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Coast of Egypt**

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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 seconds respectively. Moreover, the effects

1 of blade profile, time period and solidity on the output power (kW) value were
2 discussed.

3 Keywords: Wells turbine; Entropy generation; CFD; Analytical model; Sinusoidal
4 wave; Egyptian Coasts.

Nomenclature

A	The total blade area. $A = (z \ c \ b)$, m^2	S_{gen}	Local entropy generation rate (W/m ² K)
A_r	Rotor area $= \pi R_m^2$, m^2	S_G	Global entropy generation rate (W/K)
a	Margin distance for the end plate, m	S_{ij}	Mean strain rate
b	Blade Span, m	S_t	Thermal entropy generation rate (W/m ² K)
c	Blade chord, m	S_v	Viscous entropy generation rate (W/m ² K)
C_D	Drag force coefficient	T_o	Reservoir temperature (K)
C_L	Lift force coefficient	t_{sin}	The time period for sinusoidal wave $= 1/f$, sec
C_p	Power coefficient	T_L	Loading torque N m
C_T	Torque coefficient	TSR	Tip speed ratio $= \frac{\omega R_m}{V_{Am}}$
D	Drag Force, N	$\bar{u}_i$	Reynolds Averaged velocity component in i direction (m/s)
D_r	Rotor diameter, m	V	Axial velocity $= V_A \sin\left(\frac{2\pi t}{T}\right)$, m/s
f	Wave frequency, Hz	V_A	Maximum value of axial velocity, m/s
F_A	Axial Force, N	V_r	Resultant air velocity, m/s
F_t	Tangential Force, N	V_o	Initial velocity for computation (m/s)
g	Leading edge offsetting of a blade from an axis, m	W^*	Output power coefficient
I	Moment of inertia, kg m ²	W_{rev}	Reversible work
L	lift Force, N	X_i	Inertia coefficient
Δp	Pressure difference across the turbine, N/m ²	X_L	Loading torque coefficient

Q	Flow rate through the rotor area ,m ³ /sec	Z	Number of blades
R_h	Rotor radius at hub , m	α	Angle of attack- the angle between the chord line and the direction of the fluid velocity , degree
R_m	Mean rotor radius = $\frac{R_t+R_h}{2}$, m	η	Mean turbine efficiency
R_r	Rotor radius , m	ρ	Air specific density , kg/m ³
R_t	Rotor radius at tip , m	σ	Turbine solidity = $\frac{Z C}{2 \pi R_m}$
Q	Flow rate through the rotor area ,m ³ /sec	ϕ	Flow coefficient
		ω	Rotor angular velocity , rad/sec

1

2 **1. Introduction**

3 Egypt is now struggling to meet its own energy needs, experiencing one of its most
4 serious energy crises for decades. The number of residents has increased by a million
5 people over the past six months only, and global warming has caused an increase in the
6 use of air conditioning in summer. Egypt's demand for electricity is growing rapidly
7 and the need to develop alternative power resources is becoming ever more urgent,
8 which necessitates looking for renewable energy options to help meet the increasing
9 demand. For this end, the development of the renewable energy industry has become a
10 priority over the recent years for the Egyptian government. The utilization of wave
11 energy systems has escalated significantly over the past two decades, generally
12 depending on oscillating water column (OWC) concept [1-3]. Wells turbine is one of
13 the most efficient OWC technologies [4]. The characteristic feature of Wells turbine is
14 that oscillating air flow produces a single direction rotation of the rotor without the use
15 of a rectifying valve [5-9]. Wells turbine is usually characterized by four digit double

1 zero NACA profile [10-13], where the shape of the NACA four digit profiles is
2 determined by three parameters: the camber (first digit), the position of the camber
3 (second digit), and the percentage of thickness to chord (third and fourth digits). Hence,
4 profiles without a camber are symmetrical (NACA 00XX).

5 The overall performance of several design types of Wells turbine were investigated in
6 [14] by using a semi-empirical method for predicting the turbine's performance in [15].
7 Similar comparisons were undertaken using an experimental measurement in [16]. It
8 was observed that the contra-rotating turbine had an operational range which was
9 similar to that of the monoplane turbine with guide vanes, and achieved similar peak
10 efficiency. However, the resulting flow from the contra-rotating turbine was better than
11 the monoplane turbine with guide vanes in the post-stall regime.

12 In order to improve the performance of the Wells turbine, the effect of end plate on the
13 turbine characteristics was investigated in [17, 18]. Using an experimental model and
14 CFD method, it was shown that the peak efficiency increased by 4% approximately,
15 compared to the Wells turbine without an end plate. The calculations of the blade
16 sweeps for the Wells turbine were investigated using a numerical code by [19] and
17 experimentally with quasi-steady analysis in [20]. As a result, it was found that the
18 performance of the Wells turbines was influenced by the blade sweep area. To achieve
19 a high performance for the turbine, the appropriate sweep ratio selected was found to
20 be 35%. In addition, setting the blades at their optimum pitch angle during compression
21 and suction was expected to substantially improve turbine efficiency [8, 21-28]. This
22 setting for the blades is achieved by the turbine manufacturer in such a way that allows
23 the turbine blades to rotate around their axis with an angle equals to $\pm$ optimum blade
24 setting pitch angle. Furthermore, two-stage Wells turbines with symmetric and non-

1 symmetric airfoils were investigated in [29]; the numerical algorithms were used to
2 estimate the optimum shape of the airfoil with an increase of efficiency (by 2.1%) and
3 of tangential force coefficient (by 6%), compared to the standard NACA 2421.

