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Efficiency improvement of a tidal current turbine utilizing a larger area of channel

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ABSTRACT

There is a growing interest in utilizing tidal currents for power generation which has led to extensive research on this source of renewable energy. The amount of energy that can be extracted from tidal currents has been a topic of considerable interest to researchers for many years; still, there is no consensus on the extent to which this resource can be exploited. A turbine generates no power if it presents no resistance to the flow or if it presents so much resistance that there is no flow through it. At the same time, the estimation of exploitable resource should take into consideration the environmental, economic and social constraints. In view of these, the design of efficient turbines driven by bi-directional tidal currents has been a challenge to researchers for some time. There appears to be a general agreement among researchers that a number of turbines spread over the width of the channel can extract more energy compared to an isolated turbine. The present work is aimed at quantifying the improvement in the performance of a given type of turbine by utilizing a larger area of the channel. Numerical experiments were performed using the commercial CFD code ANSYS-CFX to study the performance of a bi-directional cross-flow turbine by simulating two cases of i) a single turbine and ii) a number of equally spaced turbines. It was found that the Coefficient of Power can be increased significantly by employing a larger area of the channel.

1. Introduction

Many countries surrounded by the oceans have rich marine energy resources, hence significant amount of electric power can be generated from the oceans. Marine currents offer a regular and predictable source of renewable energy [1]. Marine currents have only recently been looked at seriously for large-scale power generation. A marine current turbine utilizes the kinetic energy of marine currents and converts it to mechanical energy. Researchers have tried unsuccessfully to employ conventional hydro-turbines for extracting energy from marine currents, because the available head is too small. The main difference between high-head and free flow turbines is that that the latter need large flow openings to capture as much water mass as possible with low velocities and pressure. Conventional turbines, in contrast, are designed for high pressure and relatively small water ducts where all the water is made to pass through the turbine. These turbines have efficiencies as high as 90%. This is simply not possible for free flow turbines. Even the Betz limit of 59.3% is considered unachievable [2] especially by propeller-type turbines because the assumption in the Betz model is that the fluid flow remains rectilinear when passing through the turbine and maintains a uniform distribution of its pressure on the turbine. Such a uniformly distributed load leads to an overestimation of the force acting on the turbine and, as a result, an overestimation of the turbine's output and efficiency. In reality, the fluid streams are deflected from the rectilinear direction near the barrier, changing their motion to curvilinear trajectories and reducing their pressure on the turbine [2].

A tidal current turbine has to extract energy from the bi-directional flow of water. There is a growing interest in utilizing tidal currents for power generation and as a result, a surge in research efforts directed at this renewable energy resource [3–11]. Garrett and Cummins [3] did a theoretical analysis of an isolated turbine and an array of turbines in a channel. A turbine generates no power if it presents no resistance to the flow or if it presents so much resistance that there is no flow through it. They opined that an isolated turbine will inevitably have a current through it with a speed lower than the ambient current, with a consequent reduction in power generation below the metric of 0.5 ρU_o^3 per unit cross-section. They also concluded that an array of turbines in the entrance to a bay plant will be most effective if it is spread across

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Nomenclature

A	inlet area of augmentation channel, m^2
C_p	power coefficient
H1	length of augmentation channel from inlet to the axis of the turbine, m
P	rotor power, W
Po	power output of turbine, W
Pw	water power upstream of a given turbine, W
R	blade radius, m
TSR	tip speed ratio
V1	height of augmentation channel at inlet, m
Vaci	mean velocity at augmentation channel inlet, m/s
Vri	mean velocity at rotor inlet, m/s
ρ	density of sea water, kg/m^3
Ω	angular velocity, rad/s
U_o	freestream velocity, m/s

