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Performance Improvement of Wells Turbine Using Variable Shaped Blades

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Abstract

The wave energy is considered one of the most promising future sources of energy. Using the oscillating water column coupled with the Wells turbine, which is unique in that it can rotate in the same direction regardless of the direction of air flow, it is used in one of the wave energy converters. This turbine has many advantages, but on the contrary, it also has many defects that affect its performance. An experimental method has been followed by using an open wind tunnel connected to the Wells turbine and changing air flow rates to test the performance characteristics of the turbine. During this research, work is done to get rid of these defects. The performance of blade geometry has been studied to reach the optimum design, and the best performance of the turbine has been achieved when using the self-pitch controlled blade with a horizontal tail trimer. The results show an increase in the average efficiency of about 26 to 48% for 1000 rpm at the same flow coefficient (∅), with respect to the traditional Wells turbine average efficiency. Further reduction of rotational speed is expected to increase average efficiency.

Keywords: Wells turbine, oscillating water column, self-pitch controlled blade, horizontal tail, inclined tail, optimization of performance.

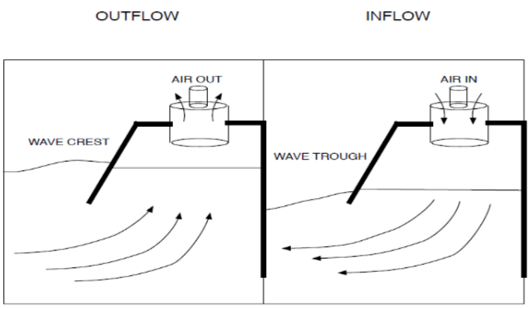
1. Introduction

There is certainly no doubt that the processes of generating energy from renewable resources are one of the most important issues that occupy the minds of the whole world in their various forms to get rid of the defects of traditional energy sources that are polluting the environment. The seas and oceans contain about 3.7 TW of energy [1], and they can provide the energy needed by the whole world, but it is difficult to extract this energy due to different marine conditions. This prompted scientists to try to develop many technologies to take advantage of this energy and increase the efficiency of its use. One of the techniques that is used is the oscillating water column (OWC), which uses a turbine called the Wells turbine, as shown in fig. (1). One of the important advantages of this turbine is that all its parts are outside the water, and therefore it does not need special kinds of materials. Also among its advantages are simplicity, low cost, suitability for low flow rate conditions, long life, the lack of need for maintenance work, and ease. On the contrary, there are many disadvantages that also affect the performance of the Wells turbine, such as its low efficiency, narrow operating range, and low output power. This is due to the occurrence of surges during the operation of the turbine, and hence the axial force is high. All these disadvantages have been modified in the present work as much as possible, and many modifications have been added, which led to the improvement in the performance.

There are a number of parameters within the design that affect the performance of a Wells turbine, such as solidity, which typically ranges from 0.3 to 0.7. [2]. This parameter affects the self-starting condition of the turbine; the value of solidity required to achieve self-starting at a hub-to-tip ratio of 0.6 is greater than 0.51 [3]. In another study, it was more than 0.45 [4], and the best value for solidity was 0.67 for the best performance in several previous studies.[5]. The recommended optimum hub-to-tip ratio value is 0.6 [6]. The aspect ratio best value for the optimum design is 0.5[7]. The tip clearance ratio suggested in previous posts is not more than 0.2% [8, 9]. These factors must be considered when designing the turbine blades, and there is a range of specific values for each parameter that gives the best performance.

A few additional modifications have also been added to the Wells turbine, such as the installation of guide vanes with the Wells turbine to enhance the performance characteristics.[5, 10, 11]. Using a hybrid system composed of an impulse turbine with a Wells turbine on a single shaft increases the operating range of the system.[12, 13]. Making a Wells turbine with self-pitch-controlled blades improved the performance, and the optimum angle of oscillation was found to be γ_b= 8° [5, 14, 15]. Different blade geometry and a multi-stage Wells turbine is used to improve the performance. These results in decreasing the blade losses, hence increasing the operating efficiency [16-18].

