Ocean Engineering 69 (2013) 9–17

Contents lists available at SciVerse ScienceDirect

Ocean Engineering

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

Power measurement of hydrokinetic turbines with free-surface and blockage effect

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ARTICLE INFO

Article history:
Received 15 October 2012
Accepted 11 May 2013
Available online 7 June 2013

Keywords:
Vertical axis turbine
River kinetic turbine
Surface effect
Blockage effect

ABSTRACT

Vertical hydrokinetic turbines in an array that extends from one side of a channel or river to the other side of it experience a fixed blockage effect as a result of the adjacent turbines and a variable free-surface effect due to water level changes above turbines. For tidal applications, the water level above turbine blades changes continuously throughout the day; for river applications, the water level changes on a seasonal basis. In this study, a vertical turbine operating in an array of turbines with one diameter lateral distance between two adjacent turbines is modeled. The model turbine is tested in a water tunnel at various water levels. Results show that the water level reduction improves the power coefficient of the turbine when the turbine is fully submerged—the power coefficient increases due to the free-surface effect, with trends in agreement with the one-dimensional actuator-disc flow theory. However, the power coefficient decreases significantly when the turbine is only partially submerged. In this particular condition, the entrained air into the water by turbine blades separates the water from the blade surface. A high-speed camera visualizes the flow separation while a transducer measures the instantaneous torque of the turbine.

1. Introduction

Peak fossil fuel issues, global warming, and the need to derive a higher percentage of our primary energy from renewables are only some of the reasons that make renewable energy technologies attractive. Hydrokinetic energy from water currents has a relatively high energy density with generally predictable energy delivered to a grid, as water currents are predominately driven by gravity rather than by weather. Achieving hydrokinetic commercial success depends on the ability to deliver predictable energy to a grid over the project lifetime at a reasonable cost.

Traditional hydro technology harnesses power of the water's potential energy by storing the water behind dams while hydrokinetic turbines harness kinetic energy of the flow at much reduced power densities. Although dams and barriers have a significant ecological foot print by blocking the fish migration path and modifying the climate in their vicinities (Baxter, 1985; El-Shamy, 1977), the environmental impacts of hydrokinetic turbines are currently being investigated, and are discussed by Fraenkel (2007). Hydrokinetic turbines do not need dams or large constructions for installation, so they are most suitable for remote power applications.

The National Research Council and Nova Energy were the first in North America to connect an in-situ hydrokinetic turbine to the power grid. After the tests by Faure et al. (1986) in the St. Lawrence River, field testing stopped until the next grid connection was established by New Energy Corporation Inc, the University of Manitoba, and Manitoba Hydro in 2008. These tests demonstrated that hydrokinetic turbines could be operated in adverse winter conditions in Manitoba; the consortium successfully grid connected 5 and 25 kW vertical hydrokinetic turbines at Pointe du Bois located on the Winnipeg River (Bibeau et al., 2009). In addition, non-grid connected demonstrations have been achieved in rivers and tidal applications (Bibeau et al., 2008).

Recently, new companies have been established that are in the prototype and demonstration stage, with commercial plans in place. The installation and operational cost estimation and power generation prediction are key concerns in the prototype testing stage. The basic requirement for cost-effective power generation is typically a mean peak flow speed exceeding 2.5 m/s (Douglas et al., 2008). Narrow channels between two large water bodies are favorable places for hydrokinetic turbine sitting. Channels are usually shallow as they pass between two elevated lands and the flow speed in channels is increased due to the funnelling effect.

The installation and maintenance of hydrokinetic turbines in deep waters are challenging; therefore many turbines operate

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http://dx.doi.org/10.1016/j.oceaneng.2013.05.023

Nomenclature

A	turbine cross section area (m^2)
A_c	channel cross section area (m^2)
B	blockage ratio
C_h	clearance coefficient
C_p	power coefficient
Fr	Froude number
f	focal length
g	gravitational force (m/s^2)
h	water depth (m)
Δh	free-surface drop behind the turbine (m)
H	water height above the turbine (m)
L	blade length/ rotor diameter of the vertical/horizontal turbine (m)
P	power ($kg\ m^2/s^3$)
Re	Reynolds number based on turbine diameter
TSR	tip speed ratio (rotational speed/free-stream speed)
V	free-stream speed (m/s)
V_b	bypass flow speed (m/s)
V_t	flow speed in the turbine plane (m/s)
V_w	flow speed in the wake (m/s)
α_{max}	maximum angle of attack
α_{pitch}	pitch angle
β	V_t/V
ε	V_w/V
$\theta_{\alpha_{max}}$	azimuth angle at which the maximum angle of attack occurs
τ	V_b/V

