Studying the Behavior of a Variable Pitch "Hydro Screw" Micro Hydro Turbine, Numerical Analysis and Experimental Investigation

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Received: 8 September 2018, Revised: 27 January 2019, Accepted: 9 February 2019

Abstract: Hydro screw is an axial micro hydro turbine of Archimedean origin. Due to ever-increasing need for clean fuel based and environmentally clean electric power, a research project was undertaken at IROST. In this study, the effect of spiral variable pitch on hydro screw turbine has been studied numerically. Based on the results, it was found that the turbine had the best efficiency with a spiral pitch of 1.5. Accordingly, the small model of this turbine was made and tested in the laboratory. The results indicate that the numerical results of the calculations are in good agreement with experimental result, and therefore they can be used safely in the course of subsequent turbine studies. In summary, the results indicate that the maximum turbine output is between 62% and 68% which is about 30% higher than the constant pitch blade turbine.

Keywords: Variable Pitch, Flow, Screw, Hydro Power

Reference: Hosseini Moghadam, A., Yassi, Y., and Nourbakhsh, A., "Studying the Behaviour of a Variable Pitch "Hydro screw" Micro Hydro Turbine, Numerical Analysis and Experimental Investigation", Int J of Advanced Design and Manufacturing Technology, Vol. 12/No. 4, 2019, pp. 57–65.

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1 INTRODUCTION

The demand for clean renewable energy sources such as hydro, solar and wind has been escalating throughout the last few decades. As a result of the increasing environmental concerns related to the wide variety of pollutants generated by production, transport, storage and consumption of fossil fuels as well as the predicted scarcity of them in relatively near future, attentions have been diverted towards the renewable energy resources and their means of production. Among the renewable energy sources, hydro power generation is one, which is of the oldest background in man's knowledge of energy production. The high cost of construction of large hydroelectric power plants, distribution and transmission networks has led to the replacement of large power plants by the dispersed and near-consumer electricity generation. The small hydro power plants are divided into three categories according to OLDE's recommendation. 1 – Very very hydro power plants (up to 50 kW). 2- Very small hydro power plants (50-500 kW). 3- Small hydro power plants (500-5000 kW). One of very very small turbines is a screw turbine [1]. This turbine has been inspired by the design of the Archimedes screw pump. The Archimedean screw is an ancient invention for a pump designed and made by Archimedes of Syracuse (287–212 BC.) Screw turbines are divided into four categories.

1- The Archimedes:
Turbine is the oldest type of screw turbines. It consists of a cylindrical axis that is wrapped around by one or more spiral rows (helices or flights) perpendicular to the axis. Around this axis is a semi-cylinder trough, covering the lower half of the helix. The turbine axis is mounted at a specific angle to the line of horizon. Water enters the screw without any special guidance (no guide vanes) and leaves without going through a draft tube. Usually, the upper end of the screw is connected to a generator through a gearbox. Figure 1 represents a schematic view of an inclined Archimedean screw turbine. the maximum head and average rotational speed of this turbine are 10 meters and 25 rpm, respectively [2]. Deciding factor in the performance of this turbine is the hydrostatic force due to the difference in water height at upstream and downstream of the turbine blade [3]. Since the power produced is the product of torque by the rotational speed and low value of the rotational speed, diameter of turbine blade would have an important and decisive contribution in the production of power. Therefore, the turbine blade diameter is between 1 and 2 meters. They also have steady and high efficiency in partial loads [4]. The turbine operates under relatively low heads with low rotational speed that is why it could be regarded as a fish friendly turbine, since they can move through the turbine from downstream to upstream or vice versa without being harmed by the blading [5].

