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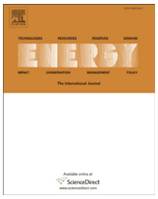

Comparative analysis of different wave turbine designs based on conditions relevant to northern coast of Egypt

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ABSTRACT

Wave energy has a great potential to solve the unrelenting energy deficiency in Egypt. The present work recommends Wells turbine as a suitable choice for the Egyptian coasts due to its simple and efficient operation under low input air flow. In addition, the possibility of extracting the wave energy from the Egyptian coasts was investigated using the oscillating water system based on real data from the site. To achieve this purpose, two-dimensional numerical models for Wells turbine airfoils, functioning under sinusoidal wave flow conditions, were built. Moreover, the running and starting characteristics under sinusoidal-flow conditions were investigated using a mathematical code. The results were discussed using the first law analysis, in addition to the second law analysis by using the entropy generation minimization method. It was found that the NACA0015 airfoil always gives a global entropy generation rate that is less than other airfoils by approximately −14%, −10.3% and −14.7% for the sinusoidal wave with time periods equal to 4, 6 and 8 s respectively. Moreover, the effects of blade profile, time period and solidity on the output power (kW) value were discussed.

1. Introduction

Egypt is now struggling to meet its own energy needs, experiencing one of its most serious energy crises for decades. The number of residents has increased by a million people over the past six months only, and global warming has caused an increase in the use of air conditioning in summer. Egypt's demand for electricity is growing rapidly and the need to develop alternative power resources is becoming ever more urgent, which necessitates looking for renewable energy options to help meet the increasing demand. For this end, the development of the renewable energy industry has become a priority over the recent years for the Egyptian government. The utilization of wave energy systems has escalated significantly over the past two decades, generally depending on oscillating water column (OWC) concept [1–3]. Wells turbine is one of the most efficient OWC technologies [4]. The characteristic feature of Wells turbine is that oscillating air flow produces a single direction rotation of the rotor without the use of a rectifying valve [5–9]. Wells turbine is usually characterized by four digit double zero NACA profile [10–13], where the shape of the NACA four digit profiles is determined by three parameters: the camber (first digit), the position of the camber (second digit), and the percentage of thickness to chord (third and fourth digits). Hence, profiles without a camber are symmetrical (NACA 00XX).

The overall performance of several design types of Wells turbine were investigated in Ref. [14] by using a semi-empirical method for predicting the turbine's performance in Ref. [15]. Similar comparisons were undertaken using an experimental measurement in Ref. [16]. It was observed that the contra-rotating turbine had an operational range which was similar to that of the monoplane turbine with guide vanes, and achieved similar peak efficiency. However, the resulting flow from the contra-rotating turbine was better than the monoplane turbine with guide vanes in the post-stall regime.

In order to improve the performance of the Wells turbine, the effect of end plate on the turbine characteristics was investigated in Refs. [17,18]. Using an experimental model and CFD method, it was shown that the peak efficiency increased by 4% approximately,

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Nomenclature

A	The total blade area. A = (z c b), m^2
A_r	Rotor area = πR_m^2, m^2
a	Margin distance for the end plate, m
b	Blade Span, m
c	Blade chord, m
C_D	Drag force coefficient
C_L	Lift force coefficient
C_P	Power coefficient
C_T	Torque coefficient
D	Drag Force, N
D_r	Rotor diameter, m
f	Wave frequency, Hz
F_A	Axial Force, N
F_t	Tangential Force, N
g	Leading edge offsetting of a blade from an axis, m
I	Moment of inertia, kg m^2
L	lift Force, N
Δp	Pressure difference across the turbine, N/m^2
Q	Flow rate through the rotor area, m^3/sec
R_h	Rotor radius at hub, m
R_m	Mean rotor radius = $\frac{R_t+R_h}{2}$, m
R_r	Rotor radius, m
R_t	Rotor radius at tip, m
Q	Flow rate through the rotor area, m^3/sec
S_{gen}	Local entropy generation rate (W/m^2K)
S_G	Global entropy generation rate (W/K)
S_{ij}	Mean strain rate
S_t	Thermal entropy generation rate (W/m^2K)
S_V	Viscous entropy generation rate (W/m^2K)
T_o	Reservoir temperature (K)
t_{sin}	The time period for sinusoidal wave = $^1/_f$, sec
T_L	Loading torque N m
TSR	Tip speed ratio = $\frac{\omega Rm}{V_{Am}}$
$\overline{u}_i$	Reynolds Averaged velocity component in i direction (m/s)
V	Axial velocity = $V_A \sin\left(\frac{2\pi t}{T}\right)$, m/s
V_A	Maximum value of axial velocity, m/s
V_r	Resultant air velocity, m/s
V_o	Initial velocity for computation (m/s)
W^*	Output power coefficient
W_{rev}	Reversible work
X_i	Inertia coefficient
X_L	Loading torque coefficient
Z	Number of blades
α	Angle of attack- the angle between the chord line and the direction of the fluid velocity, degree
η	Mean turbine efficiency
ρ	Air specific density, kg/m^3
σ	Turbine solidity = $\frac{Z\ C}{2\ \pi\ R_m}$
ϕ	Flow coefficient
ω	Rotor angular velocity, rad/sec

