International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:10, No:7, 2016

Model the Off-Shore Ocean-Sea Waves to Generate Electric Power by Design of a Converting Device

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Abstract**—**In this paper, we will present a mathematical model to design a system able to generate electricity from ocean-sea waves. We will use the basic principles of the transfer of the energy potential of waves in a chamber to force the air inside a vertical or inclined cylindrical column, which is topped by a wind turbine to rotate the electric generator. The present mathematical model included a high number of variables such as the wave, height, width, length, velocity, and frequency, as well as others for the energy cylindrical column, like varying diameters and heights, and the wave chamber shape diameter and height. While for the wells wind turbine the variables included the number of blades, length, width, and clearance, as well as the rotor and tip radius. Additionally, the turbine rotor and blades must be made from the light and strong material for a smooth blade surface. The variables were too vast and high in number. Then the program was run successfully within the MATLAB and presented very good modeling results.

Keywords**—**Water wave, model, wells turbine, MATLAB program, results.

I. Introduction

SINCE the first engineering revolution (1870) scientists everywhere searching for energy and their resources and at that time they discovered that the optimum source was petroleum and since that time huge investments have been spent on its development, distribution and on different applications, while less effort was spent on investigating other sources. The planet is facing a critical time period due to the adverse effects of global warming, where pollution and contaminants have reached dangers levels seriously affecting human existence, and more people push strongly toward clean and environmentally friendly energy alternatives such as:

1- Nuclear by fusion;
2- Wind;
3- Solar;
4- Ocean & Sea waves;
5- Bio-mass fuel; and,
6- Other sources.

However, deciding on the right technique for a cleaner future can be based on a number of important reasons including:

1- Availability;
2- Cost;
3- Level of pollution; and,
4- Needs for high technology.

After conducting an in-depth study into the alternatives, it was decided that the following techniques; ocean or sea waves, solar, and wind, could generate enough electricity for any country. This research will concentrate on ocean or sea waves due to its availability for a vast number of countries. Such work has been started in various developed country including the United States, United Kingdom, France, Japan, Norway and New Zealand, etc., [1]-[3], [7].

The technologies of electric generation from the sea or ocean waves were found to rely on three motions. The technology is relatively new. However, installations have been built or are still under the construction or still being researched in a number of countries. Several different designs have been developed to capture energy from waves, including:

1- The oscillating-water-column (OWC) is a wave energy converter class. The main method of utilize wave motion energy to generate electricity.
2- The wave energy can be used for water pumping, heating, sea water desalination, and hydrogen production.

The utilization of wave energy is a so-called paradise for inventors, but commercially, it still is lagging behind wind and solar alternatives, while it is the more promising resource for the following reasons:

1. Wave motion can originate from storms far out to sea and can travel long distances without significant energy loss, and the power produced from them is much steadier and more predictable, both day to day and season to season. This reduces project risk.
2. Contains roughly 1000 times the kinetic energy of the wind i.e. required a fraction of space and less conspicuous devices [1]-[3].
3. Available around the clock.
4. Continuous and more reliable.
5. Water density is considerably greater than that of air, thus dramatically increasing the amount of electric generation.
6. Easy to estimate the potential resource.
7. Green source of energy and low impact on the infrastructure.
8. Low noise.

For those reasons, ocean-sea wave energy is preferable and can be converted in to electricity by various techniques and the most important one is the Wave-Electricity Technique by OWC [1]-[3].

In the 1970's, two countries began to realize the potential that wave energy represented. Japan and England began to develop methods for utilizing this resource for power generation. The devices fall into two general classifications, fixed and floating. There are a number of designs of each type, and below are examples of the main types currently being implemented:

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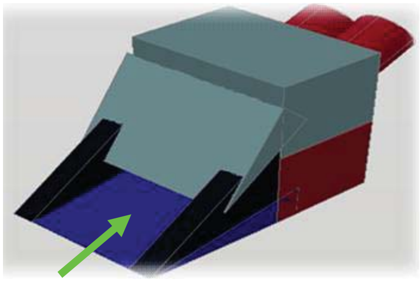