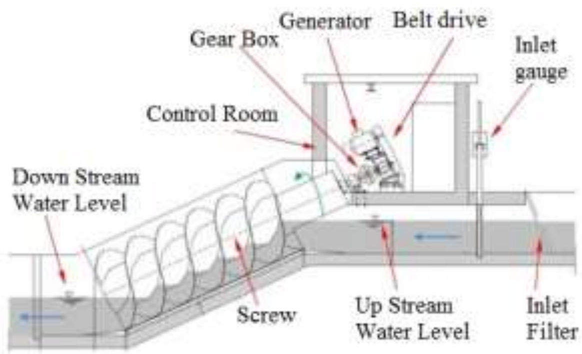

Fig. 1 A schematic view of an inclined Archimedean screw turbine.

2- Floating screw turbines:
The geometry of this turbine blade is exactly the same as the inclined screw turbine. Unlike inclined screw, this turbine has no peripheral chamber and is floating horizontally on the surface of the water [6]. The head of these turbines is close to zero [7]. And the drag force is the turbine driving force [8]. Figure 2 represents a schematic view of a Floating screw turbines.

Fig. 2 A schematic view of Floating screw turbines [8].

3- Tidal screw turbine:
These turbines are installed on the sea bed and the force of tidal currents is the turbine driving force. Figure 3 represents a schematic view of a tidal screw turbines.

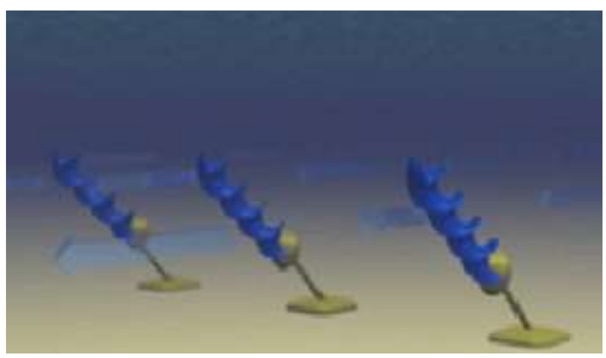

Fig. 3 A schematic view of tidal screw turbines [9].

4- Horizontal screw turbine:

Hydroscrew turbine is a type of horizontal screws. Its blades structure is almost similar to Archimedes screw turbine, except that here the turbine is mounted horizontally. Tube-shaped chamber is surrounding the turbine. In this case, the generated kinetic energy by the flow of water is the effective factor in performance of the turbine. Therefore, considering the small value of the blade tip diameter, the turbine should operate with higher rotational speeds. (Up to 2500 rpm) Since the produced power is the result of torque by rotational speed, therefore the value of the speed should have an important and decisive contribution in the production of power. Naturally, increasing the value of rotational speed results in reducing the torque which in turn may lead to reducing the geometrical dimensions of the turbine especially the diameter of the turbine. This would result in smaller, lighter and more manageable designs of the turbine. Hydroscrew has special advantages:

- Low weight and small dimensions
- Portability
- High Production Capacity
- Easy construction and low maintenance costs
- Possibility to use in matrix

A constant pitch Hydroscrew is numerically analyzed by Schleicher. He studied the effect of head and flow discharge changes on turbine performance [10]. In a numerical study, Lancaster developed geometric parameters influencing the design of a Hydroscrew turbine. He showed that the diameter ratio and the constant pitch ratio are the most effective parameters of the Hydro screw design [9]. The effect of cavitation on the Hydroscrew performance is studied by Riglin. He indicated that the occurrence of cavitation in this turbine is decisive and it can be reduced by changing the trilling angles of turbine blades [11]. In previous studies, the effect of the variable pitch blade on the performance of the Hydroscrew turbine has not been investigated. Since the pitch ratio is one of the most important parameters of the Hydroscrew turbine design, in this case, the effect of changing the variable pitch of the blade on the Hydroscrew turbine performance will be numerically and experimentally investigated and a constant pitch and variable pitch turbines will be compared.

2 HYDROSCREW TURBINE

Generally "Hydro Screw" turbine consists of three major parts which are namely, the casing, bearing holders and the screw (main shaft and the blading).

i. Casing

The casing consists of a metal pipe of predetermined diameter, made of stainless steel or Aluminium of the grade7000 family.

ii. Bearing holders

Two cross shaped enclosures are designed which house the bearings of two sides of the main shaft at their center. They are installed at the entrance and the exit of the casing tube, bearing the loads on the main shaft.

iii. Main Shaft & blading

Actually the main shaft and the blading (the screw) are so designed to be manufactured of one single raw material. Two ends of the shaft rest on bearings situated at both ends casing. Figure 4 represent a view of the main shaft (screw).