the width of the entrance in order to minimize free flow past the turbines. They also felt that too many turbines may choke the flow and reduce the power. Atwater and Lawrence [4] also did a theoretical analysis to estimate the power generation potential in a channel. They argued that it is inappropriate to use the free kinetic energy flux as the available resource because it does not account for the reduction in flow as a result of increased resistance. For the determination of the ideal turbine resistance, they suggested that a relation between friction and velocity needs to be established; normally, the variation in the head loss with velocity is linear to quadratic. If the relationship is quadratic, a maximum of 38% of the fluid power of a channel may be extracted, and if the relationship is linear, the maximum drops to 25%. They also concluded that the flow will reduce to 57% for the quadratic case and 50% for the linear case. Bryden and Couch [5] studied the possible energy extraction from a simplified channel model and concluded that the undisturbed kinetic flux density is a useful indicator of achievable resource. They suggested that if higher levels of flow alteration are acceptable, then substantial fraction (called Significant Impact Factor) of the energy may be available for extraction. In another paper, Garrett and Cummins [6] performed a theoretical analysis for the cases of an isolated turbine and a tidal fence occupying different fractions of a channel cross-section. They concluded that the maximum efficiency factor 16/27 for a turbine in an infinite medium is increased in a channel. They also concluded that the actual, rather than fractional power will increase if the ratio of turbine area to channel area is increased. Sutherland et al. [7] found that at maximum power extraction, the volume flux drops to 58% of that in the natural state and 2/3 of the original head along the whole channel gets transferred to the turbine array. Blunden and Bahaj [8] performed a review of the current understanding of tidal energy resources. The exploitable tidal current resources and some analytical models of energy extraction were reviewed. They questioned the lower achievable efficiency suggested by Gorban et al. [2] in view of the fact that some full-scale prototype tidal current turbines achieved a power coefficient of 0.4 and above.

Sun et al. [9] suggested that estimation of the exploitable resource should not only take into consideration the environmental, economic and social constraints, but also the hydrodynamic resilience of the site in question and the fact that different technologies may give different returns, depending on the nature of the site and the appropriateness of the technology. Their CFD work focused on the impact of tidal current energy extraction on the local flow conditions. Their model simulated the operational conditions for tidal energy extraction, where the flow is constrained in the channel. A wake region is formed behind the tidal energy converter, which is characterized by reduced velocity due to energy loss. Since the mean velocity in the wake is lower than the freestream velocity, the velocity outside the wake in a closed channel must be higher than the freestream in order to maintain continuity of volume flow rate. Because of this blockage effect, the flow is accelerated around the tidal current turbine. Their CFD results demonstrated that the interaction of the tidal turbine with the flow is a complicated 3D problem. The distortion of the free water surface will distort the wake and further influence the performance of the turbine [9]. Kirke [10] in a research paper opined that the marine current energy conversion technology still requires lot of research because it differs considerably from the wind turbine technology. Significant amount of power can be obtained from tidal currents and the researchers are still investigating different types of turbines and till now, none has emerged as a clear winner. He reviewed some of the turbines that were being evaluated. It was also felt by him and Blunden and Bahaj [8] that the ducted turbine, that was not found to be economically advantageous for wind energy extraction, may be an attractive option for tidal current energy extraction. Kirke [10] obtained a higher power coefficient, Cp, for the ducted turbine compared to the open one.

Bahaj et al. [11] performed power and thrust measurements of horizontal axis marine current turbines in a cavitation tunnel and a towing tank and studied the effects of tip speed ratio, the blade pitch angle, blade tip immersion and yawed in flow. The rotor diameter was 800 mm and had higher blockage ratio in the cavitation tunnel compared to the test tank. Since the blades for such a turbine generate rotation mainly by lift, tip speed ratio (TSR) values of 5–7 resulted in optimum performance. Under yawed conditions, the turbine power reduced significantly. In another work on horizontal axis tidal current turbines, Coiro et al. [12] obtained the maximum efficiency at TSR values of 3–4.

Another type of turbine that is attracting considerable attention nowadays is the cross-flow turbine. This type of turbine is suitable even for very small heads. It is essentially an impulse turbine. It can handle large quantities of water and also possesses flat efficiency characteristics. In this type of turbine, the water passes over the blades twice, resulting in a higher momentum transfer [13]. Some of the other advantages of a cross-flow turbine include cost effectiveness, ease of construction, no problem of cavitation and independence of its efficiency to variations in the flow rate [14,15]. Olgun [15] found a very small change in the maximum efficiency of their cross-flow turbine when the head was changed from 8 m to 30 m.

2. Cross-flow turbine and the augmentation channel

The cross-flow turbine studied in the present work consisted of a rotor made up of 26 equi-distant blades. An augmentation channel consisting of a nozzle at the inlet side and a diffuser at the exit side surrounded the rotor, as shown in Fig. 1. The flow through the turbine is radial and the water passes over the blades twice before exiting the rotor and entering the diffuser. This is a bi-directional turbine and the design ensures equal output and efficiency for both the directions of the flow. Due to this unique nature of flow—with the flow passage converging during the first pass and diverging during the second pass through the blades and a non-uniform distribution of flow in different blades, it is never desired to run the rotor full as the rotational force is not obtained by reaction as is the case with Francis turbine. Some more of the characteristics of the cross-flow turbine are: i) a wide range of rotational speeds can be selected, ii) turbine diameter does not depend on the flow rate, iii) efficiency levels are satisfactory, iv)