near free-surface areas. Deep waters limit accessibility and increase installation and maintenance costs. There are various installation methods for hydrokinetic turbines: installation on the riverbed or seabed, use of a vertical mast, installation beneath a floating platform, and kiting the turbine with a cable. The riverbed or seabed installation is practical when the bed is smooth. The floating platform installation is a convenient method as it offers an easy access to the turbine. However it is limited by cold weather and floating debris (Bibeau et al., 2009). Irrespective of the installations, turbines can be influenced by the free-surface, as the water level changes on a daily and seasonal basis in tidal and river applications. Blades may be above the free-surface during low tide or low river level conditions. The free-surface effect and semi-submerged blades affect the hydrodynamics and thus the power coefficient of these turbines.

2. Hydrokinetic clearance coefficient coefficient

There are few operational tidal and river hydrokinetic turbines tested in the field. Most of the hydrokinetic turbines are subjected to the free-surface effect. To classify the free-surface effect, we propose a non-dimensional clearance coefficient coefficient, C_h, defined as

$$C_h = \frac{H}{L}, \tag{1}$$

where H is the water height above the turbine and L is the rotor diameter for horizontal turbines and blade height for vertical turbines. The positive clearance coefficient coefficient means the water level is above the turbine blades; when the water level is below the top of the turbine blades, C_h is negative. We now require classifying the clearance coefficient coefficient, C_h, for recent hydrokinetic turbine demonstrations.

2.1. SeaFlow

In May 2003, 3 km north east of Lynmouth on the North Devon Coast, England, in the Bristol Channel with a tide range of 10 m, the prototype SeaFlow was installed (Thake, 2005). SeaFlow has a 2-bladed horizontal axis rotor, 11 m in diameter, and a rated power of 300 kW. Test results show that the efficiency of the single turbine is between 40% and 50% which is larger than the expected design efficiency (Fraenkel, 2004). For almost four years, SeaFlow was the world's largest offshore tidal generator. Having an average depth of 25 m at Bristol Channel, the clearance coefficient C_h of SeaFlow varies between 0.18 and 0.64.

2.2. SeaGen

SeaGen is the world's first commercial-scale grid-connected tidal turbine developed by Marine Current Turbines. The nominal output power of SeaGen is approximately 1.2 MW. Turbine consists of twin 16 m diameter axial flow rotors mounted on a crossbeam on either side of a steel vertical tower. Each rotor generates 600 kW power (Douglas et al., 2008). The first SeaGen generator was installed in Strangford Narrows between Strangford and Portaferry in Northern Ireland in April 2008 and was connected to the grid in July 2008. The Strangford Narrows has an average depth of 26.2 m at the test site. At the lowest tide the water level drops to 24 m and it rises to 28.3 m at the highest point. Based on the dimensions of the turbine and the depth of the sea the estimated clearance coefficient C_h varies between 0.25 and 0.38.

2.3. HS300

HS300 is a 300 kW prototype tested in Kvalsund, Norway and became operational in November 2003. The turbine has proven to be both efficient and reliable through deployment, operation, retrieval, maintenance and, redeployment cycle. HS300 is a three-bladed horizontal axis hydrokinetic turbine developed by Hammerest Storm (Rourke et al., 2010). The water depth is about 50 m at Kvasund test site giving a C_h of 0.75.

2.4. AK-1000

In August 2010 the Atlantis Resources Corporation's AK-1000 turbine was unveiled at Invergordon, Ross and Cromarty, Highland, Scotland. It is claimed to be the largest tidal turbine ever built. AK-1000 has twin rotor sets with fixed blades and is rated at 1 MW at a flow speed of 2.6 m/s. AK-1000 was deployed during the summer of 2011 at the European Marine Energy Centre (EMEC) facility in Orkney. EMEC's tidal test site in the Fall of Warness has a 50 m depth (Foubister and Penwarden, 2005). In this depth of water AK-1000 has a clearance coefficient of 1.02 at that location which is larger than that of the other tidal turbines demonstration projects.

2.5. Verdant Power

Verdant Power developed the world's first array of grid-connected tidal turbines in the Manhattan East River in the New York City between 2006 and 2008. Three-bladed, horizontal axis turbines with 5 m in diameter generate approximately 35 kW each