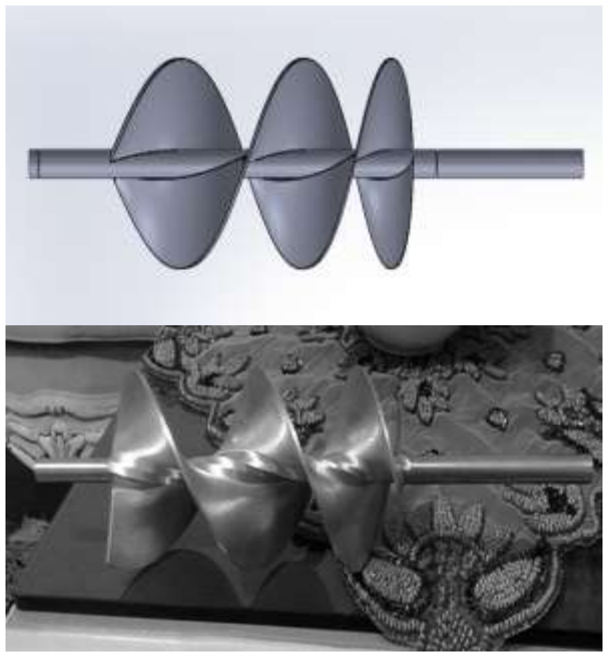

Fig. 4 A view of hydro screw turbine blade.

As far as the literature on the design of the hydro screw allows, there is not much detailed information available on the subject. Therefore, for designing an efficient turbine, it was necessary to use the results of a numerical study on "Hydro screw "design [12].

3 NUMERICAL SOLUTIONS

For performing the numerical analysis, a cylindrical solution field; consisting of three parts, was used. The first part, having a length of 0.25 times of the turbine length was introduced to prevent the effects of the incoming flow on the turbine inlet. The middle part is the turbine blade, and the third part, having three times of the turbine length; was selected to prevent the effects of the recursive flow at the turbine outlet on the turbine blade. The solution field is shown in "Fig. 5". All parts have 15cm diameter and turbine has 2cm shaft's diameter.

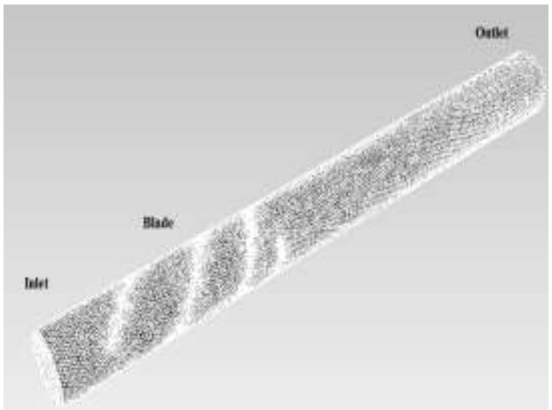

Fig. 5 Computational domain and mesh.

Generally, there are two methods to design the variable pitch blade. First, the blade is divided into several sections and one independent pitch is considered for each section, although the coherence, cohesion and continuity between the blade steps would be eliminated. The second method is to use mathematical relationships and reduce the number of variables affecting the variable pitch blade design. For this purpose, “Eq. (1)” is applied:

$$\overrightarrow{r^{\circ}_{P}} = aC_{\varphi}\hat{\imath} + aS_{\varphi}\hat{\jmath} + L_{turbine}\left(1 - \left(\frac{l_{turbine}}{L_{turbine}}\right)^{m}\right)\hat{k} \quad (1)$$

Where:
a = the radius of the blade.
L = the length of the turbine blade.
m = an exponential constant.
If m is equal to one, then the blade is of constant pitch. Higher pitch values cause more condensed pitch frequency at the inlet, moving towards less condensed frequencies as approaching the outlet. To evaluate the effect of changing the pitch value increments, five blade samples with pitch values of 1.25, 1.5, 1.75, 2 and 2.25 are designed and the results were compared against the reference model with a constant pitch.