4 Exergy analysis was performed using the numerical simulation for steady state biplane
5 Wells turbines in [30], where the upstream rotor had a design point second law
6 efficiency of 82.3%, although the downstream rotor second law efficiency was equal to
7 60.7%. The entropy generation, due to viscous dissipation, around different 2D airfoil
8 sections for Wells turbine was recently investigated by the authors in [31, 32]. When
9 Reynolds number increased from 6×10^4 to 1×10^5 , the total entropy generation
10 increased correspondingly by more than two folds for both airfoils. However, when
11 Reynolds number further increased further to 2×10^5 , the total entropy generation
12 exhibited unintuitive values ranging from 25% less to 20% higher than the
13 corresponding value at Reynolds number = 1×10^5 . The efficiency of four different
14 airfoils in compression cycle was found to be higher than suction cycle at a two-degree
15 angle of attack. But when the angle of attack increased, the efficiency of suction cycle
16 increased more than the compression one. This study suggested that there is a possible
17 existence of a critical Reynolds number at which viscous irreversibilities take minimum
18 values. Moreover, a comparison of total entropy generation, due to viscous dissipation,
19 between a suggested design (variable chord) and a constant chord Wells turbine was
20 presented in [33]. The detailed results demonstrated an increase in static pressure
21 difference around new blade and a 26.02% average decrease in total entropy generation
22 throughout the full operating range.

23 Most of the researchers investigated the performance of different airfoils designs and
24 different operational conditions where analyzing the problem was based only on the

1 parameter of first law of thermodynamics. It is essential to look at the second law of
2 thermodynamics to form a deeper understanding of the problem, since it has shown
3 very promising results in many applications, such as wind turbine in [34-39] and gas
4 turbine in [40-44]. A numerical optimization algorithm based on CFD simulation was
5 implemented in order to optimize the blade pitch angle in [45, 46]. The standard
6 NACA0021 and an optimized profile (AOP) were numerically investigated. The
7 present CFD optimization results showed that the optimum blade pitch angle for
8 NACA0021 was +0.3 degree while that of the AOP was equal to +0.6 degree. The
9 present airfoils with the optimized pitch angle showed an average efficiency with an
10 improvement of 3.4% for standard NACA0021 and 4.3% for the AOP.

11 The most bustling with life coast of the Southern Mediterranean Basin is the Egyptian
12 coast, lying between the Nile Delta and the Libyan borders, with a potential of above
13 3.35 kW/m wave power in summer and 6.8 kW/m in winter [47, 48], and wave energy
14 of about 36003 kWh/m. The most active sea states have significant wave heights
15 ranging between 1 and 4 m, and wave energy periods between 4 and 8 second. The
16 regions with increased wave energy potential are mainly the western and southern
17 coastlines of Cyprus Island, the sea area of Lebanon and Israel, as well as the coastline
18 of Egypt, especially around Alexandria. The significant differences between the sea in
19 Egypt and other seas are that the sea wave in Egypt is relatively low but also stable.
20 Hence, the potential wave energy can be revealed and exploited [49]. Otherwise, sea
21 states with wave heights greater than 5 m are not very important for the annual energy
22 [50].

23 The objective of this work is to carry out a study to prove that the Wells turbine could
24 be a suitable wave energy extractor for the Egyptian coasts and breakwater, through a

1 study on the force analysis (torque coefficient) and velocity analysis (global entropy
 2 generation rate) for different turbine airfoils. To achieve this goal, the CFD technique
 3 was used along with an analytical model that investigated the main flow characteristics
 4 and estimated the hydrodynamics output power. According to the literature, it is the
 5 first time to study the availability of extracted wave energy around Egyptian coast area
 6 via a Wells turbine.

7 **2. Mathematical formulations**

8 This section describes the first law analysis method used in this study to measure. In
 9 addition, the efficiency calculations for the Wells turbine under sinusoidal-flow
 10 conditions were studied using an analytical mathematical model. The net torque which
 11 drives the Wells turbine is resultant of the summation of all torques exerted on the
 12 turbine as follows:

$$13 \quad \sum Torque = T_{aerodynamic} - T_{Load} - T_{Loss} \quad (1)$$

$$14 \quad \sum Torque = \frac{1}{2} \rho (V_a^2 + (\omega R_m)^2) A R_m C_T - T_L - T_{Loss} \quad (2)$$

15 where T_L is the load torque

16 By applying the angular moment equation of motion along turbine axis, we get

$$I \frac{d\omega}{dt} = \sum Torque \quad (3)$$

17 where I is the rotor mass moment of inertia and ω is the angular velocity of the rotor
 18 varying with time.

19 Neglecting the torque losses and substituting from eq. (2) into (3) we get:

$$I \frac{d\omega}{dt} = \frac{1}{2} \rho (V_a^2 + (\omega R_m)^2) z c b R_m C_T - T_L \quad (4)$$

1 The load torque can be expressed in a non-dimensional form as:

$$X_L = \frac{T_L}{\rho \pi R_m^3 V_a^2} \quad (5)$$

2 Hence, the rotor equation of motion is:

$$I \frac{d\omega}{dt} = \frac{1}{2} \rho (V_a^2 + (\omega R_m)^2) z c b R_m C_T - X_L \rho \pi R_m^3 V_a^2 \quad (6)$$

$$\frac{d\omega}{dt} = \frac{\frac{1}{2} \rho (V_a^2 + (\omega R_m)^2) z c b R_m C_T - X_L \rho \pi R_m^3 V_a^2}{I} \quad (7)$$

$$\int d\omega = \int \frac{\frac{1}{2} \rho (V_a^2 + (\omega R_m)^2) z c b R_m C_T - X_L \rho \pi R_m^3 V_a^2}{I} dt \quad (8)$$

$$\omega_2 - \omega_1 = \frac{\frac{1}{2} \rho (V_a^2 + (\omega R_m)^2) z c b R_m C_T - X_L \rho \pi R_m^3 V_a^2}{I} t_2 - t_1 \quad (9)$$

