Available online at www.sciencedirect.com

ScienceDirect

Publishing Services by Elsevier

International Journal of Naval Architecture and Ocean Engineering 8 (2016) 456–465
http://www.journals.elsevier.com/international-journal-of-naval-architecture-and-ocean-engineering/

Numerical study on Wells turbine with penetrating blade tip treatments for wave energy conversion

Ying Cui, Beom-Soo Hyun*

Division of Naval Architecture and Ocean Systems Engineering, Korea Maritime and Ocean University, Busan, South Korea

Received 23 November 2015; accepted 30 May 2016
Available online 16 July 2016

Abstract

In order to optimize the performance of a Wells turbine with fixed guide vanes, the designs of an end plate and a ring on the tip of the turbine rotor are proposed as penetrating blade tip treatments. In this study, numerical investigations are made using computational fluid dynamics (CFD)-based ANSYS Fluent software, and validated by corresponding experimental data. The flow fields are analyzed and non-dimensional coefficients C_A, C_T and η are calculated under steady-state conditions. Numerical results show that the stalling phenomenon on a ring-type Wells turbine occurs at a flow coefficient of $\phi = 0.36$, and its peak efficiency can reach 0.54, which is 16% higher than that of an unmodified turbine and 9% higher than in the case of an endplate-type turbine. In addition, quasi-steady analysis is used to calculate the mean efficiency and output work of a wave cycle under sinusoidal flow conditions. As a result, it has been found that the ring-type turbine is superior to other types of Wells turbines.

Keywords: Oscillating water column (OWC); Wells turbine; Computational fluid dynamics (CFD); Blade tip treatment; Endplate-type rotor; Ring-type rotor; Steady & quasi-steady analysis

---

1. Introduction

Among various renewable energy sources, wave energy from the oceans is one of the most promising. A series of technologies has been developed to extract energy from waves and convert it to mechanical energy or electric energy, such as the Oscillating Water Column (OWC), the overtopping system, the floating buoy, the point absorber, and the tapered channel (TAPCHAN) device. In recent times, the OWC wave energy converter has been widely utilized to harness wave energy, such as the 500 kW LIMPET in the UK, the 500 kW PICO in Portugal, and the 2 × 250 kW Yongsoo in South Korea (Cruz, 2008). The OWC system has a large chamber to take in incident waves and generate the oscillating water column. Then, the pressure difference between the atmosphere and the chamber compresses the air to exhale and inhale through the air turbine. As the essential part for the second energy conversion stage, air turbines are capable of converting low pressure pneumatic energy into mechanical shaft power. The most popular self-rectifying air turbines include the impulse turbine and the Wells turbine. Both can rotate in one direction through the pivot under bi-directional air flows. Since the impulse turbine was proposed by Kim et al. (1988), an agreement has been gradually reached that it has several advantages over the Wells turbine in terms of a wider operating flow range, better self-starting performance, and lower working noise. While, the Wells turbine, which was proposed by Wells in 1976 (Raghunathan, 1985), has higher operating efficiency, lower expense on fabrication and maintenance, and is more suitable for a higher rotational regime. Hence, enhancing its operating performance will play a crucial role in increasing the efficiency of wave energy conversion for an

---

* Corresponding author.
E-mail address: bshyun@kmou.ac.kr (B.-S. Hyun).

Peer review under responsibility of Society of Naval Architects of Korea.

http://dx.doi.org/10.1016/j.ijnaoe.2016.05.009

Nomenclature

b	blade height
C_A	input coefficient
C_T	torque coefficient
D	duct diameter
f	circular frequency of rotor blade
G	gap between guide vane and rotor blade
l_a	axial length of rotor blade
l_g	chord length of guide vane
l_r	chord length of rotor blade
Q	air flow rate
r_R	mean radius of blade
Re	Reynolds number
T	wave period
T_O	turbine output torque
U_R	circumferential velocity at r_R
v_a	mean axial flow velocity
V_a	peak value in sinusoidal flow
W	output-work of a wave cycle
y	distance from the wall to cell center
z	number of rotor blades
Δp	total pressure drop between setting chamber and atmosphere
ϕ	flow coefficient
Φ	flow coefficient under sinusoidal flow condition
γ	stagger angle of guide vanes
η	turbine efficiency
$\overline{\eta}$	mean turbine efficiency under sinusoidal flow condition
θ	chamber angle of guide vane
ρ_a	air density
μ	molecular viscosity
τ_w	wall shear stress
ν	hub-to-tip ratio
ω	angular velocity of turbine rotor

OWC plant, and help overcome the fossil fuel crisis consequently.

