DOE Analysis and Improvement of a Rotor Design for OWC Radial Impulse Turbines

Khalid Elatife*[1] and Abdelatif El Marjani**[1]
[1]*Labo. de Turbomachines, Ecole Mohammadia d'Ingénieurs, Université Mohammed V*
B.P. 765 Agdal, Rabat, Maroc

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Abstract: Wave energy exploitation is of great interests nowadays due to its sustainability, reliability and large potential. A brief analyze of wave energy potential in the Moroccan coastline with an idea on the importance of implementing WEC, and presents secondly an implementation of the experimental design method to optimize the self-rectifying impulse radial turbine in the OWC devices, which is the most exploited system, for wave energy extraction are presented in this paper. A novel design with circular arcs and straight lines for the rotor blade will be presented. A first work of optimizing the rotor blade design in terms of the turbine efficiency by the design of experiment method has been done. The work has done as outputs two optimal rotor blade profiles, one for the exhalation and the other for the inhalation modes. As a second part of the work, optimizing the solidities of the guide vanes and of the rotor by implementing a second design of experiment will be established.

NOMENCLATURE

$C_A = \dfrac{\Delta P}{\frac{1}{2}\rho(v_R{}^2 + u_R{}^2)}$: Input coefficient

$C_T = \dfrac{\Delta P}{\frac{1}{2}\rho(v_R{}^2 + u_R{}^2)A_R r_R}$: Torque coefficient

ΔP : Total pressure drop
r_R : Mean radius
A_R : Characteristic area
ρ : Air density
$u_R = w r_R$: Circumferential velocity at r_R
$v_R = \dfrac{q}{2\pi r_R b}$: Mean radial velocity
q : Flow rate
b : Rotor blade height
η : Turbine efficiency
r_s: Radius of the suction side of the blade rotor
r_p: Radius of the pressure side of the blade rotor
l_r: Blade chord*
t: Inter-distance between centre of the two circular arcs of the blade rotor
β*: Geometrical angle in the leading and trailing edges of the blade rotor
α: Guide vane incidence angle
ϕ : Flow coefficient

1 INTRODUCTION

One of the most abundant resources of renewable energy in the world is the ocean energy. In the world, its potential is estimated of about 8 000-80 000 TWh/year (AEA Energy & Environment on the behalf of Sustainable Energy Ireland for the IEA's Implementing Agreement on Ocean Energy Systems, 2006), and on the Moroccan coasts to 25-30 kW/m, which is for about 700 to 900 TWh/year (ELATIFE & EL MARJANI, 2014). It encloses energy resources such as: wave energy, tidal energy, thermal energy and marine currents energy. In the R&D field, great efforts were made during the last decades, in order to harvesting this huge energy for covering the continuous growing of the human energy needs. For the wave energy extraction field for instance, several energy system converters were introduced, especially the oscillating Water Column (OWC) which is the most used design for its low cost of installation and the simplicity of its maintenance.

The OWC devices are composed of three parts: air chamber, air turbine and electrical generator. The first component is used to convert wave energy to pneumatic one; the second one is used to convert this pneumatic energy to mechanical energy which is finally converted to electrical energy in the generator. Several OWC devices are built in 1990s and are still working, such as the Picot plant in Azores, Portugal (FALCAO, 2000) and the LIMPET plant in Islay, Scotland (Heath &Whitakker & Boake, 2000).

The air turbine equipping the OWC device should rotate in one direction despite of the bidirectional air flow over it due to the water oscillating inside the air chamber. The first turbines used in the OWC prototypes are the Wells type turbines. However, through exploitation of this turbine, some disadvantages have been encountered (Falcao, 2003), such as: high efficiency in a narrow range of flow rates, poor starting characteristics, high speed operation, high noise level, high periodical axial thrust and finally the crucial problem of stall. An alternative type turbine was proposed by I.A. Babinstev in order to overcome these drawbacks (Babinstev, 1975), which is impulse type turbine.

The axial and the radial are the two configuration types of impulse turbine that have been introduced. According to research investigations, it has been found that the radial impulse turbine has some advantages compared to the axial one in terms of low manufacturing cost, high torque due to the radial configuration and the absence of the oscillating axial thrust. However, a main problem of the large aerodynamic losses due to the important incidence air flow angle in the inner and outer guide vanes can be presented for the impulse turbine. It is due to the required symmetry of the two rows of guide vanes because of the bidirectional movement of the air flow.