3 For the first law of thermodynamics, the lift and drag coefficient C_L and C_D are
 4 computed from the post processing software. Then, the torque coefficient can be
 5 expressed as [51]:

$$C_T = (C_L \sin \alpha - C_D \cos \alpha) \quad (10)$$

7 The flow coefficient ϕ relating tangential and axial velocities of the rotor is defined as:

$$\phi = \frac{V_a}{\omega * R_m} \quad (11)$$

9 where the α angle of attack is equal to:

$$\alpha = \tan^{-1} \frac{V_a}{\omega R_m} \quad (12)$$

11 The mean output power is expressed as:

$$\text{Output Power} = T_L * \omega_{avr} \quad (13)$$

12 where ω_{avr} is the average velocity during a complete cycle given by:

$$\omega_{avr} = \frac{1}{T} \int_0^T \omega(t) dt \quad (14)$$

1 Hence, the output is

$$Output Power = X_L * \pi * \rho * V_{Am}^2 * R_m^3 * \omega_{avr} \quad (15)$$

2 where X_L is the non-dimensional loading torque.

$$Input power = \frac{1}{T} \int_0^T \Delta P * Q dt \quad (16)$$

3 where Q is the valume flow rate passing through the rotor area to the turbine and given

4 by:

$$Q = V_A A_r \quad (17)$$

5 The efficiency in the first law of thermodynamics (μ_F) is defined as:

$$6 \quad \mu_F = \text{mean value of } \frac{Output Power}{Input Power} = \frac{\frac{1}{T} \int_0^T T_L \omega(t) dt}{\frac{1}{T} \int_0^T \Delta P * Q dt} \quad (18)$$

7 Figure 1 shows the flow chart that displays the main steps that apply the mathematical
 8 model using the MATLAB software. These steps are based on the equations that are
 9 derived above, starting from setting the initial angular velocity which causes the initial
 10 motion, and operational conditions. The aim is to calculate the generated force on the
 11 blade, the instantaneous angular velocity, the output power, and the turbine efficiency.
 12 In this work, the rotor geometry data from existing Wells turbine projects (the
 13 OSPREY) [52] is used as inlet parameters for the mathematical model. This is in
 14 addition to the operating condition data based on the real data from the site, namely,
 15 the Southern Mediterranean Basin [50].

3. Numerical methodology

The numerical simulations were conducted with the commercial CFD software ANSYS Fluent. The unsteady Navier-Stokes equations were solved by a finite volume for an incompressible flow and turbulence was modeled using the Large Eddy Simulation. The governing equations employed for Large Eddy Simulation (LES) were obtained by filtering the time-dependent Navier-Stokes equations. The filtering process was chosen as it effectively filters out eddies whose scales are smaller than the filter width or grid spacing used in the computations. The resulting equations, thus, govern the dynamics of large eddies. A filtered variable (denoted by an over-bar) is defined by:

$$\bar{\phi}(x) = \int_D \phi(x') G(x, x') dx' \quad (19)$$

where D is the fluid domain and G is the filter function that determines the scale of the resolved eddies. In FLUENT, the finite-volume discretization itself implicitly provides the filtering operation [53]:

$$\bar{\phi}(x) = \frac{1}{V} \int_V \phi(x') dx', \quad x' \in V \quad (20)$$

where V is the volume of a computational cell, the filter function, $G(x, x')$, implied here is then

$$G(x, x') = \begin{cases} 1/V & \text{for } x' \in V \\ 0 & \text{otherwise} \end{cases} \quad (21)$$

The LES model was applied to essentially incompressible (but not necessarily constant-density) flows. Filtering the incompressible Navier-Stokes equations, one obtained [54]

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho \bar{u}_i}{\partial x_i} = 0 \quad (22)$$

$$\frac{\partial}{\partial t} (\rho \bar{u}_i) + \frac{\partial}{\partial x_j} (\rho \bar{u}_i \bar{u}_j) = \frac{\partial}{\partial x_j} \left(\mu \frac{\partial \bar{u}_i}{\partial x_j} \right) - \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} \quad (23)$$

1 where τ_{ij} is the sub-grid-scale stress defined by

$$2 \quad \tau_{ij} = \rho \overline{u_i u_j} - \rho \overline{u_i} \overline{u_j} \quad (24)$$

3 The sub-grid-scale stresses resulting from the filtering operation were unknown, and
4 required modeling. The majority of sub-grid-scale models were eddy viscosity models
5 of the following form:

$$6 \quad \tau_{ij} - \frac{1}{3} \tau_{kk} \sigma_{ij} = -2\mu_t \overline{S}_{ij} \quad (25)$$

7 where $\overline{S}_{ij}$ is the rate-of-strain tensor for the resolved scale defined by:

$$8 \quad \overline{S}_{ij} = \frac{1}{2} \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right) \quad (26)$$

9 and μ_t is the sub-grid-scale turbulent viscosity, for which the Smagorinsky-Lilly model
10 is used. The most basic of sub-grid-scale models for “Smagorinsky-Lilly model” was
11 proposed by Smagorinsky [55] and further developed by Lilly [56]. In the
12 Smagorinsky-Lilly model, the eddy viscosity is modeled by:

$$13 \quad \mu_t = \rho L_s^2 |\overline{S}| \quad (27)$$

14 where L_s is the mixing length for sub-grid-scale models and $|\overline{S}| = \sqrt{2\overline{S}_{ij}\overline{S}_{ij}}$. The L_s is
15 computed using:

$$16 \quad L_s = \min(kd, C_s V^{1/3}) \quad (28)$$

17 where C_s is the Smagorinsky constant, $k = 0.42$, d is the distance to the closest wall,
18 and V is the volume of the computational cell. Lilly derived a value of 0.23 for C_s from
19 homogeneous isotropic turbulence. However, this value was found to cause excessive
20 damping of large-scale fluctuations in the presence of mean shear or in transitional
21 flows. $C_s = 0.1$ was found to yield the best results for a wide range of flows.