Fig. 1 Oscillating wave column device

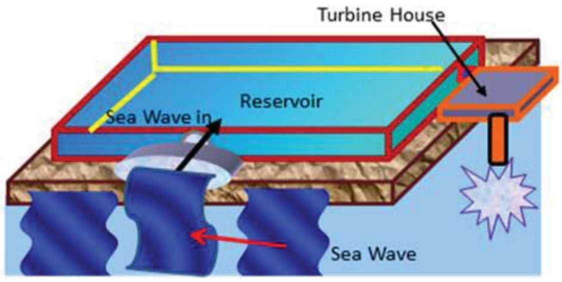


Fig. 2 Wave convergence energy reservoir device

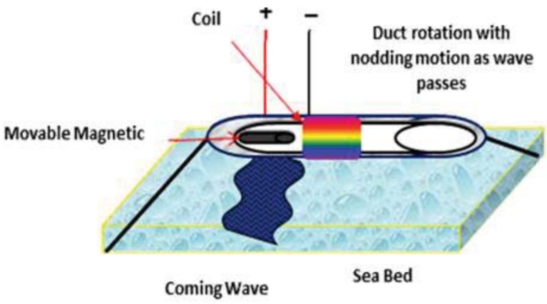


Fig. 3 PWP device

a- OWC wave energy device (Fig. 1).
b- Wave convergence reservoir wave (WCR) energy device (Fig. 2).
c- Pendulum wave power (PWP) device (Fig. 3).

The present research will focus on OWC.

II. The Present Model

This research will present a model by which the potential of the oscillating Sea-Ocean waves can be converted into electricity. The basic principle of this technique uses waves to drive the air within an energy column to rotate a wind turbine, and in turn the electric generator, which must be fixed on the top of the vertical or inclined column as shown in Figs. 1 and 4. For the purpose of this study, the entire generation process will be mathematically formulated into a well-constructed energy generation model to achieve the following goals:

1- Efficient electric generation
2- Highly unsusceptible to the weather change
3- Able to work on mean wave height

A complete sketch of the present system, as shown in Fig. 4), in which we start the modeling at point (o) 'from the measured wave amplitude' [11], where the deep water wave of a certain power will move through the water chamber:

$$vw1 = (2 \times g \times h)^{0.5} \tag{1}$$

Then the wave period [12]:

$$t = 2\pi \times vw1 \times g^{-1} \tag{2}$$

While wave length can be calculated as:

$$le = \frac{t^2 \times vw1}{2\pi} \tag{3}$$

And its width due to the movement on both sides:

$$w = 2vw1 \times t \tag{4}$$

Those wave parameters will be used to evaluate the water weight and flow rate:

$$mw = (2/3) \times dw \times h \times (le/4)^2 \tag{5}$$

and flow rate will be:

$$mwt = mw \div t \tag{6}$$

The water velocity will be change due to the contraction area toward the entrance of the water chamber (level o-1):

$$vw1 = vwo \times k_1^{-1} \tag{7}$$

Then from the rectangular cross-section to the circular water chamber (level 1-2):

$$vw2 = \left(\frac{vw1^2}{1+k_2}\right)^{0.5} \tag{8}$$

$k_{1\,\&2}$: the change factors evaluated according to [4], [5].

While due to entering the circular air energy column (level 2-3):

$$vw3 = vw2 \times k_3^{-1} \tag{9}$$

The water will be bushed inside the water chamber to a height equivalent to:

$$hw = (0.5 \times mwt \times vw2^2)/g \tag{10}$$

The water will enter the vertical cylinder and push the air by similar velocity i.e.:

$$va1 = ((\rho_{water} \times vw3^2) \times (0.5 \times \rho_{air})^{-1})^{0.5} \tag{11}$$

The air amount will be:

$$ma = \pi \times rcw^2 \times hw \times \rho air \tag{12}$$

while its flow rate will is:

$$mat = ma \times t^{-1} \tag{13}$$

From which the volumetric flow rate can be evaluated:

$$voa = mat \times \rho air^{-1} \tag{14}$$

The air will push inside the column up to a height:

$$ya = 0.3 \times (rcw^2 \times rca^{-2}) \times hw \tag{15}$$

Then after the calculation to the gravity and friction losses [13] the air velocity becomes:

$$va2 = (va1^2 - 2 \times paf \times mat - 2 \times g \times ya \times mat)^{0.5} \tag{16}$$

The total wave power can be calculated from its height by:

$$pwav = 0.39 \times \pi \times \rho w \times g \times h^2 \tag{17}$$

and its kinetic energy at level (1) will be:

$$pwavk = \frac{1}{2} \times mwt \times vw1^2 \tag{18}$$

While it's net energy at the chamber is level (3):

$$pww = \frac{1}{8} \times mwt \times vw3^2 - (\frac{1}{2} \times mwt \times g \times hw + pwf) \tag{19}$$

The power losses within the whole process due to various causes such as the, air-water friction, gravity, area contraction, and mechanical losses can be formulated by:

$$plt = paf + pag + pwf + pwg + pco + pm \tag{20}$$

The air will rotate the vertical wells turbine which was study and design as shown on Fig. 5. The turbine power can be evaluated from the following well known formula [4]-[6], [13]:

$$pth1 = Fth \times rt \times wrs \tag{21}$$

The flow angles and the velocity components on the turbine blades are clearly shown in Fig. 5.