All the aforementioned modifications were intended to improve the performance of the Wells turbine. During this research, the experimental results of a Wells turbine designed and manufactured for experiments will be presented. The performance of the Wells turbine will be studied on blade code NACA 0024 (National Advisory Committee for Aeronautics) in four different modes to reach the optimum position that gives the best performance. The aim of this work is to verify experimentally the extent of performance improvement of a Wells turbine provided with variable-shaped blades. Such blades are self-pitch ones with swinging tails. A comparison between traditional and self-pitch blades is introduced.



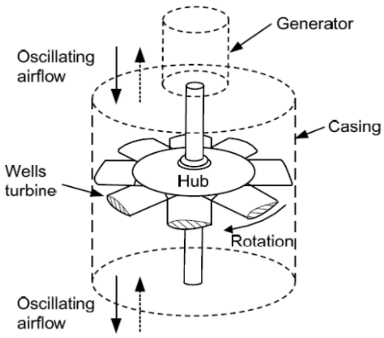
- Fig (١): The Oscillating Water Column (OWC) Wave Energy Converter system [19].

2. Principle of operation of Wells turbine:

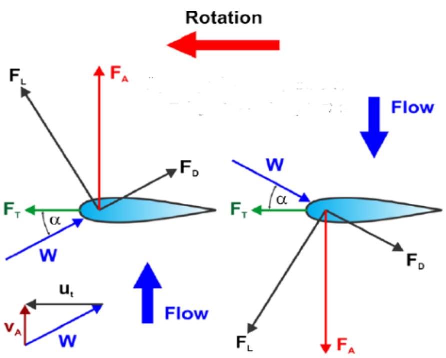
The Wells turbine shown in Fig. 2-a, is one of the most important types of air turbines that have been built to rotate in the same direction, regardless of the direction of the air passing through it. The basic working theory of the Wells turbine is as follows: with the entry of the wave in the upward direction into the chamber partially submerged in water, it pushes the air through the turbine; and in the event of a downward direction, it pulls the air in the opposite direction through the turbine. Wells turbine that Alan Arthur Wells invented in the late 1970s, uses symmetrical airfoil blades that make the tangential turning force (Torque Force) go in the same direction regardless of the direction of flow, the turning torque is obtained by combining the tangential components of the lift and drag forces, as shown in Fig. 2-b.

$F_T = F_L \sin\alpha - F_D \cos\alpha$

$F_A = F_L \cos\alpha + F_D \sin\alpha$



- Fig (2-a) Schematic diagram of wells turbine[20]

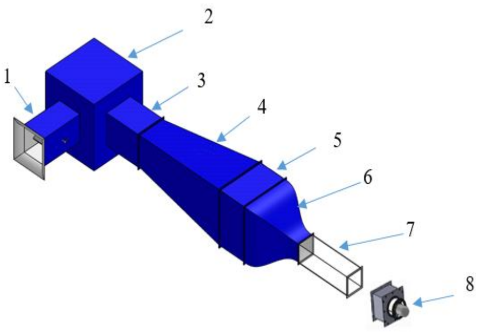


- Fig (2-b) Aerodynamic forces acting on air foil[21].

3. Experimental Procedures

3.1 Design of test rig

The movement of the waves, whether in the case of air being pushed or pulled, causes a specific flow rate. In the actual case, the value is variable between two values: minimum and maximum. The work is based on the average value between the two mentioned values. The test rig is composed mainly of a wind tunnel test section in which the flow is pushed and controlled at different flow rates in one direction. It is assumed that the performance is symmetric between the two entry sides of the rotor blades [22]. Therefore, experiments can be conducted on the turbine in the case of air pushing and taken to study the performance of the turbine by varying flow rates through the wind tunnel to express the average values of the rate of flow during actual application with sea and ocean waves. The wind tunnel is operated by a centrifugal blower of type Fan THLZ 450 FF with maximum shaft power 8 kW and as shown in Fig 3-a, the fan pulls air through a control box (1) consisting of a bell mouth inlet duct with gate – box. This leads to a pass-through fan located inside a Fan house (2) which pushes air into the wind tunnel composed of a guide vanes duct (3), diffuser (4), and settling chamber with honeycomb (5), contraction nozzle (6) and test section (7) .The test which is connected to Wells turbine (8). Figure 3-b illustrates the manufactured Wells turbine with different blades, U-tube manometer to measure pressure difference across the turbine rotor and the brake which is used for measuring frictional torque and power on the shaft of the turbine to control its rotational speed.