In order to optimise the impulse turbine performances, several investigation researches were elaborated since the early 1990s. In the last decade, many improvements in turbine geometries were proposed. According to investigation results of reference (Pereiras & Castro & El marjani & Rodriguez, 2011), improved performances can be obtained in both operating modes (inhalation and exhalation) by modifying the aerodynamic design of the inner guide vanes in the radial impulse turbine. A model of his improved turbine has been manufactured and installed in the EMI' Turbomachinery Laboratory for experimental tests. An alternative design of the axial impulse turbine has been introduced (Takao & Setogushi, 2012) in which the solution consists of coupling two turbines installed in a twin configuration for optimizing the efficiency in inhalation and in exhalation operating modes. Tests have revealed significant improvement in the efficiency. a varying radius model of the axial impulse turbine is another design that has been also considered in order to reduce the aerodynamic losses and consequently increase the efficiency (Natanzi & Teixeira & Laird, 2011). Recently, a novel bi-radial turbine has been proposed for which a notable increasing efficiency (close to 80 %) has been reached (Falcao & Gato & Nunes, 2013a; Falcao & Gato & Nunes, 2013b).

In this paper, we will analyse the wave energy potential in the Moroccan coastline that can gives an idea on the importance of implementing WEC, and presenting a numerical experimental design method with ANSYS FLUENT for optimizing the impulse radial turbine in terms of some design parameters. A new rotor blade design has been proposed with two circular arcs that have dependent radii and two straight lines in the leading and trailing edges. This work has consisted on optimizing the blade rotor design by drawing up a numerical experimental design of four factors; the radius of the suction side, the chord, the inter-distance between centre of the two circular arcs and the geometrical angle in the leading and trailing edges of the blade rotor. Two optimal rotor blade profiles have been found, one for the exhalation and the other for the inhalation modes. The future research work will consist on optimizing the solidities of the inner and outer guide vanes and of the rotor by implementing a second design of experiment.

2 WAVE ENERGY IN THE MOROCCAN COASTLINE

Over the last years, a set of fixed, floating and submerged wave energy converters has been installed in order to estimate the wave energy potential. Each device is regarded to extract wave energy over a range of operating conditions in terms of wave period and height.

To justify the interest of implementing wave energy converters in the coastlines of any country, it is required to analyse its wave power.

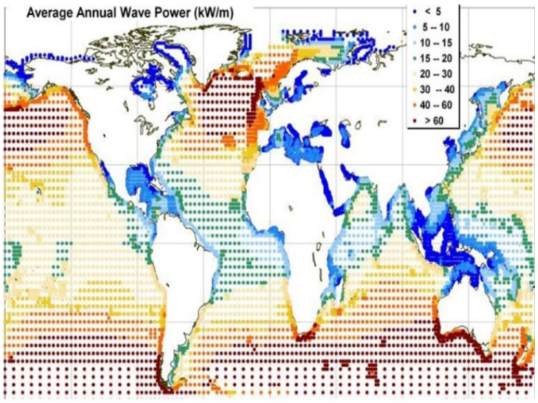

Figure 1: Worldwide average wave power potential (kW/m) (Lagune & Benalia & Benbouzid, 2010)

Figure 1 shows the distribution of the wave energy potential in the world. It can be noticed from this figure that the average annual wave power in the Moroccan coasts is estimated to be between 25 and 30 kW/m.

According to the previous graphs, it can be noticed that the implementation of the wave energy converters in the Moroccan coastlines will be highly profitable in terms of the amount of energy that can be extracted from wave. The Moroccan coastline energy potential is estimated for the length of 3400 km to 900 TWh/year.

One of the most studied wave energy converters is the OWC device, which is due to its simplicity. The OWC devices are composed of three parts: air chamber, air turbine and electrical generator. The first component is used to convert wave energy to pneumatic one, and the second from the pneumatic to mechanical one, and finally from mechanical to electrical energy in an electrical generator. As a result, the global efficiency will depend on the efficiency at each phase of this energy conversion chain. For high OWC performances, great attention should be paid in the design of the turbine (El marjani & Castro & Rodriguez & Parra Santos, 2008).

For this reason, our present work consists on optimizing the impulse radial turbine efficiency, especially the rotor blade design, for a better harvesting of the huge wave energy in the Moroccan coastlines.