1 The transport equations of such models can be found in turbulence modeling texts such
 2 as [57]. The second law of thermodynamics defines the net-work transfer rate $\dot{W}$ as
 3 [58]:

$$4 \quad \dot{W}_{rev} - \dot{W} = T_o S_{gen} \quad (29)$$

5 With the use of entropy analysis method, it is possible to express the irreversible
 6 entropy generation in terms of the derivatives of local flow quantities in the absence of
 7 phase changes and chemical reactions. The two dissipative mechanisms in viscous flow
 8 are the strain-originated dissipation and the thermal dissipation, which correspond to a
 9 viscous and a thermal entropy generation respectively [59], and can be expressed as:

$$10 \quad S_{gen} = S_v + S_{th} \quad (30)$$

11 In incompressible isothermal flow, such as the case in hand, the thermal dissipation
 12 term vanishes. The local viscous irreversibilities, therefore, can be expressed as:

$$13 \quad S_v = \frac{\mu}{T_o} \dot{\phi} \quad (31)$$

14 where $\dot{\phi}$ is the viscous dissipation term that is expressed in two dimensional Cartesian
 15 coordinates as [59]:

$$16 \quad \dot{\phi} = 2 \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial v}{\partial y} \right)^2 \right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 \quad (32)$$

17 and the global entropy generation rate is hence expressed as [31]:

$$18 \quad S_G = \iint_{xy} S_v dy dx \quad (33)$$

19 and finally, the second law efficiency is defined as [32]:

$$20 \quad \eta_s = \frac{KE}{Exergy} \quad (34)$$

21 where $Exergy = KE + S_G$ and $KE = \frac{1}{2} V^2$

1 From the above equation, it can be concluded that the increase in torque coefficient
2 leads to an increase in the first law efficiency. On the other hand, the decrease in the
3 global entropy generation rate leads to an increase in the second law efficiency.

4 **3.1. Computational model and boundary conditions**

5 Two-dimensional numerical models for NACA0015 airfoils were built up and validated
6 against experimental measurements under unsteady flow conditions. The
7 computational domain was discretized to Cartesian structured finite volume cells using
8 GAMBIT code. The second order upwind interpolation scheme was used in this work,
9 where its results were approximately similar to those yielded by third order MUSCL
10 scheme in the present situation. In addition, in some cases the third order MUSCL
11 scheme showed high oscillatory residual during the solution.

12 The axial flow of Wells Turbine is modeled as a sinusoidal wave in this simulation.
13 Therefore, inlet boundary conditions are set to change with time. In order to apply the
14 inlet boundary condition, inlet velocity with periodic function (see Figure 2) is
15 generated as follows:

$$16 \quad V_{(t)} = V_o + V_A \sin (\sin 2\pi f t_{sin}) \quad (35)$$

17 where t_{sin} is equal to (4, 6, and 8) seconds and is set as one period in this simulation,
18 considering the real data from the Egyptian coasts. The time step is set as 0.000296721
19 second in order to satisfy CFL (Courant Friedrichs Lewy) condition equal to 1 [60].
20 Furthermore, the sinusoidal wave condition creates various Reynolds numbers up to 2
21 $\times 10^4$.

3.2. Grid sensitivity test (Verification)

In order to ensure that the numerical model is free from numerical diffusion and artificial viscosity errors, several grid numbers were tested to estimate the number of grid cells required to establish a grid-independent solution. Table 1 shows the specifications of different grids used in unsteady two-dimensional models with constant velocity. Figure 3 shows the pressure coefficient distribution on the upper and lower surfaces of the NACA0012 airfoil as computed by the four grids. Grid D required more time than grid C, yielding similar results. Therefore, grid C was chosen to conduct the analysis presented hereafter.

4. Models validation

4.1. Validation of the Analytical Model

The experimental data from [61, 62] for an unsteady flow was used to validate our analytical mathematical model. The experimental data from a test rig was used by Wave Energy Research Team, University of Limerick. It consisted of a bell mouth entry, test section, drive and transmission section, a plenum chamber with honeycomb section, a calibrated nozzle, and a centrifugal fan. The turbine test section had an internal diameter of 600 mm and a fabricated rotor of a 598 mm diameter, leaving a tip clearance of 1 mm. The hub diameter is 358.8 mm, providing a hub to tip ratio of 0.6 and chord length of 120 mm. The turbine was mounted on a shaft in a cylindrical annular duct. The shaft was coupled to motor/generator via a torque meter. The turbine blades (8 blades for solidity = 0.64 and 6 blades for solidity = 0.48) were set on the hub at a 90° angle of stagger along the y-axis. Figure 4 shows a good agreement between the mean efficiency

1 from reference [61, 62] with t_{sin} equal to 9.2 sec, and the predicted mean efficiency
2 from the mathematical code at same t_{sin} .

3 **4.2. Validation of the CFD model**

4 Large Eddy Simulation model was used to model the flow around NACA0015 airfoil
5 in order to give the best agreement with experimental data adopted from [63-65]. The
6 Eddy model proved effective, where the data was used to simulate and validate the CFD
7 model as it had a suitable Reynolds number equal to 2×10^4 , and where the torque
8 coefficient result was clear. The validation case details for Wells turbine prototype are
9 characterized by the following parameters: hub radius, is equal to 101 mm; tip radius,
10 equal to 155 mm; NACA0015 blade profile with constant chord length, equal to 74
11 mm; and a number of blades, equal to 7. Therefore, the hub-to-tip ratio and the solidity
12 are equal to 0.65 and 0.64, respectively. The blades were produced with composite
13 material reinforced by carbon fiber with suitable attachment. The experimental data
14 was at steady flow conditions. Therefore, the average value for the lift and drag
15 coefficient was used to calculate one value for the torque coefficient for each angle of
16 attack. Figure 5 displays the result of using the computational model under sinusoidal
17 inlet flow velocity with experimental data from [63-65]. A very good agreement was
18 achieved.