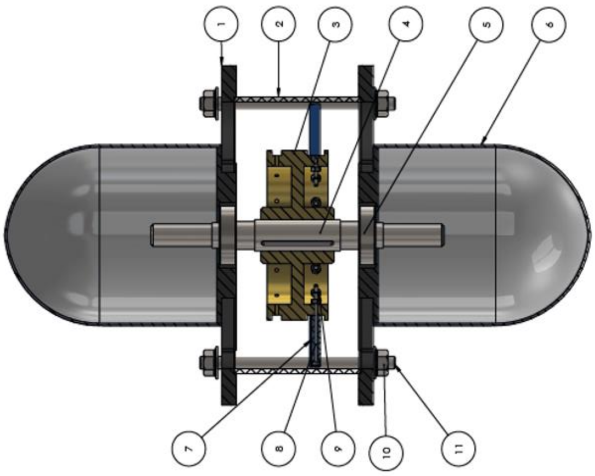


- Fig (3-a) An Open-Type Wind Tunnel connected to it Wells turbine.

- Fig (3-b) The Manufactured Wells turbine.

3.2 Design of Wells turbine model

The turbine main parts are as shown in fig. 4 consists of 1. Turbine housing (1), turbine casing (2), turbine hub (3). Turbine shaft (4), angular ball bearing (5), turbine hub (6), turbine blades (7), socket head cap screw M3 (8), blade fixing hexagonal nut M3 (9), casing fixing nuts M10 (10) and frame holding stud M10 (11). The Wells turbine is fitted to the end of the test section of the wind tunnel. The turbine design has considered a hub-to-tip ratio of an existing turbine of Islay LIMPET wave power plant [23]. A number of modifications have been added to the design to improve turbine performance so that various effects on turbine performance can be studied. The hub-to-tip ratio of the existing turbine of Islay LIMPET wave power plant is 0.62 and the turbine tip diameter is 2.6 m [23]. A model of scale ratio of 1:12. The model Parameters are tip diameter 0.217 m, hub diameter 0.135 m and mean diameter of 0.176 m. The annulus area and blade height became 0.0227m^2 and 0.041 m respectively. The blade profile was changed to NACA0024 and its cord length increased from 0.027 m to 0.032 m to get a thicker profile to facilitate fixation. The number of blades was increased from 7 to 12 to improve solidity from 0.3386 to around 0.69.

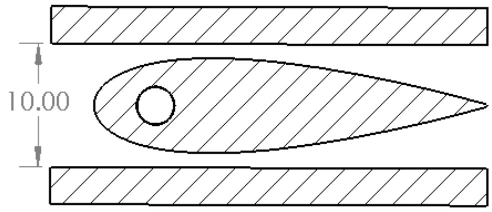


▪ Fig (4). Wells turbine main parts.

3.3 The model blades design procedures

To improve the Wells turbine performance, it was decided to split the blade profile into two parts. The front 20 mm long would be allowed to act as a self-pitched controlled unit which is allowed to swing, around a center pivot 5 mm from its tip, between ± 8.5º in a groove 2mm high in the turbine hub. The tail end 12 mm long would be allowed to swing freely around another pivot trailing the first by15 mm. The rotation angel is controlled by varying the position of 12 small pins with a diameter of 2 mm are used; located on the groove on the hub. Depending on the depth of these pins, the tail angle required can be easily obtained as shown in Fig (6).