The force component on the blades can be evaluated from:

$Fx = L\cos\alpha + D\sin\alpha$ Lifting force and must be small (22)

$F\theta = L\sin\alpha - D\cos\alpha$ The Rotational force and must be large enough (23)

The previous empirical relation of the VRML Model [2] derived the following formula:

$$pth = (pair + \frac{1}{2} \times \rho a \times va3^2) \times va3 \times \pi \times rc^2 \tag{24}$$

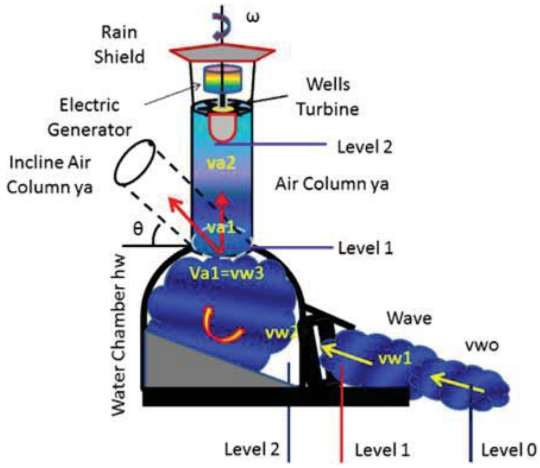


Fig. 4 General sketch for the present project

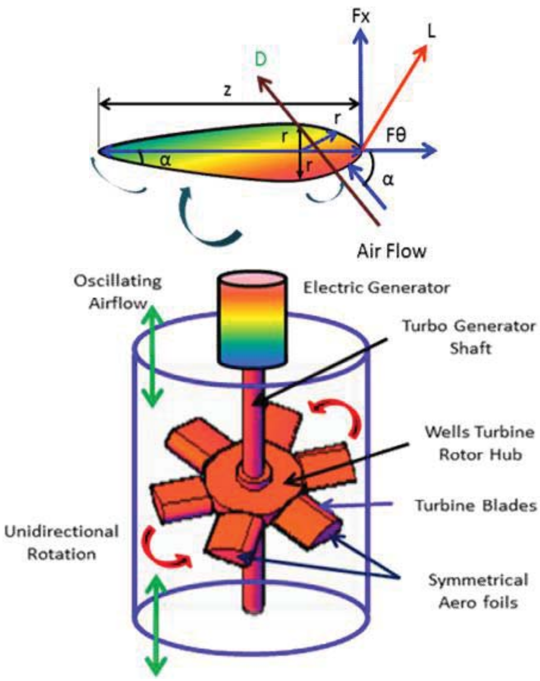


Fig. 5 Air velocity diagram on the turbine blades

III. The Computer Program

To solve the present model, a computer program was constructed inside MATLAB. This program was built based on the present conditions to evaluate the water-air energy exchange and the electric generated power and the associated conditions of the Wells turbine design. The data were for the different wave conditions and for certain technical assumptions, as will be presented later. The success of the present program was enhanced, and all operation steps are shown in Fig. 6.