Several researchers have explored the pneumatic characteristics of air turbines with experimental and numerical methods. The basic principle of improving their performances is changing the configuration of the blades or guide vanes with respect to the original design, and searching for the optimum geometry parameters. For an impulse turbine, a series of experiments, which was carried out by Setoguchi et al. (2001) and Takao and Setoguchi (2012), summarized years of research achievements, and provided optimum geometry parameters. Thakker and Dhanasekaran (2003, 2005) and Thakker et al. (2005) systematically established three-dimensional (3-D) numerical models to explore the effects of tip clearance, guide vane losses, and guide vane shapes, respectively. It was reported that an optimum tip clearance of 0.25%D was suggested wherein the effect of tip leakage flow was almost negligible. Inspired by the winglet of an airplane, Hyun et al. (2005) first applied the design of an end plate to an impulse turbine, and investigated the performance of this special-type turbine at various design parameters using the numerical method. Results showed that a penetrating end plate increased the turbine efficiency due to a decrease in the input coefficient. Meanwhile, a so-called ring-type impulse turbine was also proposed and analyzed numerically to minimize the adverse effects of tip clearance by Hyun et al. (2006). Hence, it is reasonable to expect that applying an end plate or ring to a Wells turbine could improve the operating performance. In addition, Cui et al. (2015a) proposed a staggered turbine with a positive setting angle of rotor blades, which was numerically proved to be superior to the original design for the case of asymmetrical air flows.

For Wells turbine, a research by Raghunathan (1995) revealed that a decrease in tip clearance advanced the stall but increased efficiency as a result of reduced leakage losses. A turbine with a relatively large tip clearance could operate over a much wider range of flow coefficients without stalling. Several experiments were performed by Takao et al. (2001) and Setoguchi et al. (2003b). Their reports described the effects of guide vanes and rotor geometry. It was concluded that the guide vane contributed to postpone stalling, improving the turbine efficiency and the starting and transitional characteristics under running conditions. And the NACA four digit series with the thickness ratio of 20% was found to be a suitable choice for the blade profile of the Wells turbine. A modified Wells turbine, which has a positive setting angle of blades, was also shown to fit the asymmetric profile of flow rate with better performance characteristics (Setoguchi et al., 2003a). Kim et al. (2002a, 2003) employed numerical simulation to study the hysteretic characteristics and the effects of blade sweep. The numerical model was well validated to predict the performance of a Wells turbine without guide vanes, which provides the reference to the numerical simulation in this paper. Takao et al. (2006) applied the end plate to a Wells turbine without guide vanes, and experimentally studied the effects of plate size, plate type, and tip clearance. Results revealed that the attribution of the end plate existed in an increase in the torque coefficient. Mohamed et al. (2011) and Mohamed and Shapaan (2014) numerically optimized the airfoil shape to increase the tangential force, and studied the effects of blade pitch angle on improving the turbine efficiency. Finally it is worth noting that Halder et al. (2015) recently investigated the effects of blade tip clearance and a tip penetrating depth into casing on the performance of Wells turbine. They showed that the penetrating depth of 3% of the chord length produced highest power and widest operating range.

According to the study by Thakker and Dhanasekaran (2003), minimizing the adverse effects of tip clearance improved the turbine efficiency. Hence, the geometry of a blade penetrating into the duct is expected to reduce the tip clearance compared to the original turbine. And in the wing system of an airplane, the induced drag is generated by the distribution of lift across the wing, and is strongly influenced by tip vortices. Then the winglets are designed to reduce the strength of tip vortices and therefore cause the flow across the wing to be more two-dimensional (2-D) with less induced