Four cases that have been studied during practical experiments as shown in following figures:



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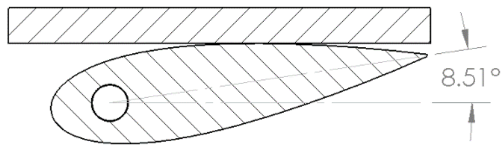

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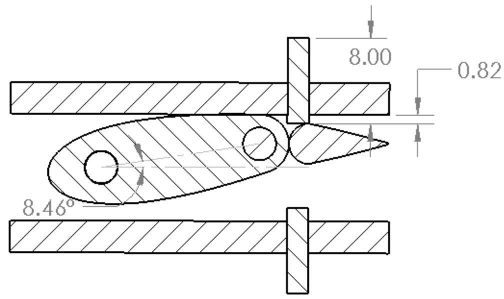

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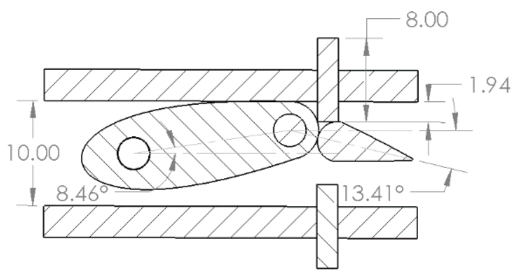
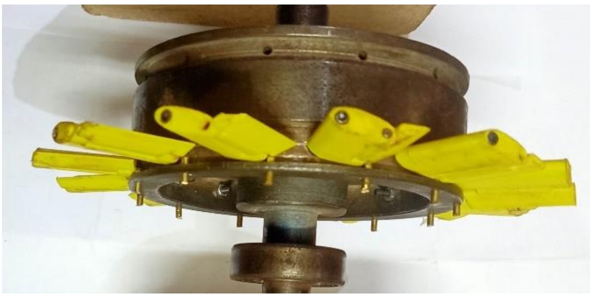


(d)

▪ Fig (5). The different profiles used in the experiments, (a) the blade profile of traditional Wells turbine (Zero-Pitch blade), (b) the profile of Self-pitch-controlled blade, (C) The profile of the Self-Pitch Controlled blade with Horizontal Tail Trimer, (d) The profile of the Self-Pitch Controlled blade with Inclined Tail Trimer.



▪ Fig (6). Wells turbine model with small pins responsible for tail position.

4. Mathematical Relations:

There is a set of mathematical relationships that are used to illustrate the performance of the Wells turbine. The most important of these relationships are torque coefficient (C_T), input coefficient (C_A), flow coefficient (ϕ), efficiency (η) and power coefficient ($\hat{P}$).
The input coefficient may be calculated by[24];

$$C_A = \frac{2\,\Delta P\,\dot{Q}}{\rho_a\,(V_A{}^2 + U_m{}^2)\,b\,C\,Z\,V_A}$$

The torque coefficient may be calculated by[24];

$$C_T = \frac{4\,T_o}{\rho_a\,(V_A{}^2 + U_m{}^2)\,b\,C\,Z\,D_m}$$

The flow coefficient may be calculated by[24];

$$\phi = \frac{V_A}{U_m}$$

The efficiency may be calculated by[24];

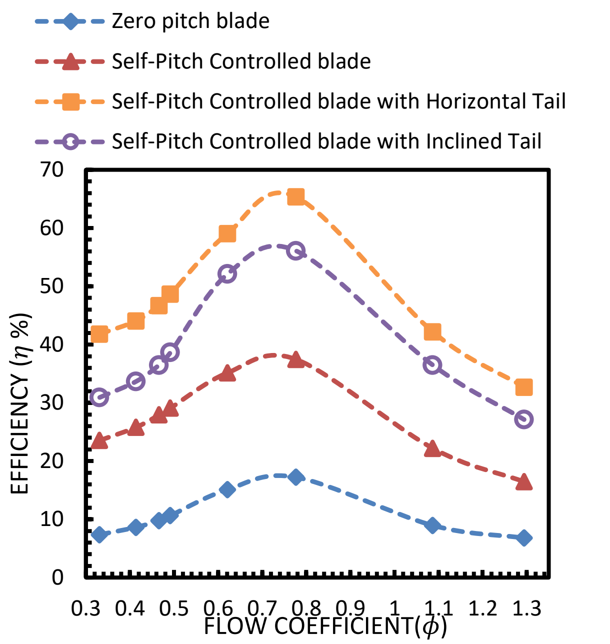
$$\eta = \frac{T_o\,\omega}{\Delta P\,\dot{Q}} = \frac{C_T}{C_A\,\phi}$$