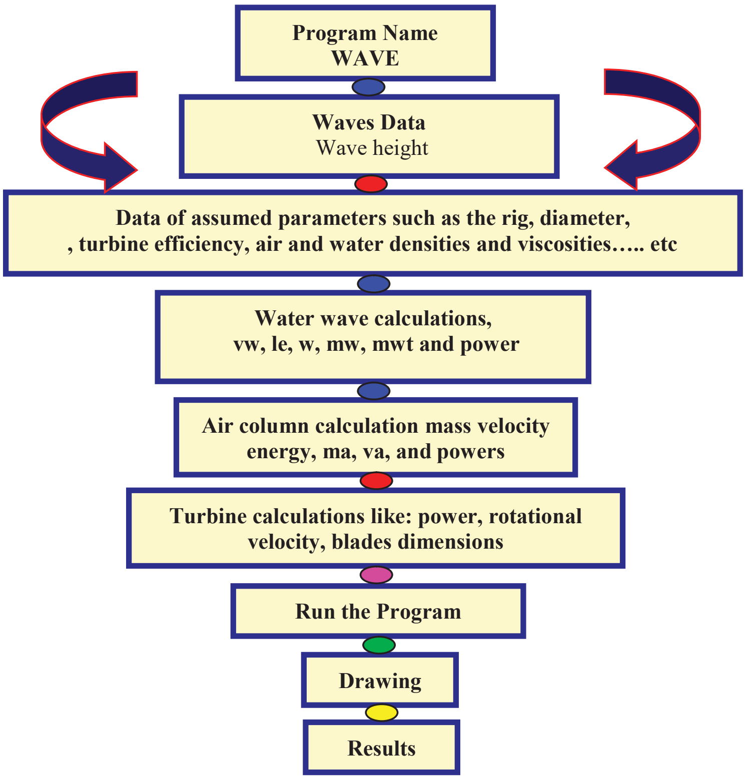


Fig. 6 The present computer chart

IV. Results and Discussions

The present model was run based on the major parameters listed in Table I. The sample data were obtained from the Syria Data Office in Tartous Port (2008, 2009, & 2010), as listed in Tables II-IV.

TABLE I
Sea Wave Measured Parameters

Symbol	Definition	Units
h	Wave Amplitude	m
t	Wave period	sec
w	Wave width	m
le	Wave height	m
vwo	Initial wave velocity	m/s

From the available data, it was found that the mean values of the wave amplitude and temperature are h=1 m and Tw=21.4 °C. Moreover, the assumed parameters and constant values are:

$ef=0.6;\ k=0.5;\ dc=1.0;\ \rho wo=1025;\ \rho ao=1.19;\ nb=30;\ \mu wo=1.79\times10^{3};\ \mu ao=1.71\times10^{5};\ fa=0.011;\ cs=1236;\ g=9.8066$

Based on those data values on the Syrian coast and the required known constants, the program was successfully run and the obtained results are shown in Figs. 7-15. Fig. 7 shows the relation between wave velocity, period, height, and length, while the comparison between the required water, air, and total column heights within the energy chamber are shown on Fig. 8. Further, the comparison between the water and air Reynolds numbers is shown in Fig. 9. The wave velocity and kinetic power, as well as the losses within the conversion processes are shown in Fig. 10. The results of the wave power calculated using various methods are shown in Fig. 11. Furthermore, the comparison between the generated power of the present and previous work VRML [2] is presented in Fig. 12. The present generation shows the highest value which could be due to the over or under estimation of some parameters. The comparison between previous studies on wave power and losses due to friction, gravity, and bend in both the water and air (Fig. 12) before electricity generation, showed a maximum value of 34.48%. Fig. 13 shows the relation between the wave velocity and final air velocity entering the turbine (a) and the turbine angular velocity (b).

More results of the present calculation are shown in Fig. 14, which presents the heights of the water chamber, air column, and the overall total. Finally, the relation between the wave velocity and turbine efficiency at various wave heights is clearly displayed. The present program proved that higher wave velocity means higher turbine rotational speed and electric power will be generated.

International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:10, No:7, 2016