3 A NEW ROTOR BLADE DESIGN OF IMPULSE TURBINE

From the literature, several aerodynamic problems have been investigated for the self-rectifying impulse turbine, like the flow separation at the outlet guide vanes (Setoguchi & Takao & Kinoue & Kaneko & Santhakumar & Inoue, 1999). Another problem that leads to energy losses is the separation of the boundary layer in the suction side of the rotor blade. In order to minimize theses energy losses, a new rotor blade design with circular arcs in the pressure and suction sides has been elaborated. The Figure 2 shows the new blade geometry.

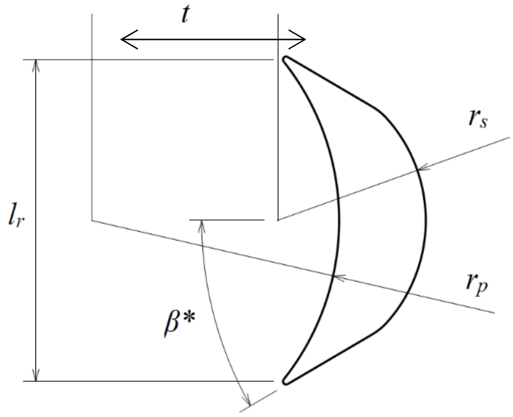

Figure 2: New blade rotor geometry

4 EXPERIMENTAL DESIGN FOR OPTIMIZING THE ROTOR BLADE

Method Approach. Experimental design is an optimization method that uses experimental testing by ordered sequence called experimental design of an experiment, each to acquire new knowledge by controlling one or more input parameters to obtain results validating a model with a good economy (number of trials as low as possible, for example).

For our case, a 2D numerical experimental design has been used for the radial impulse turbine and considering as the input parameters the geometrical characteristics of the blade rotor. The other parameters have been fixed and based on the values of the reference (Setoguchi & Santhakumar & Takao & Kanako, 2002). Four variables parameters have been considered; the radius of the suction side rs, the blade chord lr, the inter-distance between centre of the two circular arcs t, and the geometrical angle in the leading and trailing edges of the blade rotor β*. The guide vane incidence angle α has been chosen with respect of the triangle velocity of the air flow. The output result considered is the turbine efficiency. The radius of the pressure side rp and of the suction side rs are joined by a Brilling rule that found in the literature:

$$r_s = \frac{5}{3}.r_p \qquad (1)$$

The mathematical model for this case of study is as follows:

$$\eta = a_1 + a_2.rs + a_3.lr + a_4.\ \beta^* + a_5.t \qquad (2)$$

Each input parameter has two levels of variation, as presented in the Table 4:

Table 1: Dimensionless values of the four input parameters for the two levels (with respect to the value: 55 mm)

Level	**r_s (mm)**	**l_r (mm)**	**β***	**t (mm)**
-1	0.436	0.818	25°	0.545
1	0.545	1	35°	0.6

Instead of using an exhaustive experimental design which needs 24 tests, it is interesting to use an optimized experimental design (Lundstedt, 1998) that needs lesser tests, for example the matrix of Hadamard that needs just 8 tests for this case. This matrix is presented in the Table 2.

Table 2: Hadamard matrix for four parameters and two levels

N°	**r_s**	**l_r**	**β***	**t**
1	1	1	1	-1
2	-1	1	1	1
3	-1	-1	1	1
4	1	-1	-1	1
5	-1	1	-1	-1
6	1	-1	1	-1
7	1	1	-1	1
8	-1	-1	-1	-1

The values of ai, i=1,…,5 , for the two phases; inhalation and exhalation, have been obtained in matrix form as follows:

$$[\eta] = [H] . [a] \qquad (3)$$

With: $[\eta]t=[\eta1,…,\eta8]$; [a]t= [a1,…, a5] ; [H] is the Hadamard matrix for a dimension of 8 × 5 with the first column is a unitary column.

The numerical tests have been performed with ANSYS FLUENT for the rotor torque extraction for different flow coefficient ϕ . The standard k-ε model has been used to model the flow turbulence. A segregated solver has been used to solve the coupled conservation equations of mass, momentum and energy. The algorithm of SIMPLEC is adopted to perform the pressure-velocity coupling

The turbine is composed of a rotating part, the rotor, and a fixed part, the stator, Figure 3. In order to manage the relative movement between the fixing and the moving part of the turbine, the sliding mesh technique is used. The boundary conditions adopted is a uniform total pressure at the inlet and a uniform static pressure at the flow outlet. The condition of non-slip is adopted for all the walls.