19

5. Results and Discussion

The CFD models were used, the results of which simulated the compression cycle with accelerating and decelerating flow. Otherwise, the wave cycle with the compression and suction stage was used in the analytical method.

5.1. First law of thermodynamics analysis

The comparison between the torque coefficient for accelerating and decelerating flow with four different airfoils was shown in Figure 6. It can be noted that the sinusoidal wave with t_{sin} of 4 sec has a large torque coefficient. Moreover, the torque coefficient value at decelerating flow is always higher than that at accelerating flow, except NACA0015 for sinusoidal wave with 6 sec. In addition, the sinusoidal wave with 8 sec has the smallest difference in torque coefficient values between accelerating and decelerating flow as show in Table 2.

To understand the reasons why the torque coefficient at decelerating flow is mostly higher than that at accelerating flow, the contours and path line of velocity around the blade were investigated. Figures 7 and 8 show the contours and path line of velocity magnitude around the NACA0020 airfoil blade at the same instantaneous velocity (2.08 m/s). It can be shown that at an accelerating flow, the airfoil has very low velocities (see Figure 7) and a high separation layer (see Figure 8) at the trailing edge area than that in a decelerating flow condition. This difference between the accelerating and the decelerating flow decreases, with an increase in t_{sin} for the sinusoidal wave.

Figures 9 and 10 show the pressure distribution around the upper and lower surface of NACA0020, at accelerating and decelerating flow, and at velocity equal to 2.09 m/s with different time periods. The difference between the pressure value at upper and lower surface has a direct effect on the torque coefficient value, whereby, this difference

1 at decelerating flow was lower than that at accelerating flow except t_{sin} with 8 sec. This
2 behaviour is the same as that of the torque coefficient value. When comparing between
3 the accelerating and decelerating flow, it can be noted that the decelerating flow has a
4 negative pressure value. Furthermore, the increase in time period is accompanied by a
5 decrease in pressure value at accelerating flow. On the other hand, the increase in time
6 period is accompanied by an increase in pressure value at decelerating flow. The low-
7 pressure area was shown around the trailing edge, and increased with the increase of
8 time period.

9 The total average torque coefficient during the cycle for four different airfoils at
10 different time periods was shown in Figure 11. It can be concluded that the sinusoidal
11 wave, with t_{sin} equal to 4 sec, has the highest torque coefficient, where, NACA0020
12 (with t_{sin} equal to 4 sec) gives a torque coefficient higher than NACA0012 by 13%,
13 NACA0015 by 5% and NACA0021 by 2%. For the sinusoidal wave with t_{sin} of 6 sec,
14 the airfoil NACA0012 gives a torque coefficient higher than NACA0015 by 4%, but it
15 was approximately the same as NACA0020, with an increase of only 0.6%. Also,
16 NACA0012 gives a torque coefficient that is 6% higher than NACA0021. Finally, for
17 the sinusoidal wave with t_{sin} equal to 8 sec, the NACA0012 gives a torque coefficient
18 higher than NACA0015 by 7%, NACA0020 by 18% and NACA0021 by 17%.

19 Figure 12 shows the instantaneous torque coefficient at a compression cycle for
20 different airfoils (NACA0012, NACA0015, NACA0020 and NACA0021) with
21 different time periods (4 sec, 6 sec and 8 sec). It can be seen that in the first half of each
22 cycle (accelerating flow), NACA0012 always has a higher torque coefficient. The
23 comparison between the maximum torque coefficient values for each time period cycle
24 was shown in Figure 13. The NACA0012 airfoil section has the highest value at

1 sinusoidal wave cycles with t_{sin} equal to 6 sec and with t_{sin} equal to 8 sec. On the other
2 hand, the NACA0020 airfoil section has the highest value at the sinusoidal wave cycle
3 with t_{sin} equal to 4 sec. In addition, the NACA0020 airfoil section (with t_{sin} equal to
4 4 sec) creates a torque coefficient more than NACA0012 (with t_{sin} equal to 8 sec) by
5 54%, NACA0012 (with t_{sin} equal to 6 sec) by 44%, and NACA0012 (with t_{sin} equal
6 to 4 sec) by 13%.

7 Figure 14 highlights the effect of the low velocity area and separation layer at trailing
8 edge by velocity contours and path line around the NACA0012 airfoil at a maximum
9 velocity of 2.92 m/s. It is clear that the torque coefficient is influenced by the low
10 velocity area and separation layer at trailing edge. When the low velocity area at trailing
11 edge increases, the torque coefficient value decreases. Similarly, as the separation layer
12 at trailing edge increases, the torque coefficient value also decreases. The pressure
13 distribution around the upper and lower surface of airfoil at accelerating and
14 decelerating flow was shown in Figure 15 at a maximum velocity of (2.92 m/s), with
15 different time periods (4, 6 and 8 sec). The higher disturbances occurring in separation
16 layers at the upper surface than those occurring at the lower surface (Figure 14) is due
17 to the irregular values of pressure at the upper surface. The low pressure areas around
18 the trailing edge increase the separation layer at the trailing edge; therefore, the
19 separation layers at a 4 second time period have lowest disturbances and lowest low-
20 pressure areas around the trailing edge. Table 3 summarizes the torque coefficient at
21 different time periods (t_{sin} equal to 4 sec, 6 sec and 8 sec) for the four airfoils
22 (NACA0012, NACA0015, NACA0020 and NACA0021).