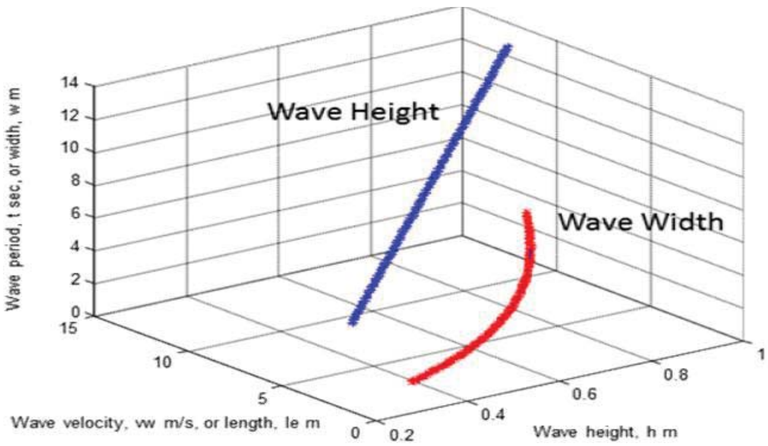


Fig. 7 Relation between the wave length, height, velocity, and period

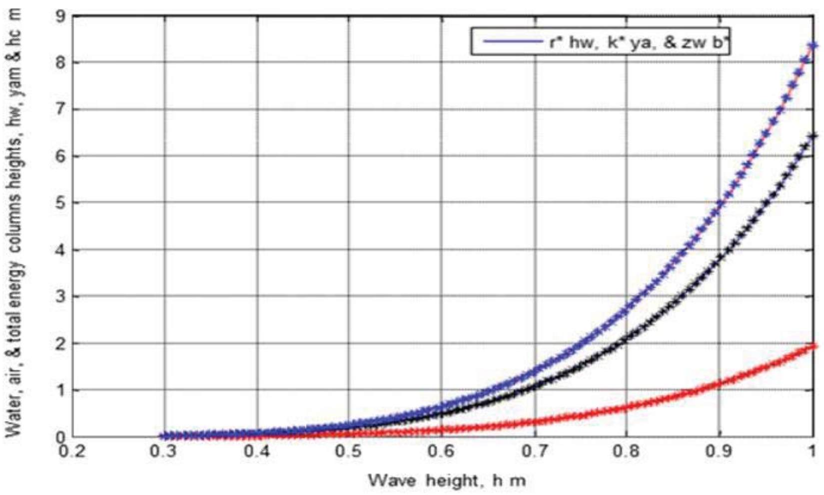


Fig. 8 Relation between the water, air, and total columns heights

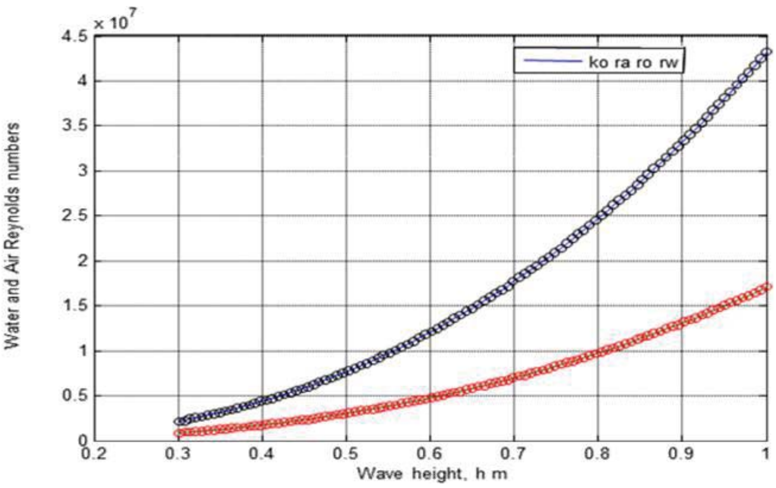


Fig. 9 Comparison between the water and air Reynolds number

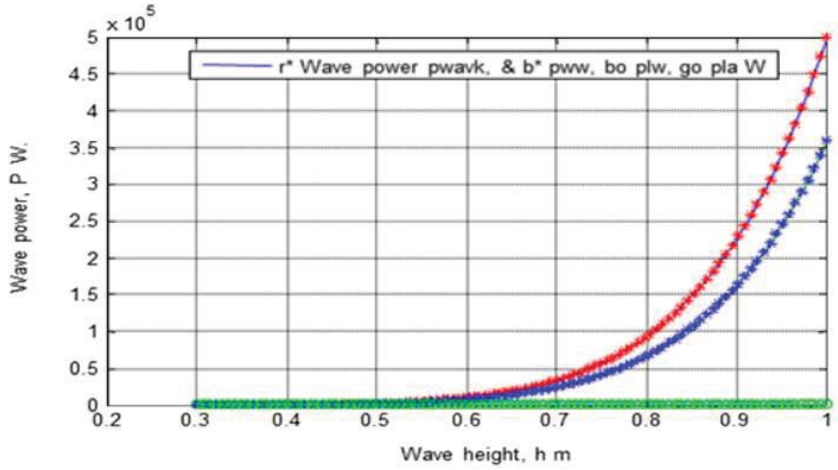


Fig. 10 Relation between the wave height and its powers loses

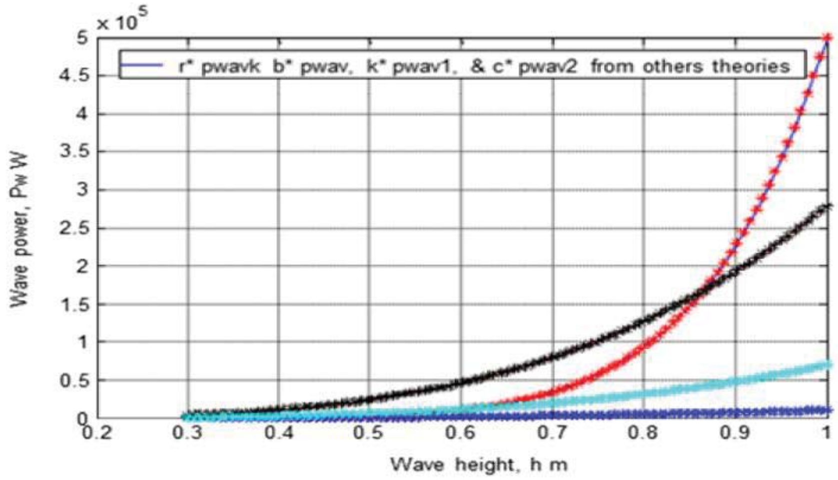


Fig. 11 Relation between the wave height and kinetic, net powers, and the values calculated from previous theories and work