Power Coefficient may be calculated by:

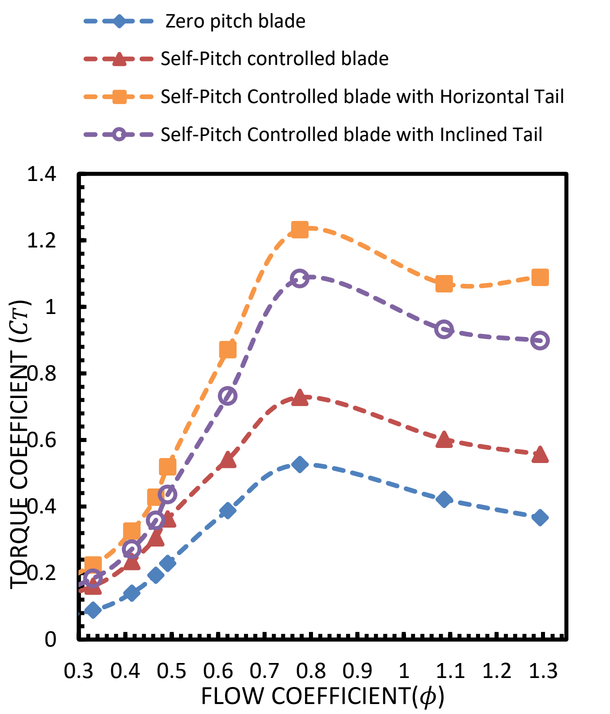
$$\hat{P} = \frac{P}{\rho_a N^3 D_m{}^5}$$

5. Results and Discussion

Experimental measurements were carried out on the turbine manufactured for the above four cases, and the flow rate was determined through the wind tunnel. The different performance parameters of the turbine were calculated in the different cases to be studied. Experiments were conducted at three different rotational speeds: 1000, 1500, and 2000 rpm.
The following results show the change of the various important performance parameters, such as the change in efficiency, torque coefficient, input coefficient (C_A) and power coefficient ($\hat{P}$) with flow coefficient, from which it is possible to know the best case in performance.
From the experimental results shown in Fig. (7), it is clear that the performance is improved in the case of the self -pitch-controlled blade compared to the original Wells turbine, while the best performance was found in case of the self-pitch-controlled blade with a horizontal tail trimer.
This increase in tangential force occurs because the resultant tangential force in this case is the sum of the components of the tangential force of lift and drag forces for the first part of the blade and the additional tangential force of the change of momentum for the tail part of the blade. Thus the generation of torque that can be used for generating power increases, which increases the efficiency of the turbine and improves its performance.
From the results shown in fig. (7-a, b), it is clear that the higher the tail angle in sloping, the lower the efficiency and torque coefficient of the turbine and thus reduce the performance characteristics of the turbine, as in the case of the self-pitch controlled blade with an inclined tail with a small angle of slope, which was lower than the self-pitch controlled blade with a horizontal tail but better than the mode of the self-pitch controlled blades.
Also, from the results of the experiments, it's clear that for the self-pitch-controlled blade with a horizontal tail trimer shown in fig. (7-c) of the input coefficient, the pressure difference through the rotor of the turbine is the lowest, so that the input power is lowered, and the output power is increased. As a result, the efficiency of the Wells turbine increases and its performance is enhanced.
Results in fig. (7-d) show that the output power increases with increasing flow rate, but after the best efficiency point the output power rate of increase is reduced with increase in flow coefficient. This is due to flow separation and the occurrence of surge. Note that the output power increases while the average efficiency decreases.