5.2. Second law of thermodynamics analysis

Figure 16 highlights the comparison between the global entropy generation rate for accelerating and decelerating flows for the four different airfoils. All airfoils in the accelerating flow create global entropy generation rate lower than that created in the decelerating flow. The difference in the global entropy generation rate between the accelerating and decelerating flows is not influenced by the change in time period (see Table 4). As an average for all airfoils, the sinusoidal wave cycle with t_{sin} of 8 sec has the lowest difference in S_G between accelerating and decelerating flows for the four different airfoils.

The contours of global entropy generation rate around the NACA0021 at the instantaneous velocity (2.08 m/s) for the accelerating and decelerating flow were represented in Figure 17. It can be seen that the global entropy generation rate around the airfoil section in the decelerating flow was higher than that in the accelerating flow at the three different time periods (as noted above in Figure 16). The average value of the global entropy generation rate for each airfoil during the sinusoidal cycle with three different time periods was shown in Figure 18. It can be concluded that the NACA0015 has the lowest value of the global entropy generation rate at the three different time periods (4 sec, 6 sec and 8 sec), when it was compared with other airfoils (NACA0012, NACA0020 and NACA0021). See Table 5 for more details.

Figure 19 shows the contours of the global entropy generation rate at a maximum velocity (2.92 m/s) around NACA0015 airfoil with three different time periods. It can be seen that NACA0015 at sinusoidal wave with t_{sin} equal to 8 sec has a lower global entropy generation rate than other time periods for the same airfoil (NACA0015) and same velocity (2.92 m/s). Hence, Figure 20 compares between the values of S_G (Figure

20, A) and μ_S (Figure 20, B) for NACA0015 at three different time periods. It can be concluded that the NACA0015 (with t_{sin} equal to 8 sec) has lower S_G than NACA0015 (with t_{sin} equal to 6 sec) by -6% and NACA0015 (with t_{sin} equal to 4 sec) by -3%. In addition, the μ_S of NACA0015 (with t_{sin} equal to 8 sec) is higher than NACA0015 (with t_{sin} equal to 6 sec) by 1% and NACA0015 (with t_{sin} equal to 4 sec) by 2%. Table 6 summarizes the global entropy generation rate values at different time periods (t_{sin} equal to 4 sec, 6 sec and 8 sec) for the four airfoils (NACA0012, NACA0015, NACA0020 and NACA0021).

5.3. Analytical analysis

To examine the effect of wave time period (operating parameter), as well as solidity and airfoil section (design parameters) on the starting and running characteristics, a mathematical analysis was used. It is also used to estimate the turbine efficiency and the output power. The mathematical model gives the relationship of rotor angular velocity with time as a curve in Figure 21, where the figure shows the NACA0012 airfoil at a time period equal to 6 sec with solidity equal to 0.64 in free running condition and with different loading torque coefficients. Furthermore, it can be noted that the rotor angular velocity was oscillating around a certain average value due to the oscillating inlet velocity.

Figure 22 represents starting and running characteristics by change in specific parameters, such as time period, solidity and airfoil section. It can be noted that the crawling condition appears at the starting period for the sinusoidal wave cycle with t_{sin} equal to 4 sec (Figure 22 A). Otherwise, the three different time periods give the same average velocity (51.6 rad/s) after the starting period. According to Figure 22 B the change in solidity from 0.64 to 0.8 does not have an effect (approximately) on the

1 starting and running characteristics. On the other hand, the NACA0015 airfoil section
2 has the same starting characteristics of NACA0012 but lower rotor average velocity
3 (45.9 rad/s) than NACA0012, see Figure 22 C.

4 The mean turbine efficiency under sinusoidal flow conditions with different operating
5 and design parameters was shown in Figure 23. It can be noted that the peak efficiency
6 of the turbine which has sinusoidal wave with t_{sin} equal to 4 sec is higher than that with
7 6 sec and 8 sec by 8%, as shown in Figure 23 A. It can also be noted that the turbine
8 which has sinusoidal wave with t_{sin} equal to 4 sec works with a higher flow coefficient
9 than that with 6 sec and 8 sec by 17%. Figure 23 B shows that the increase in turbine
10 solidity from 0.64 to 0.8 decreases the peak efficiency by 1% and does not have an
11 effect on the flow coefficient. On the other hand, the change in the airfoil section of a
12 turbine from NACA0012 to NACA0015 does not have an effect on the peak efficiency.
13 However, the turbine with NACA0015 airfoil section works with a higher flow
14 coefficient by 15% than that with NACA0012 airfoil section.

15 Figure 24 presents the net output power for the Wells turbine under different operating
16 and design parameters based on the real data from the Egyptian northern coast. It can
17 be concluded that the operating condition inlet flow with 6 sec time period gives a
18 maximum output power that is higher than 4 sec by 19%, and 8 sec by 1%, see Figure
19 24 A. In addition, the change in the design parameters had an effect on the output power
20 value. So, the increase in solidity from 0.64 to 0.8 came with an increase in the net
21 output power by 18% (Figure 24 B). Moreover, Figure 24 C shows that the Wells
22 turbine with NACA0012 airfoil section has a higher net output power than that with
23 NACA0015 airfoil section by 31%. These values were generated from one turbine
24 without any attached guide vans or other enhanced performances, but in the real station,
25 the number of turbine reached two turbines such as the Prototype OWC device (biplane)

[66] and LIMPET [67-72] (contra-rotating) in Scotland. Furthermore, the number of turbines can reach four as in the OSPREY [52] used in Scotland or sixteen turbines such as in Mutriku Wave Energy Plant [73, 74] in Spain. In addition, the guide vans can be attached to increase the turbine performance such as Mighty Whale [75] in Japan and The Pico Power Plant [76-81] in Portugal.