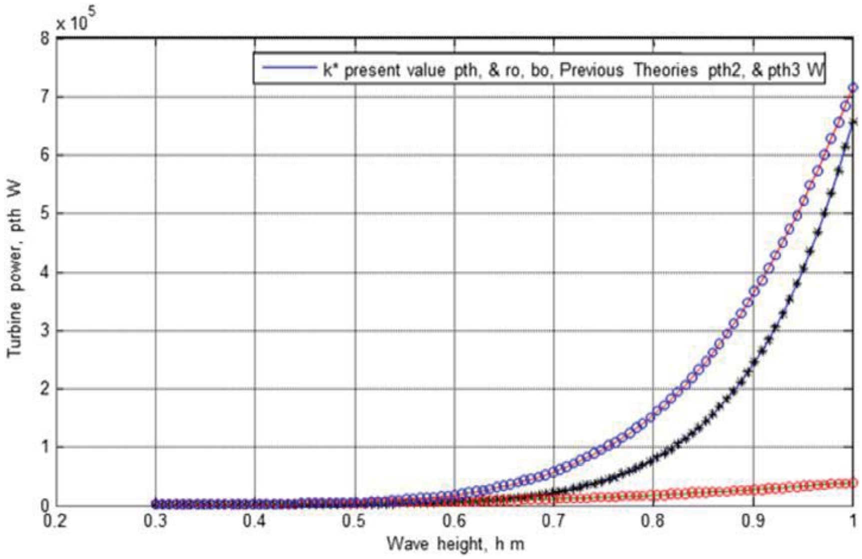
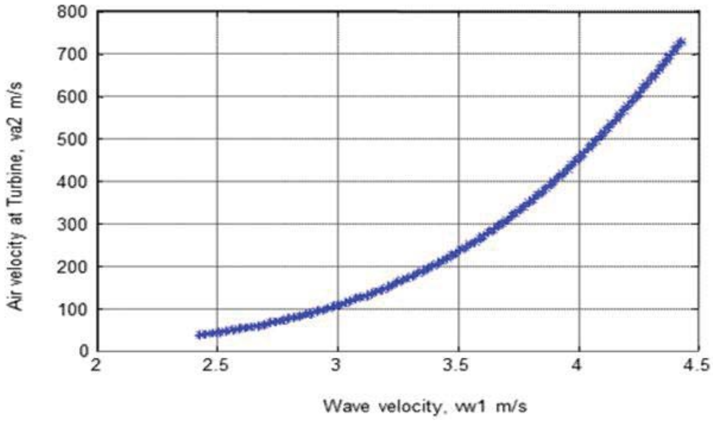
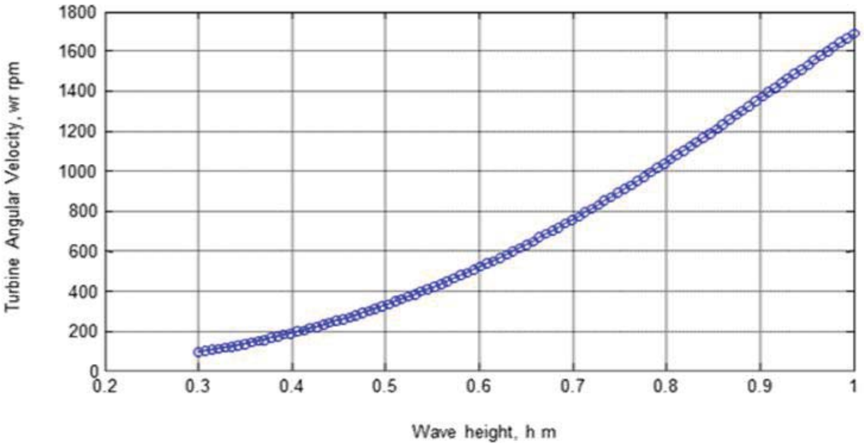


Fig. 12 Relation between turbine power and the wave kinetic energy and the values calculated from previous theories and work



(a)



(b)

Fig. 13 Relation between the wave height and a- air velocity at the turbine entrance, and b- the turbine rotational velocity

