at the hub
k, ω, $\omega 2$	denotes different colure coefficients
i,j,l,q,s,t	tensor indices
m	at the mean value
r	relative
T	turbulent/thrust
t	at the tip

sections and thus can affect the power output from the rotor. Hwang et al. [10] studied a vertical axis turbine that actively controlled blade attack to maximize power output and improved self-start. They showed that by individually controlling each blade's attack based on the oncoming flow that there was a 25% improvement in performance compared to pure cycloidal motion for the same operating conditions.

The design principles used for wind turbines, marine propellers, and propeller turbines can be used in hydrokinetic designs. Massouh and Dobrev [11] studied the vortex wake behind a horizontal axis wind turbine in a wind tunnel and compared the results to CFD analysis. Their results showed that the tip vortices are not limited to a cylindrical surface as predicted from linear propeller theory, and expand radially as they move downstream. This increases the diameter of the stream-tube that encompasses the turbine. Vermeer et al. [12] also studied the wake characteristics behind wind turbines in the near and far wake regions. Alexander et al. [13] have studied axial-flow, flat blade propeller turbines that can be manufactured in underdeveloped countries to provide sustainable power generation for communities. They have shown that simplifying the blade geometry on propeller turbines can still produce a significant amount of power and can be easier to manufacture for locations where advanced machining may not be possible. The work of Alexander et al. [13] was validated and compared with an Archimedean screw turbine by Schleicher et al. [14], who have studied different micro-hydro systems [15,16]. Singh and Nestmann [17] experimentally studied the part-load performance on small axial-flow propeller turbines and found that modifying the exit tip region on their studied propellers consistently showed an increase in flow and output shaft power and thus the hydraulic efficiency of the blades. Hayati et al. [18] investigated the effect of rake angle on marine propeller performance and concluded that increasing the rake angle improved the thrust performance of conventional propellers. Even though these propellers are imposing energy onto the fluid and not absorbing the energy, it is possible that adjusting the rake angle may improve thrust performance in the energy absorbing case.

2. Hydraulic design

Some design parameters must be assumed *a priori* to the design process. These input variables are shown in Table 1.

First, the tip diameter (D_t), hub diameter (D_h), and mean diameter (D_m) are calculated. A rough estimate of the required tip diameter (D_t^*) is calculated as shown in equation (1). This relationship is derived from the fluid's power flux through the rotor blade. This equation assumes that there is no hub, therefore the result must be rounded up to account for the area lost by the hub. Once the rounded tip diameter (D_t) is selected, the hub diameter is

Table 1
Input design variables selected *a priori*.

Input variable	Description
P	Designed mechanical power output [W]
C_P	Designed power coefficient [−]
U	Designed free-stream velocity [$m\ s^{-1}$]
Ω	Designed rotation rate [$rad\ s^{-1}$]
Z_B	Designed number of blades [−]
σ	Designed solidity [−]
b	Designed blade thickness [m]