(a)



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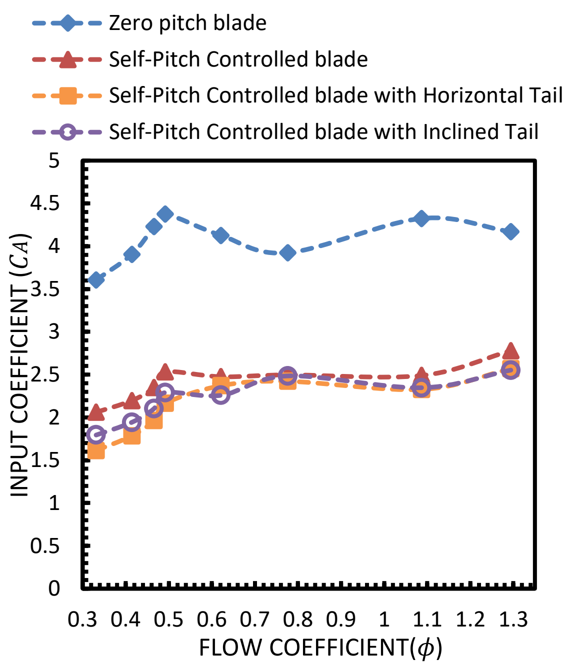

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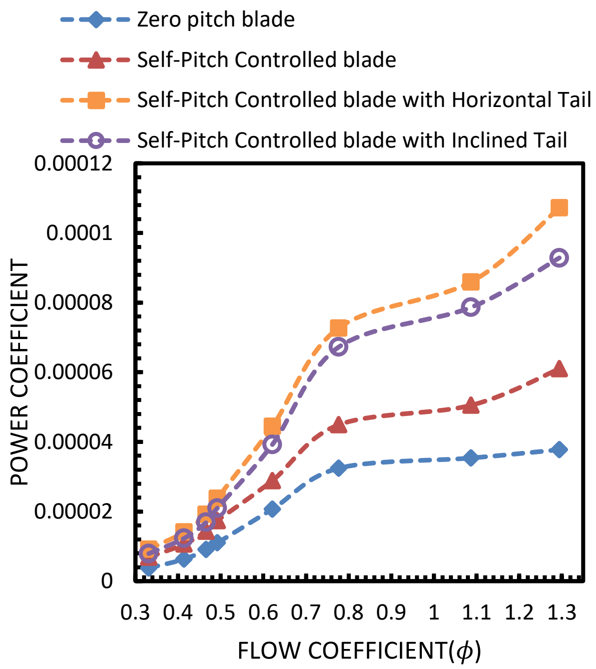
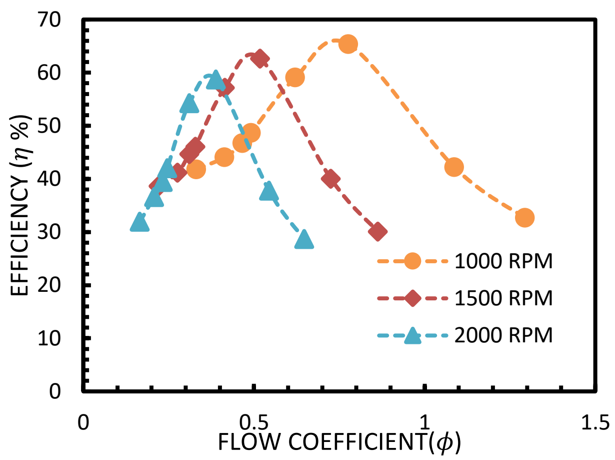


(d)