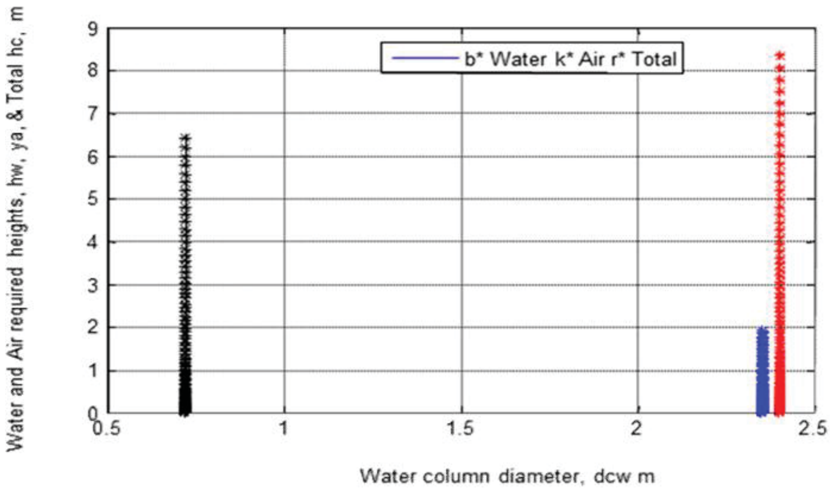


Fig. 14 Comparison between the water and air and total diameters and heights

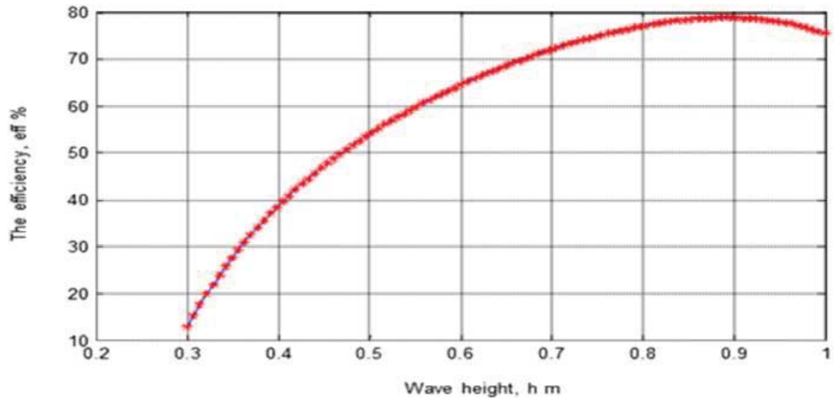


Fig. 15 Relation between wave height and the turbine efficiency

V. Turbine Design

In the present work the authors designed a Wells turbine based on the following assumption:

- h2 Wave height =1 m
- dcw Water column diameter = 2.4 m
- dca Air column diameter = 0.72 m
- eff1 Turbine Efficiency = 61.706 %
- rr Rotor diameter = 0.126 m
- nb Blades number = 6
- bl Blades length = 0.21601 m
- bw Blade width = 0.13174 m
- ph1 Blade angle, Degree = 16.377°
- bc Blade separate distance = 0.1508 m
- bclr Blades clearance = 0.0060012 m
- rt Tip radius = 0.0819 m
- rai Ratio of rt/rr = 0.65
- rmid Mid radius = 0.10395 m

VI. Conclusions

From the present work one can conclude the following major facts:

1- That such a system required more and deeper steady and wider investigation locally to solve all the related problems.

2- Accurate turbine blade design can be very efficient for two-way air movements.

3- The major losses in water energy are due to area contraction, gravity, and friction.

4- The project must be well constructed to withstand unpredictable weather and corrosion.

5- Such a project will benefit from increase in rainfall in the region and fish farming, but negatively act as a shelter for the sea or ocean wreckage and waste.

6- Oman is one of few Arabic Countries with a long coastline of 2,092 km, from which we can generate electric power equivalent to 35.56 GW [9], while rate needs according to the international data [8], [10] is only 2 GW for a population of around 5 million, while for project safety, the designer must construct on a maximum wave height of more than at GUNO storm time, which was about 4.2 m [10].