4 SOLUTION INDEPENDENCE OF THE NETWORKING

A prerequisite for any numerical analysis is the independence of the results from the networking of the solution field. For this purpose, three different networks were applied. A low density network with a total of 552123 volumetric cells, a balanced or moderate network with 1184355 cells and a condensed or high density network with 2732365 cells were used. “Table 1 and Table 2” show the sharpness, slip values (perpendicularity) and the quantity of YPlus for the first layer near the wall and the blade.

Table 1 Mesh quality of computational domain

Title	Number of cells	Orthogonal min	Skeweness max
Low density	5521223	0.19731	0.89981
Medium density	1184355	0.17326	0.89996
High density	2732265	0.17124	0.89994

Table 2 YPlus for different domain

Definition	High		Medium		Low	
	Casing	Blade	Casing	Blade	Casing	Blade
YPlus min	10.4	1.41	18.2	1.92	4.53	1.02
YPlus ave	45.5	15.8	59	36.2	86.8	75.2
YPlus max	64.5	73.2	89.9	109	163	243

To obtain higher levels of accuracy in results, the YPlus value should be between 30 and 40 [4]. As shown in “Fig. 4”, a constant 5- meter input head and a constant 500 rpm rotational speed were designated.
For all three networks, a mutation or a jump can be seen within the primary 0.25 seconds, after which an overall stability is achieved. The low density network reaches to stability faster than the other two, but it is less precise. The precision of the results for the moderate and high density networks is roughly equal. Therefore, considering the suitable solving time of the moderate density network, it was used for all remaining calculations (1).
Figures 6 to 8 represent samples of plots resulted from the numerical analysis for available head of 5 (m) and various rotational speeds.

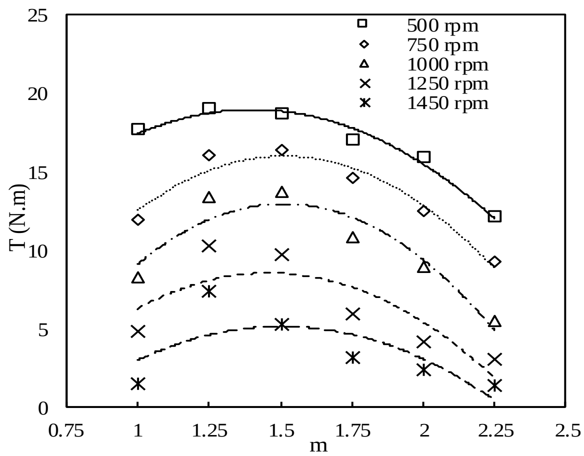

Fig. 6 Commutated Torque vs. m.

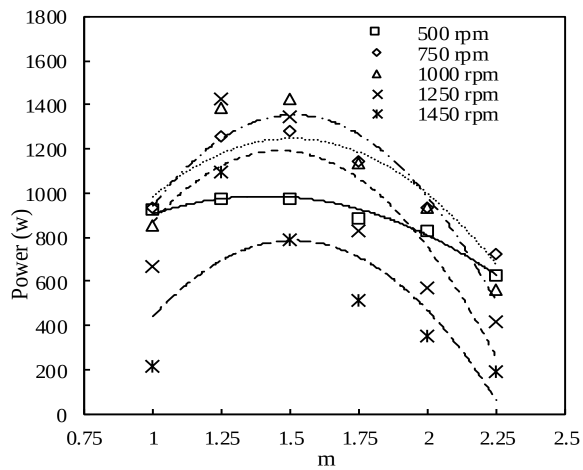

Fig. 7 Commutated Power vs. m.