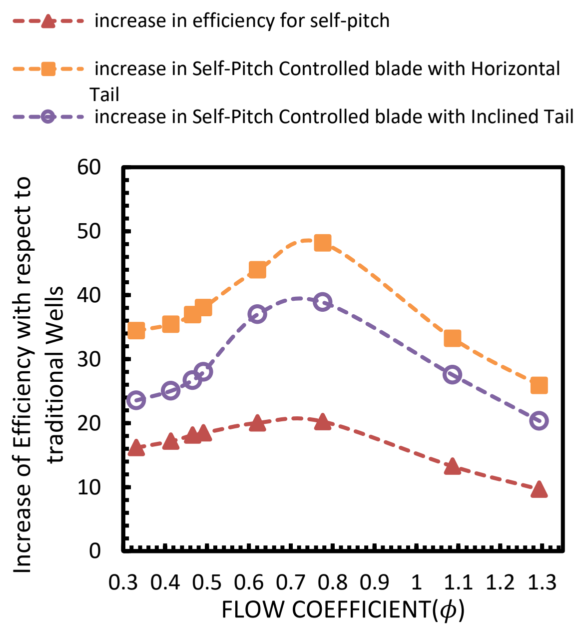
- Fig (7). Performance parameters for 1000 rpm (a) Efficiency vs flow coefficient, (b) Torque coefficient vs flow coefficient, (c) Input coefficient vs flow coefficient and (d) Power coefficient vs flow coefficient.

For 1000, 1500, and 2000 rpm, the performance characteristics follow almost the same trend, but with increasing speed the maximum efficiency decreases as shown in fig (8) and the best case at all is the self-pitch-controlled blade with horizontal tail for all speeds

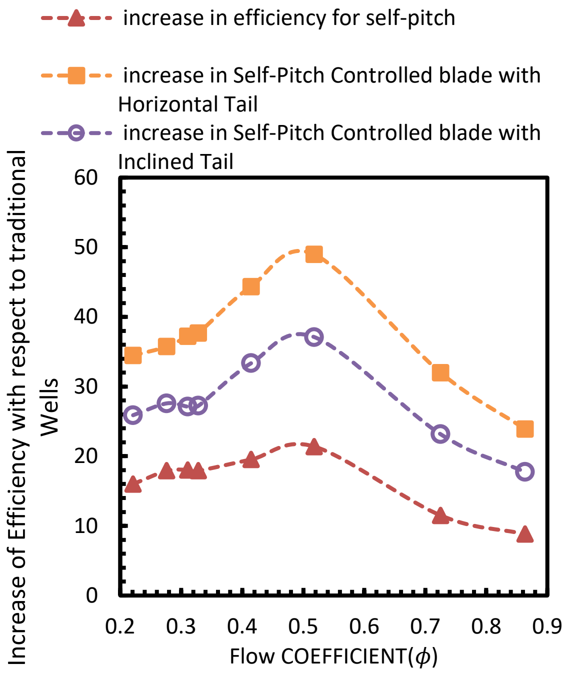


- Fig (8). Efficiency vs flow coefficient for self-pitch controlled blade with horizontal tail trimer for 1000, 1500 and 2000 rpm.

From results for 1000 rpm, the self-pitch-controlled blade increases the average efficiency by a range of 10:24 %, the self-pitch controlled blade with horizontal tail trimer increases the average efficiency a range of 26:48 % and the self-pitch controlled blade with inclined tail increases the average efficiency by a range of 20:39 %. From results for 1500 rpm, the self-pitch controlled blade increases the average efficiency by a range of 9:21 %, the self-pitch controlled blade with horizontal tail trimer increases the average efficiency by a range of 24:49 % and the self-pitch controlled blade with inclined tail trimer increases the average efficiency by a range of 18:37 %. From results for 2000 rpm, the self-pitch controlled blade increases the average efficiency by a range of 8:21 %, the self-pitch controlled blade with horizontal tail increases the average efficiency by a range of 23:47 % and the self-pitch controlled blade with inclined tail increases the average efficiency by a range of 18:35 % as shown in fig (9).