Nomenclature

Definitions of the Main Mathematical Symbols

Symbol	Definition	Units
C	Relative air velocity	m/s
$dc = 2rc$	Energy chamber diameter	m
ef	Turbine efficiency	-
f	Force on turbine blade	N
g	Gravity constant	9.80665 m/s²
h	Wave height	m
hb	Turbine blade height	m
hw	Water column height	m
k	Area contraction coefficient in the water stream	
lb	Turbine blade length	m
le	Wave length	m
ma	Air mass	Kg
mat	Rate of air mass	Kg/s
mw	Wave mass	Kg
mwt	Rate of wave mass	Kg/s
nb	Turbine blade number	Blades
p	Power	W
po	Atmospheric pressure	Atmos
$pair$	Air pressure at the turbine inlet	Pasc
$pwav$	Net wave power	W
$pwavk$	Wave kinetic power	W
rc	Radius of the energy chamber	m
t	Wave period	sec
tf	Water-Air temperature	°C
to	Initial temperature	°C
u	Turbine velocity	m/s
v	Velocity	m/s
w	Wave width	m
xb	Distance separating the turbine blades	m
ya	Air chamber height	m
ρa	Air density	Kg/m³
ρw	Sea water density	Kg/m³
π	Constant	
α	Air angle	°
β	Blade Angle	°
μ	Viscosity	N.s/m.^2

International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:10, No:7, 2016

ρa Air density Kg/m³

Note: That the following suffixes are referring to: 1, 2, and 3 locations within the project gates (See Fig. 4)

Definitions for the Suffices

Suffix	Definition
a	Air
af	Air friction with the wall
ag	Air gravity
b	Blade
con	Area contraction
f	Final condition
m	Mechanical
lt	Total losses
o	Initial condition
t	Turbine or Rate
th	Previous theory
w	Water
wf	Water friction with wall
wg	Water gravity
x	x Direction
y	y Direction

APPENDIX

TABLE II
SEA WAVE MEASURED PARAMETERS DATE OF YEAR 2008

Mont of the Year	Max Temp °C	Min Temp °C	Atmospheric Pressure in 10^5 Pascal	% Humidity	Air Velocity m/s	Wave Amplitude m	Water Temp °C
January	18	10	1.018	70	20.5	1.15	16.5
February	18.5	10.9	1.017	69.6	22.9	1.34	16.8
March	19.3	11.2	1.015	68.7	19.2	1.15	17.3
April	22	15	1.011	71.2	18.6	1.15	19
May	24	16	1.011	67.5	16.5	1.15	21
June	28	19	1.007	68	17.7	1.15	23
July	32	26	1.005	72	16	1.15	26
August	32.5	27	1.006	68	13.3	1.15	27
September	30.2	24	1.008	73	13,5	1.15	26.7
October	25.5	18.5	1.015	67	15.7	1.15	24.2
November	24	15.5	1.018	60.7	14.2	1.15	23
December	20	10	1.017	65.5	23	1.15	19

TABLE III
SEA WAVE MEASURED PARAMETERS DATE OF YEAR 2009

Mont of the Year	Max Temp °C	Min Temp °C	Atmospheric Pressure in 10^5 Pascal	% Humidity	Air Velocity m/s	Wave Amplitude m	Water Temp °C
January	17.5	10	1.016	69	29.5	1.31	16.8
February	18.2	11	1.017	72	28	1.56	16.9
March	19.9	11	1.016	70	19	1.00	17.00
April	21.3	14	1.012	71	18	0.95	19.5
May	24.8	16	1.011	70	20	1.1	21.3
June	27.2	18.5	1.008	68	16.5	0.8	22.8
July	31.9	25	1.005	73	14	0.5	26.4
August	32.2	26	1.006	70	10	0.3	27
September	30	24	1.008	71	13	0.4	26
October	25	18	1.012	68	15	0.6	23.8
November	24	15	1.016	65	14.3	0.45	22
December	20.9	11	1.017	70	22	1.1	19.5

TABLE IV
SEA WAVE MEASURED PARAMETERS DATE OF YEAR 2010

Mont of the Year	Max Temp °C	Min Temp °C	Atmospheric Pressure in 10^5 Pascal	% Humidity	Air Velocity m/s	Wave Amplitude m	Water Temp °C
January	17.5	10	1.016	69	29.5	1.31	16.8
February	18.2	11	1.017	72	28	1.56	16.9
March	19.9	11	1.016	70	19	1.00	17.00
April	21.3	14	1.012	71	18	0.95	19.5
May	24.8	16	1.011	70	20	1.1	21.3
June	27.2	18.5	1.008	68	16.5	0.8	22.8
July	31.9	25	1.005	73	14	0.5	26.4
August	32.2	26	1.006	70	10	0.3	27
September	30	24	1.008	71	13	0.4	26
October	25	18	1.012	68	15	0.6	23.8
November	24	15	1.016	65	14.3	0.45	22
December	20.9	11	1.017	70	22	1.1	19.5

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