6. Conclusion

The performance of Wells turbine was investigated by the aerodynamic force (i.e. first law) efficiency as well as the entropy (i.e. second law) efficiency under oscillating flow conditions. The work was performed by using time-dependent CFD models of different NACA airfoils under sinusoidal flow boundary conditions. Besides, an analytical analysis was used to study the starting and running characteristics under sinusoidal flow conditions with different operating and design parameters. Furthermore, the turbine efficiency curve and the net output power were estimated. From the comparison between the maximum torque coefficient values for each time period cycle it can be concluded that the generating torque coefficient on the NACA0020 airfoil section (with t_{sin} equal to 4 sec) was higher than NACA0012 (with t_{sin} equal to 8 sec) by 54%, NACA0012 (with t_{sin} equal to 6 sec) by 44% and NACA0012 (with t_{sin} equal to 4 sec) by 13%. Moreover, NACA0015 had shown a decrease in the value of S_G at the three different t_{sin} (4 sec, 6 sec and 8 sec) by -14%, -10.3% and -14.7%, respectively as an average value. On the other hand, for NACA0015, the lowest S_G was generated when t_{sin} was equal to 8 sec with an average of -4.5% less S_G than that of t_{sin} equal to 4 and 6 sec. 2.2 kW was the maximum output power value that can be achieved by Wells turbine with NACA0012 airfoil section and solidity equal to 0.8, under sinusoidal wave with t_{sin} equal to 6 sec.

1 Future research should focus on design optimization to create an optimum design,
2 which has a maximum torque coefficient, a minimum entropy generation, in addition
3 to the highest output power value. Furthermore, the study recommends the use of wave
4 energy in Egypt as a way to cut down on excessive high fossil fuel usage.

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1 Highlights:

- 2 • The wave energy in Egypt is the way to reduce fossil fuel usage.
- 3 • First and second law analyses of flow features around the blade were
- 4 presented.
- 5 • The running and starting characteristics have been investigated using
- 6 analytical code.
- 7 • NACA0015 airfoil always gives global entropy generation rate less than
- 8 other airfoils.
- 9 • The effect of operating and design parameters on the output power value
- 10 was discussed.

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Figure 1 Flow chart of implementing analytical mathematical model on Wells turbine performance

Figure 2 The sinusoidal waves boundary condition, which represents a regular oscillating water column

Figure 3 Pressure coefficient plotted on the normalized airfoil cord at different grid resolutions

Figure 4 Mean efficiency of NACA0015 under sinusoidal flow conditions with solidity = 0.64

Figure 5 Measured torque coefficient from reference (63-65) and calculated torque coefficient from CFD unsteady flow with sinusoidal inlet velocity

Figure 6 Comparisons between the torque coefficient during the accelerating and decelerating flow for four different airfoils, A) $t_{sin} = 4$ sec, B) $t_{sin} = 6$ sec and C) $t_{sin} = 8$ sec.

Figure 7 Contour of velocity magnitude at velocity equal to 2.08 (m/s) around the NACA0020 airfoil for sinusoidal input flow, Accelerating flow A) $t_{sin} = 4$ sec, C) $t_{sin} = 6$ sec, E) $t_{sin} = 8$ sec and Decelerating flow B) $t_{sin} = 4$ sec, D) $t_{sin} = 6$ sec, , F) $t_{sin} = 8$ sec

Figure 8 Path line of velocity magnitude at velocity equal to 2.08 (m/s) around the NACA0020 airfoil for sinusoidal input flow, Accelerating flow A) $t_{sin} = 4$ sec, C) $t_{sin} = 6$ sec, E) $t_{sin} = 8$ sec and Decelerating flow B) $t_{sin} = 4$ sec, D) $t_{sin} = 6$ sec, , F) $t_{sin} = 8$ sec

Figure 9 Contours of pressure coefficient around the airfoil, Accelerating flow A) $t_{sin} = 4$ sec, C) $t_{sin} = 6$ sec, E) $t_{sin} = 8$ sec and Decelerating flow B) $t_{sin} = 4$ sec, D) $t_{sin} = 6$ sec, F) $t_{sin} = 8$ sec

Figure 10 Pressure coefficient distribution on the upper and lower surface of the airfoil, Accelerating flow A) $t_{sin} = 4$ sec, C) $t_{sin} = 6$ sec, E) $t_{sin} = 8$ sec and Decelerating flow B) $t_{sin} = 4$ sec, D) $t_{sin} = 6$ sec, F) $t_{sin} = 8$ sec

Figure 11 Total average values for the torque coefficient during the velocity cycle for the four different airfoils, A) $t_{sin} = 4$ sec, B) $t_{sin} = 6$ sec and D) $t_{sin} = 8$ sec.

Figure 12 The instantaneous values for the torque coefficient during the compression cycle for four different airfoils, A) $t_{sin} = 4$ sec, B) $t_{sin} = 6$ sec and D) $t_{sin} = 8$ sec.

Figure 13 The comparison between the maximum torque coefficients for each velocity cycle.

Figure 14 Contours of velocity magnitude at maximum velocity equal to 2.92 (m/s) around the NACA0012 airfoil for sinusoidal input flow, A) $t_{sin} = 4$ sec, C) $t_{sin} = 6$ sec, E) $t_{sin} = 8$ sec, and path line colored by velocity magnitude for B) $t_{sin} = 4$ sec, D) $t_{sin} = 6$ sec, F) $t_{sin} = 8$ sec

Figure 15 Contours of pressure coefficient A) $t_{sin} = 4$ sec, C) $t_{sin} = 6$ sec, E) $t_{sin} = 8$ sec, and Pressure coefficient distribution on the upper and lower surface of the airfoil B) $t_{sin} = 4$ sec, D) $t_{sin} = 6$ sec, F) $t_{sin} = 8$ sec

Figure 16 Comparisons between the global entropy generation rate during the accelerating and decelerating flow for the four different airfoils, A) $t_{sin} = 4$ sec, B) $t_{sin} = 6$ sec and C) $t_{sin} = 8$ sec.