(a)



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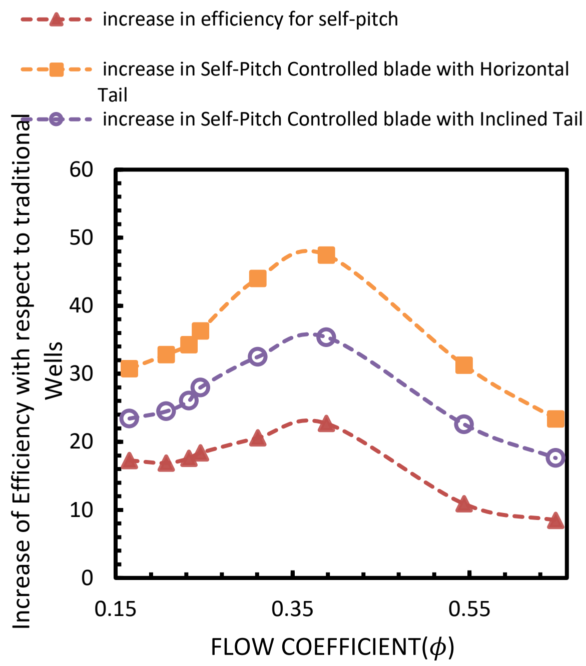

(c)

- Fig (9). Increase in the average efficiency for (a) 1000 rpm, (b) 1500 rpm, and (c) 2000 rpm.

Table (1). Performance Range For 1000 rpm cases.

Blade Type	**Best Efficiency Point**			**Reasonable start point***			**Reasonable End point***			**Operating Range**
	η %	**φ**	C_T	**η %**	**φ**	C_T	**η %**	**φ**	C_T	
Traditional Wells turbine	17.22	0.776	0.526	10	0.47	0.19	10	0.98	0.46	0.47 : 0.98
Self-pitch-controlled blade	37.47	0.776	0.728	24	0.34	0.16	22	1.08	0.6	0.34 : 1.08
Self-Pitch Controlled blade with Horizontal Tail Trimer.	65.35	0.776	1.232	42	0.34	0.23	32	1.28	1.08	0.34 : 1.28
Self-Pitch Controlled blade with Inclined Tail Trimer.	56.1	0.776	1.085	31	0.34	0.18	30	1.15	0.91	0.34 : 1.15

* Proposed by authors.

6. Conclusions

Getting rid of the defects in the Wells turbine is the main concern of researchers in this field, and they are working to raise its performance characteristics. Indeed, during this research, the effect of the geometry change of the blade on the performance characteristics of the turbine was studied, and it was found that the best design was the self-pitch-controlled blade with a horizontal tail trimer when working at a speed of 1000 rpm.This led to an increase in the maximum efficiency of the turbine from 17% in the case of the zero-pitch blade to 65% in the case of the self-pitch-controlled blade with a horizontal tail trimer. It also led to the widening of the operating range across all cases as shown in table 1. It also became clear that it is better to work at lower rotational speeds as the best performance was found at 1000 rpm, where the efficiency was 65%, and that efficiency decreased in the case of 1500 rpm to 62%, and in the case of 2000 rpm, it decreased to 58%. Finally, it is expected that the efficiency will increase and a wider range of flow coefficient will result at speeds below 1000 rpm.

Nomenclature

b : The blade height.
C : The chord length.
C_A : The input coefficient.
C_T : The torque coefficient.
D_m : The mean diameter of blade.
F_A : The Axial force.
F_D : The Drag force.

F_L : The Lift force.
F_T : The Tangential force.
h : The hub to tip ratio.
N : Rotational speed.
ΔP : The pressure difference across rotor.
$\dot{Q}$: The flow rate.
R_t : The tip radius.
S : The Solidity.
U_m The mean circumferential velocity.
V_A : The mean axial flow velocity.
Z : The blades number.
α : The Angle of attack.
ρ_a : The air density.
$\emptyset$: The flow coefficient.
η : The efficiency of the Wells turbine.
NACA: National Advisory Committee for Aeronautics.
$\hat{P}$: Power coefficient.

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