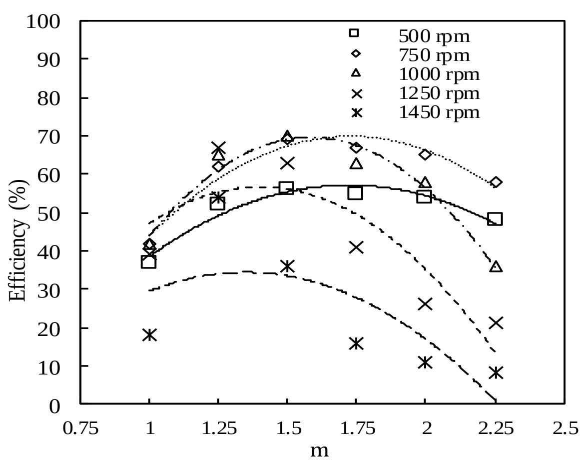

Fig. 8 Commutated efficiency vs. m**.**

According to the results of the numerical study, the most efficient design for the screw is a variable pitch screw of the pitch value of 1.5.

5 CONSTRUCTION AND TESTING THE TURBINES

For the purpose of testing the turbine, a turbine prototype was constructed and tested at the hydraulic and turbo machinery laboratory of IROST. For the construction of the turbine, due to the complexity of the blade manufacturing process which required integrated turning of the blade and the turbine axis, a 1:2 model was manufactured. In order to test this turbine, an appropriate test bed was required. Therefore, the current available test bed was modified, according to the turbine and test requirements. Figure 9 shows schematic and the actual image of the main test circuit. In addition, "Fig. 10" shows a complete view of the turbine respectively.

In this laboratory, 6 electro pumps of 11 kW generate the required head and flow rates. An UF5000 ultrasonic flow meter is used to measure the flow rate. A digital tachometer sensor AP 501 measures the turbine speed.

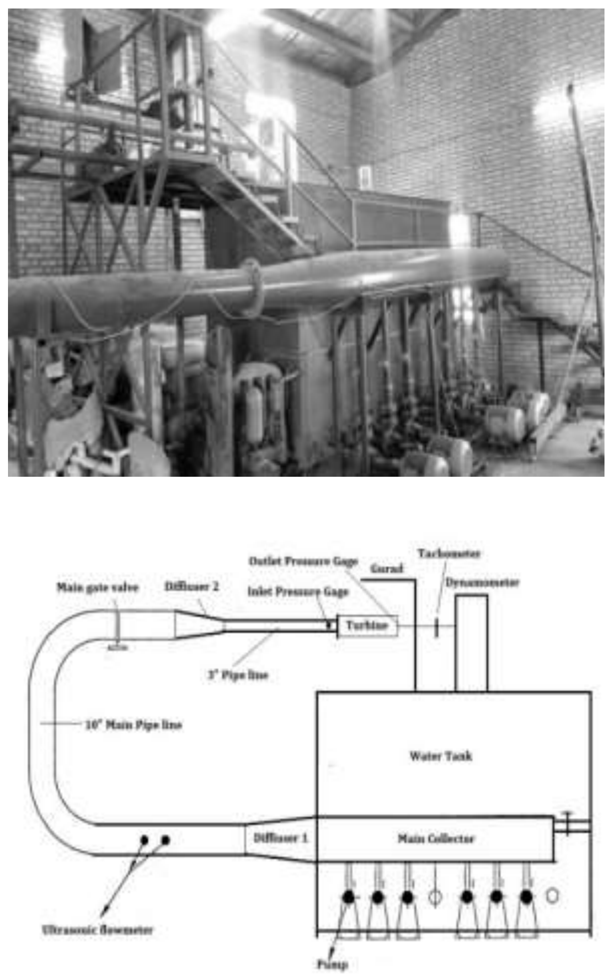

Fig. 9 Schematic and real view of the test laboratory at IROST.

Fig. 10 Constructed turbine while being tested.