compared to the Wells turbine without an end plate. The calculations of the blade sweeps for the Wells turbine were investigated using a numerical code by Ref. [19] and experimentally with quasi-steady analysis in Ref. [20]. As a result, it was found that the performance of the Wells turbines was influenced by the blade sweep area. To achieve a high performance for the turbine, the appropriate sweep ratio selected was found to be 35%. In addition, setting the blades at their optimum pitch angle during compression and suction was expected to substantially improve turbine efficiency [8,21–28]. This setting for the blades is achieved by the turbine manufacturer in such a way that allows the turbine blades to rotate around their axis with an angle equals to ± optimum blade setting pitch angle. Furthermore, two-stage Wells turbines with symmetric and non-symmetric airfoils were investigated in Ref. [29]; the numerical algorithms were used to estimate the optimum shape of the airfoil with an increase of efficiency (by 2.1%) and of tangential force coefficient (by 6%), compared to the standard NACA 2421.

Exergy analysis was performed using the numerical simulation for steady state biplane Wells turbines in Ref. [30], where the upstream rotor had a design point second law efficiency of 82.3%, although the downstream rotor second law efficiency was equal to 60.7%. The entropy generation, due to viscous dissipation, around different 2D airfoil sections for Wells turbine was recently investigated by the authors in Refs. [31,32]. When Reynolds number increased from 6 × 104 to 1 × 105, the total entropy generation increased correspondingly by more than two folds for both airfoils. However, when Reynolds number further increased further to 2 × 105, the total entropy generation exhibited unintuitive values ranging from 25% less to 20% higher than the corresponding value at Reynolds number = 1 × 105. The efficiency of four different airfoils in compression cycle was found to be higher than suction cycle at a two-degree angle of attack. But when the angle of attack increased, the efficiency of suction cycle increased more than the compression one. This study suggested that there is a possible existence of a critical Reynolds number at which viscous irreversibilities take minimum values. Moreover, a comparison of total entropy generation, due to viscous dissipation, between a suggested design (variable chord) and a constant chord Wells turbine was presented in Ref. [33]. The detailed results demonstrated an increase in static pressure difference around new blade and a 26.02% average decrease in total entropy generation throughout the full operating range.

Most of the researchers investigated the performance of different airfoils designs and different operational conditions where analyzing the problem was based only on the parameter of first law of thermodynamics. It is essential to look at the second law of thermodynamics to form a deeper understanding of the problem, since it has shown very promising results in many applications, such as wind turbine in Refs. [34–39] and gas turbine in Refs. [40–44]. A numerical optimization algorithm based on CFD simulation was implemented in order to optimize the blade pitch angle in Refs. [45,46]. The standard NACA0021 and an optimized profile (AOP) were numerically investigated. The present CFD optimization results showed that the optimum blade pitch angle for NACA0021 was +0.3° while that of the AOP was equal to +0.6°. The present airfoils with the optimized pitch angle showed an average efficiency with an improvement of 3.4% for standard NACA0021 and 4.3% for the AOP.

The most bustling with life coast of the Southern Mediterranean Basin is the Egyptian coast, lying between the Nile Delta and the Libyan borders, with a potential of above 3.35 kW/m wave power in summer and 6.8 kW/m in winter [47,48], and wave energy of about 36003 kWh/m. The most active sea states have significant wave heights ranging between 1 and 4 m, and wave energy periods between 4 and 8 s. The regions with increased wave energy potential are mainly the western and southern coastlines of Cyprus Island,

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