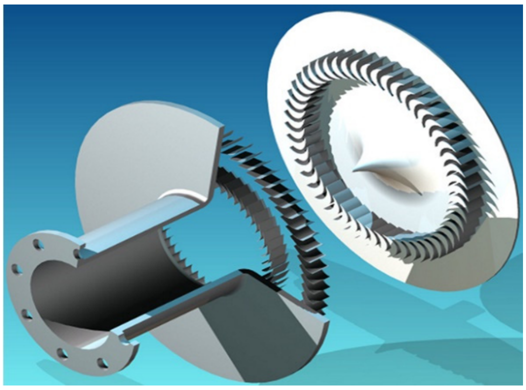

Figure 3: Rotor and stator of radial impulse turbine (Pereiras & Castro & El marjani & Rodriguez, 2011)

Results and Discussion. The turbine efficiency η is expressed in terms of the torque coefficient CT, input coefficient CA and the flow coefficient ϕ as mentioned above:

$$\eta = \frac{T_0.w}{\Delta p.Q} = \frac{C_T}{C_A.\phi} \qquad (4)$$

With the rotational speed of the rotor w chosen is 234 rpm.

The results of the eight tests by numerical simulation in both two phases; exhalation and inhalation are plotted in Figures 4 and 5, η=f (ϕ).

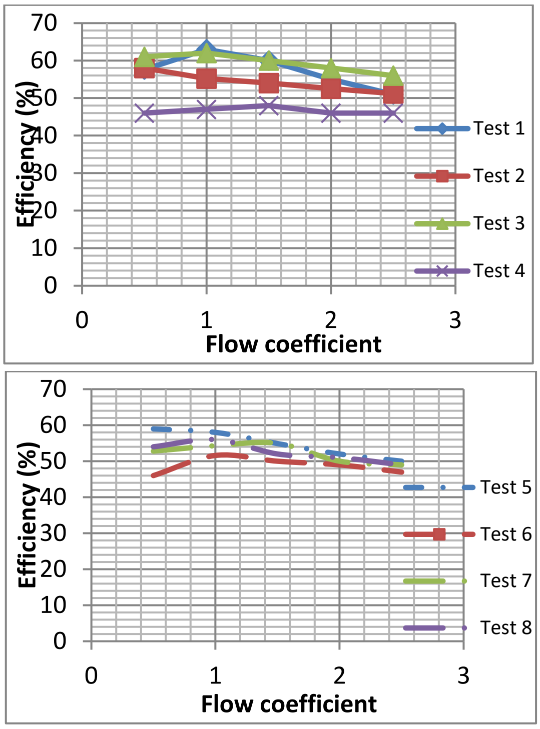

Figure 4-a) and 4-b): Turbine efficiency for exhalation mode for the eight tests

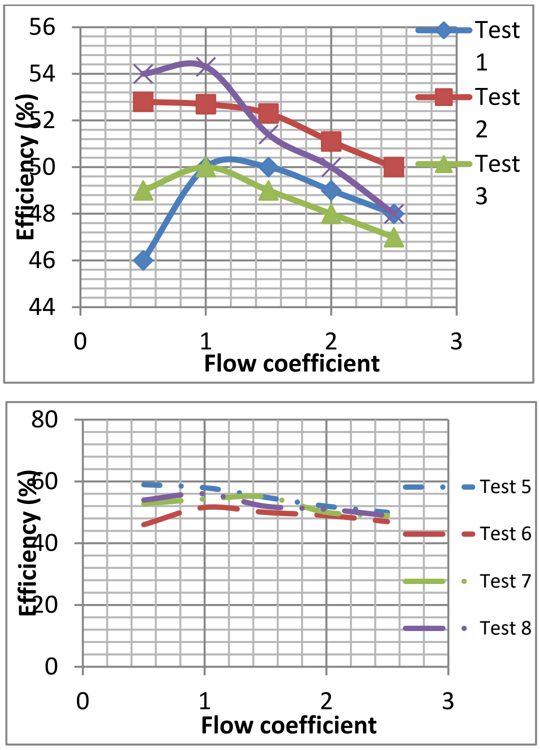

Figure 5-a) and 5-b): Turbine efficiency for inhalation mode for the eight tests

For the rest of the work, three flow coefficients have been chosen to optimize the turbine efficiency for both phases; exhalation and inhalation, which are: 0.5, 1.5 and 2.5.

The values of the coefficients ai, i=1,…,5 are presented in the two Tables 3 for exhalation and inhalation modes.