To measure the power generated by the turbine, a suitable Pronney mechanical dynamometer was designed and manufactured. For measuring the turbine torque, a UBO-10 load cell with a capacity of 10 kg was installed on the dynamometer. This dynamometer is connected to the turbine with a suitable coupling and shielded against water splashes by a thin metal guard.

6 THEORY

Since the prime objective of this study was to determine the behaviour of the variable pitch "screw hydro" turbine of a certain pitch value, then required parameters for constructing the standard characteristic curves were taken during the tests. In all, the turbine was tested for many times and readings were taken for constant speed and constant head conditions and the required data for constructing constant efficiency curves were extracted thereof. Construction of the main characteristic curves requires data for flow rate, torque, power and efficiency for various speeds under constant heads. The "Eq. (2)-(5)" show the main characteristic:

$$\dot{T} = T/H \quad (2)$$

$$\dot{Q} = Q/\sqrt{H} \quad (3)$$

$$\dot{P} = P/\sqrt[3]{H} \quad (4)$$

$$\dot{N} = N/\sqrt{H} \quad (5)$$

Where:
T = Torque (Nm)
H = Available head (m)
Q = Flow rate (m3/s)
P = Output power (w)
N = Rotational speed (rads/s)

Also:

Power input: Pin = ηgQH (w)
Power output: Pout= T. N (w)
η = Efficiency (%)

Here, plots are in terms of (Unit torque v Unit speed), (Unit flow rate v Unit speed), (Unit power v Unit speed) and finally (efficiency v Unit speed). The above main characteristics curves were constructed for constant heads of 0.5, 1.4, 1.8, 2.4, 3 and 3.5 meters. In addition, for constructing the operating characteristics, the same data is required. These plots were made for constant speeds of 200, 400, 600, 800, 1000 and 1200 rpm, as follows:

Joint (efficiency and power vs. flow rate) curve for determining the operating point of the turbine. Power v flow rate, Efficiency v flow rate.

7 RESULTS & DISCUSSION

The experimental results were tabulated and presented in the form of the above-mentioned characteristics curves. Figures 11 to 14 represent the main characteristic curves for the experimental measurements. Moreover, "Fig. 15 to 16" show samples of operating characteristic curves constructed by the experimental values. Actually the results for the head value of 2.4 (m) were selected because the best performance for the turbine was achieved under this head.

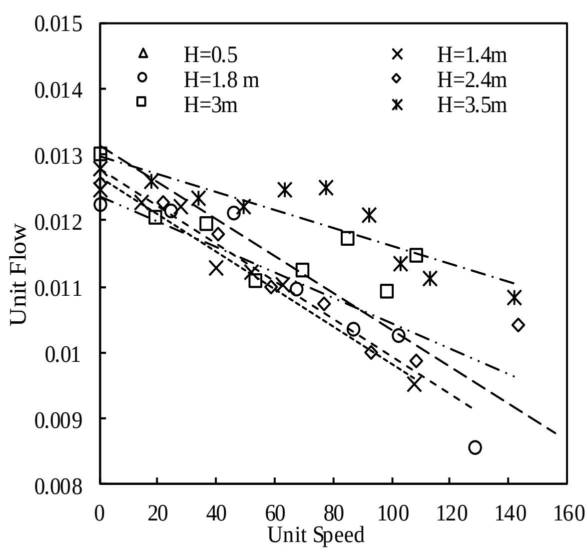

Fig. 11 Main characteristic, Unit flow v Unit speed.

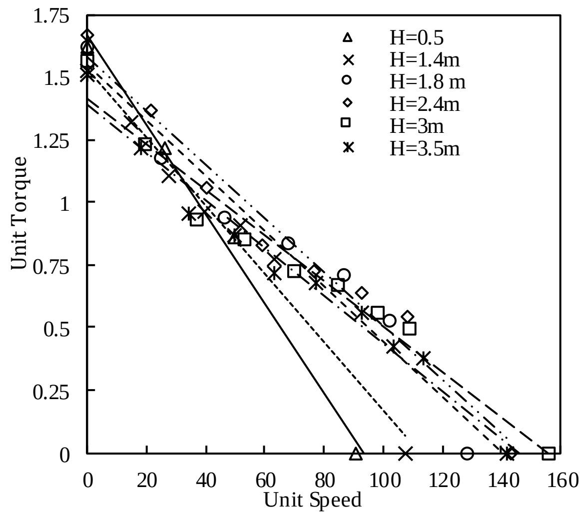

Fig. 12 Main characteristic, Unit torque v Unit speed.