Figure 17 Contour of global entropy generation rate at velocity equal to 2.08 (m/s) around the NACA0021 airfoil for sinusoidal input flow, A) accelerating flow with $t_{sin} = 4$ sec, B) decelerating flow with $t_{sin} = 4$ sec, C) accelerating flow with $t_{sin} = 6$ sec, D) decelerating flow with $t_{sin} = 6$ sec, E) accelerating flow with $t_{sin} = 8$ sec, F) decelerating flow with $t_{sin} = 8$ sec.

Figure 18 Total average values for the global entropy generation rate during the velocity cycle for four different airfoils, A) $t_{sin} = 4$ sec, B) $t_{sin} = 6$ sec and C) $t_{sin} = 8$ sec.

Figure 19 Contour of global entropy generation rate at maximum velocity equal to 2.92 (m/s) around the NACA0015 airfoil for sinusoidal input flow, A) $t_{sin} = 4$ sec, B) $t_{sin} = 6$ sec and C) $t_{sin} = 8$ sec.

Figure 20 The comparison between the NACA0015 at three different time periods (8 sec, 6 sec and 4 sec), A) the global entropy generation rate and B) the second law efficiency.

Figure 21 Angular velocity variations with time for different loading torque coefficient.

Figure 22 Angular velocity variation with time in free running condition, A) different time period ($t_{sin} = 4$ sec, 6 sec and 8 sec), B) different solidity (0.64 and 0.8) and C) different airfoils section (NACA0012 and NACA0015).

Figure 23 The mean efficiency of turbine under sinusoidal flow conditions, A) different time periods ($t_{sin} = 4$ sec, 6 sec and 8 sec), B) different solidity (0.64 and 0.8) and C) different airfoils section (NACA0012 and NACA0015).

Figure 24 The value of output power for the turbine under sinusoidal flow conditions, A) different time periods ($t_{sin} = 4 \text{ sec}, 6 \text{ sec}$ and 8 sec), B) different solidity (0.64 and 0.8) and C) different airfoils section (NACA0012 and NACA0015).

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Table 1 Specification of grids

Grid	No. of Cells	First cell	Growth rate	Aspect ratio	Equi-Angle skew
A	112603	1×10^{-4}	1.02	1.996	0.429
B	200017	1×10^{-5}	1.015	2.466	0.475
C	312951	1×10^{-5}	1.012	2.376	0.514
D	446889	1×10^{-6}	1.01	2.551	0.513

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Table 2 The percentage of torque coefficient difference between decelerating and accelerating flow

Airfoil section	C_T at decelerating flow is higher than that in accelerating flow by		
	For t_{sin} equal to 4 sec	For t_{sin} equal to 6 sec	For t_{sin} equal to 8 sec
NACA0012	24%	13%	12.5%
NACA0015	45%	-1%	12%
NACA0020	114%	46%	13%
NACA0021	122%	33%	20%

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Table 3 A summary of the torque coefficient values at different time periods for the four airfoils

Airfoil section	C_T ($t_{sin} = 4$ sec)			C_T ($t_{sin} = 6$ sec)			C_T ($t_{sin} = 8$ sec)		
	Accelerating	Decelerating	Average	Accelerating	Decelerating	Average	Accelerating	Decelerating	Average
NACA0012	0.096	0.118	0.107	0.078	0.0885	0.0834	0.073	0.0825	0.0779
NACA0015	0.094	0.136	0.115	0.08	0.08	0.080	0.069	0.0773	0.0731
NACA0020	0.077	0.164	0.12036	0.0675	0.099	0.0829	0.0619	0.06984	0.0659
NACA0021	0.07	0.163	0.11799	0.0676	0.0902	0.0789	0.0608	0.0729	0.0669

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Table 4 The percentage of global entropy generation rate (difference between decelerating and accelerating flow)

Airfoil section	S_G at decelerating flow is higher than that in accelerating flow by		
	For t_{sin} equal to 4 sec	For t_{sin} equal to 6 sec	For t_{sin} equal to 8 sec
NACA0012	34%	25%	26%
NACA0015	33%	43%	26%
NACA0020	35%	23%	19%
NACA0021	31%	35%	30%
Average value	33.3%	31.5%	25.3%

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Table 5 Comparison between S_G for the NACA0015 and other airfoils

Airfoil section	NACA0015 less than		
	NACA0012	NACA0020	NACA0021
t_{sin} equal to 4 sec	-13%	-15%	-14%
t_{sin} equal to 6 sec	-6%	-10%	-15%
t_{sin} equal to 8 sec	-11%	-15%	-18%

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Table 6 A summary of the global entropy generation rate values at different time periods for the four airfoils

Airfoil section	S_G (kW) $t_{sin} = 4$ sec			S_G (kW) $t_{sin} = 6$ sec			S_G (kW) $t_{sin} = 8$ sec		
	Accelerating	Decelerating	Average	Accelerating	Decelerating	Average	Accelerating	Decelerating	Average
NACA0012	0.0505	0.06785	0.05918	0.05	0.063	0.0567	0.0496	0.06265	0.0561
NACA0015	0.0444	0.05899	0.0517	0.0437	0.0625	0.0531	0.04434	0.0557	0.05003
NACA0020	0.05152	0.06958	0.0606	0.053	0.065	0.0589	0.0535	0.0639	0.0587
NACA0021	0.05239	0.06844	0.0604	0.053	0.072	0.062	0.05302	0.0687	0.06086

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