Table 3: The coefficients a_i, i=1,..,5 for exhalation and inhalation

	Inhalation			Exhalation		
ϕ	**-0.5**	**-1.5**	**-2.5**	**0.5**	**1.5**	**2.5**
a1	58.35	54.87	50.25	59.54	59.74	54.6
a2	24	24	24	24	24	24
a3	55	55	55	55	45	45
a4	25	25	25	35	35	35
a5	33	33	30	33	30	30

5 OPTIMIZATION OF BLADE ROTOR GEOMETRY

In order to determine the combination (s) of the four input parameters that maximize the turbine efficiency for the two phases of functioning, an optimizing program has been elaborated with MATLAB.

The objective function is the equation (2) and the variable inputs are the input parameters of the design of experiment. Their variation is inside their two levels with a step of 1 mm for rs, lr and t, and 2° for β*.

The optimal combination for the three flow coefficient values in both phases is presented in the Table 4 below:

Table 4: Dimensionless values of optimal combinations for the three flow coefficient values for exhalation and inhalation modes

	Exhalation $(r_s\ ;l_r\ ;\beta^*;\ t)$	**Inhalation** $(r_s\ ;l_r\ ;\beta^*;\ t)$
ϕ =0.5	(0.436;1;35°;0.6)	(0.436 ; 1 ; 25° ; 0.6)
ϕ =1.5	(0.436 ; 0.818 ; 35° ; 0.545)	(0.436 ; 1 ; 25° ; 0.6)
ϕ =2.5	(0.436 ; 0.818 ; 35° ; 0.545)	(0.436 ; 1 ; 25° ; 0.6)

It can be noticed that there are two optimal combinations for exhalation; C1(0.436;1;35°;0.6) and

C2(0.436 ; 0.818 ; 35° ; 0.545), and one for inhalation; C3= (0.436 ; 1 ; 25° ; 0.6). The combination C3 is chosen for optimizing the turbine efficiency in inhalation mode, and for choosing one of the two combinations C1 and C2 that optimizes the efficiency for the exhalation mode, new simulation tests has been done for the two combinations in exhalation mode in order to choose the one which maximise the some of the three efficiencies for different flow coefficients. The Table 5 represent the values of efficiencies for the combinations C1 and C2.

Table 5: Turbine efficiency for the combinations C1 and C2 in exhalation mode

ϕ	C1	C2
0.5	58%	62%
1.5	54%	58.5%
2.5	51.2%	52.7%

From the numerical tests results, the combination C2 for the exhalation mode has the maximum efficiency in all the three flow coefficients. So C2 is the optimal combination for the exhalation mode.

The Table 6 represent a recapitulation of the optimal combinations for exhalation and inhalation modes.

Table 6: Dimensionless values of optimal combinations for exhalation and inhalation modes

Mode	$(r_s ;l_r ;\beta^*; t)$
Exhalation	(0.436 ; 0.818 ; 35° ; 0.545)
Inhalation	(0.436 ; 1 ; 25° ; 0.6)

The optimized rotor profiles for the two phases; exhalation and inhalation are presented in Figures 6 and 7.

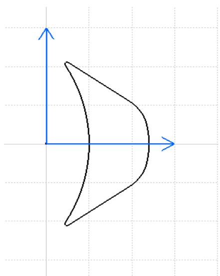

Figure 6: Optimized rotor blade profile for exhalation

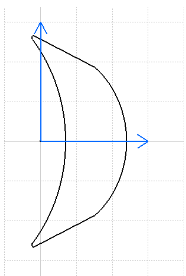

Figure 7: Optimized rotor blade profile for inhalation

6 CONCLUSION

In this paper, we have applied the design of experiemnt method to optimize the rotor blade geometry in order to maximise the turbine efficiency. The tests have been done by 2D numerical simulation with ANSYS FLUENT for time exigencies. Four variables parameters has been chosen as inputs; the radius of the suction side, the blade chord, the inter-distance between centre of the two circular arcs, and the geometrical angle in the leading and trailing edges of the blade rotor, and one as output; the turbine efficiency. The other parameters have been fixed.

An optimizing program has been elaborated with MATLAB and two combinations of the inputs parameters that maximize the output parameter; the turbine efficiency, in exhalation and inhalation modes have been found; (rs ;lr ;β*; t) = (0.436 ; 0.818 ; 35° ; 0.545) for exhalation and (rs ;lr ;β*; t) = (0.436 ; 1 ; 25° ; 0.6) for inhalation.

For the future work, a second design of experiment will be elaborated for optimizing the guide vanes and the rotor solidities, in order to find an optimal design of the turbine in exhalation and inhalation modes.

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