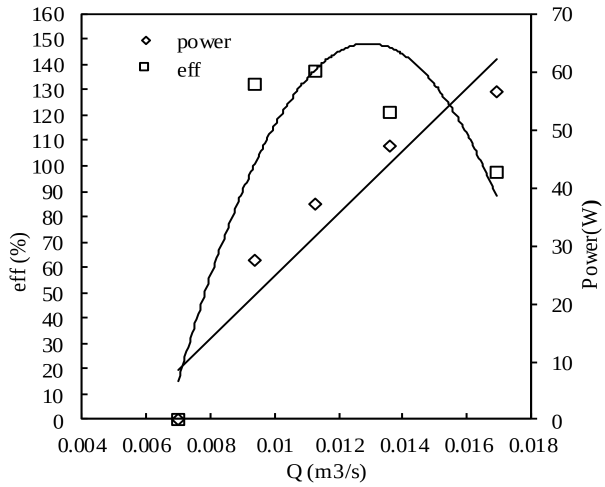

Fig. 15 Operating characteristic: Operating point for the speed of 1000 rpm.

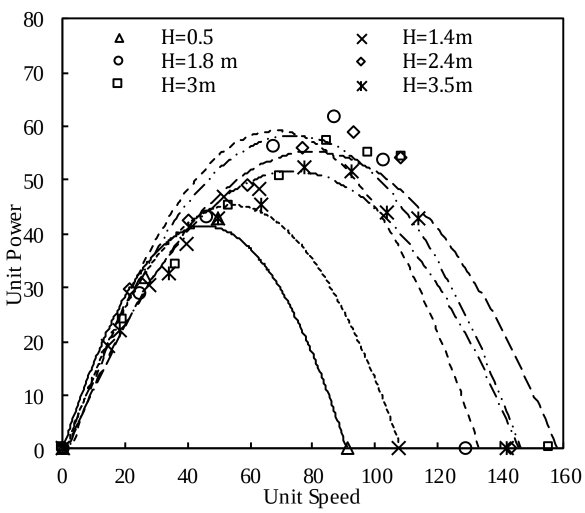

Fig. 13 Main characteristic, Unit power v Unit speed.

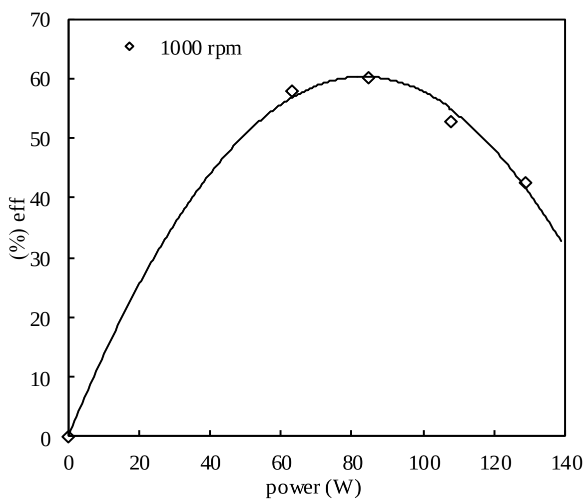

Fig. 16 Operating characteristic: Efficiency V power curve for the speed of 1000rpm.

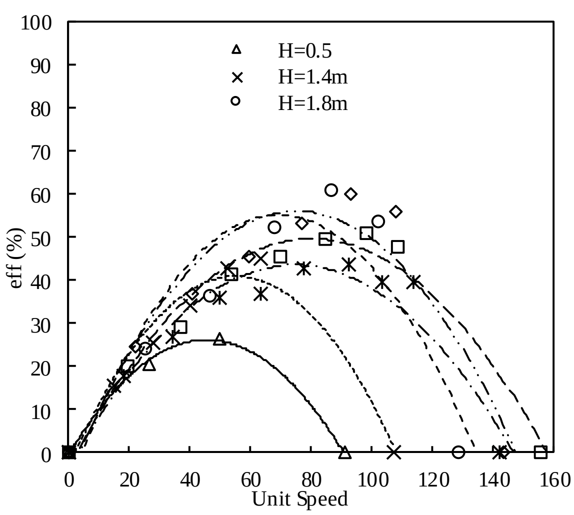

Fig. 14 Main characteristic, Efficiency v Unit speed.

Furthermore, results for an effective head of 2.4 (m) for both numerical (indexed "run") and experimental (indexed "test") are tabulated in "Table 3".

As may be observed, the test values for the flow rate have so been determined to be as close as possible to those of the numerical values. As a matter of fact, the soft wear actually determines the value of the flow rate according to the effective head and manipulation of the input data is not possible for getting exact values to match those of the experimental values.

On the other hand, pump adjustment to obtain exact values as required to match the numerical values faces a degree of limitation, so there is some discrepancy observed between the decisive values of the flow rate. However, regardless the discrepancies, yet a tangible agreement are observed between the values of torque, power and the efficiency for numerical and experimental values.

Table 3 Turbine numerical and experimental data

rpm	400	600	800	1000	1200
$Q_{.test}$	0.0122	0.0117	0.0116	0.0112	0.0133
$Q_{.run}$	0.0116	0.0115	0.0111	0.0107	0.0129
$T_{.test}$	1.113	0.924	0.849	0.795	0.72
$T_{.run}$	1.103	1.011	0.934	0.872	0.75
$P_{.test}$	44.54	59.21	72.54	84.9	92.27
$P_{.run}$	46.17	63.49	78.2	91.26	94.2
$eff_{.test}$	36.97	45.53	53.35	60.22	52.49
$eff_{.run}$	37.8	49.67	60.55	68.13	55.24
H	2.4	2.4	2.4	2.4	2.4

However, the highest value of discrepancy is about 11% in values of the efficiency for the speed of 1000 rpm. The percentage difference between the numerical results and experimental ones are lower than this value which indicates reasonable accuracy of the numerical results. Therefore, due to the verification of numerical results by the experimental results, it could be concluded that the numerical results may be regarded as good approaches to the actual values.

Study of the results shows that the turbine operates at its best for the speed of 1000 rpm for an available head of 2.4 (m), a flow rate of.01072 (m3/s) attaining an efficiency of 68%. In addition, the efficiency value drops by 13% when the rotational speed increases from 1000 rpm to 1200 rpm (a 200 rpm speed increase step). Whereas the increasing steps of the efficiency are regressive for speed increase steps of 200 rpm up to the highest efficiency value of 68%. Therefore, the "hydro screw" may be used by its simple and light present form for low potentials of less than 2.5 meters head and 11 lit/s flow rate to generate local electrical power without any special constructional requirements.

8 CONCLUSION

- Hydroscrew turbine is suitable for low head and discharge flows up to 5 meters.
- By changing the structure of the turbine blade from a constant pitch to a variable pitch, at the best operating point, the efficiency of turbine is increased by more than 30%.
- The best variable pitch can be achieved by a constant coefficient of 1.5. In other words, there must be balanced between high frequency of blade's pitch of blade inlet and short frequency of blade outlet.
- In constructed sample with a scale of 1:2, the highest efficiency is 68% at a speed of 1000 rpm.
- Constructed sample with a scale of 1:2, at its best operating point at input head of 2.4 meters and a flow discharge rate of 15 liters per second, produces 123 watts of power with 56% efficiency.
- Unlike the Archimedes screw turbine, the Hydroscrew efficiency decreases at partial loads.

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