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Experimental Study of a High Speed Micro Waterwheel

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Waterwheels are the oldest types of hydraulic machines. These turbines are of relatively simple design, large diameter, low rotational speed and high torques. But applying them as micro hydros of high speed and small diameter is yet to be explored. A micro hydro waterwheel of one meter diameter was designed and manufactured at the Iranian Researc[†]h Organization for Science and Technology (IROST) as a part of a joint research program between IROST and the Iranian Ministry of Power. The model turbine was then tested. Test results as standard turbine curves are also presented in this article. According to the results it was concluded that micro hydro waterwheels can operate efficiently at sites with high flow velocity.

Keyword: Micro hydro turbine, waterwheel, high speed turbine, micro waterwheel, high speed waterwheel

1 Introduction

Production of clean and sustainable energies is one of the most important issues that authorities, and therefore, specialists have to deal with. Recent concerns over global warming and an over reliance on fossil fuels have led to an increased political, academic and public interest in renewable energies. Micro hydro power plays an important role in this regard. Waterwheel, one of the oldest types of hydro turbines, was initially used to lift water and irrigate fields but was later used as a means to generate mechanical power for milling. The rapid industrialization of the Middle Ages lead to an increase in waterwheel usage[1,2],leading to various designs of the wheel such as over shot, breast shot and under shot waterwheels. Britain and Germany were the two major countries which benefitted the use of waterwheels most, in Europe [3]. However the lack of strong and reliable gearing systems, coupled with the advent of steam power and the introduction of higher speed water turbines rapidly led to the demise of the waterwheel [2,4]. Waterwheel is experiencing a revival mainly due to its low head and flow requirements, relatively low cost, “fish friendly” slow rotation, and ease of construction. Waterwheels are especially relevant to small residential projects, where the long payback period of turbines is prohibitive [2], and for developing countries, where maintenance and fabrication has to be simple. Usually they are installed in water ways with low flow velocity, limited or no head and high volume flow rate.

In (2005), Zoe Jones of the Heriot - Watt University embarked upon a research work on

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waterwheels [2]. In this work he presented some technical back ground and mathematical CAD model for designing waterwheels. In (2003) M. Denny performed analysis on the physics of waterwheels, constructing simple models to show the reasons behind the efficiency difference of overshot and undershot waterwheels. In his work the most important design parameters were pointed out [5]. Although their results enlightened the behavior of over shot and under shot waterwheels yet they did not cover the performance of micro waterwheels (i.e. the high speed micro waterwheels). P. Bromely presented his experience in revitalizing of waterwheel in the U.K. and Sri Lanka in (1999) [6]. Also in (2001) Gotoh et al released results of the further works in the same context [7]. Muller et al. worked on design and model test of a breast shot wheel [8]. They manufactured and tested the model turbine and presented the performance characteristic of the wheel [8, 9]. Later a joint research work was carried out by the Universities of Southampton and Berlin TU, in (2005). They worked on a 500 mm under shot (stream wheel type) waterwheel aiming at developing characteristics of the turbine [10].

In Iran, due to presence of thousands of micro hydro potentials in rural and semi mountainous parts of Iran [11, 12] the Iranian research organization for science and technology; IROST; carried out a number of research projects on micro hydro machinery [13,14]. Therefore a micro under shot waterwheel suitable for low or no head micro hydro potentials in Iran was selected as the main subject of a joint research program with the ministry of power. The wheel was then designed, manufactured and tested at the mechanical engineering research center of IROST. This paper presents the experimental results of this research work.

2 Design parameters

Large diameter, low rotational speed and high torques may be regarded as the most important characteristics of waterwheels [2,15]. In a waterwheel, the rotational speed is inversely proportional to the wheel diameter.

$$\omega \propto (1/D) \qquad (1)$$

This is due to the nature of the waterwheels, as they are the type of turbine designed for potentials with low flow speeds. Since the wheel rotational speed is directly proportional to the flow speed then in order to maintain the power generation capacity of the wheel at sites with lower flow speeds the wheel diameter should be increased to generate higher torques, to compensate for the low speed of the turbine.

This is due to the fact that; the torque gained, which is the product of the water force and the radius of the wheel is directly proportional to the wheel diameter [15].

$$T = F * D//2 \qquad (2)$$

On the other hand, the power gained is also the product of the torque and the rotational speed.

$$P_{out} = T * \omega \qquad (3)$$

From (1) in (2) it can be concluded that:

$$P_{out} = F * \omega * D/2 \qquad (4)$$

Therefore, in micro waterwheels (wheels with smaller diameter) for maintaining the power generating capacity of the turbine the low values of torque due to small wheel diameter should be compensated by increasing the rotational speed of the wheel (equation (3)). Therefore in designing a micro hydro waterwheel, consideration of high rotational speed is a pre requisite

Also; the output power is a product of the moment of inertia of the rotating wheel, angular velocity and the angular acceleration:

$$P_{out} = I.\ \alpha.\ \omega \qquad (5)$$

Where;

$$I = (mr^2/2) \qquad (6)$$

$$P_{out} = (mr^2/2).\ \alpha.\ \omega \qquad (7)$$

From Eq. (4) it is shown that the power output is directly proportional to the mass and to the angular velocity. Considering the inverse relationship between the mass of the wheel and the angular velocity, (i.e. the more the mass of the rotating wheel, the lower the angular velocity), then, it may be concluded that, in addition to the angular velocity, the mass of the wheel may also be regarded as another decisive design parameter of the wheel for a particular hydro potential.

As far as calculation of the efficiency of the turbine is concerned, although different procedures have been suggested for this purpose [15, 16], yet, it mostly depends on the type of the waterwheel applied. Generally, efficiency is defined as follows:

$$\eta = P_{out} / P_{in} \qquad (8)$$

Here the power input may be defined as the sum of the potential energy and the kinetic energy, i.e.

$$P_{in} = \tfrac{1}{2}\,(\dot{m}.u^2) \qquad (9)$$

Where; P_{out} ; has been given by equations (4) and (6).

3 Experiments

3.1 The experimental turbine

The turbine is an undershot type waterwheel. It is of one meter diameter, with twenty blades supporting its power generation capacity. Undershot wheels normally require heads between 0.3m to 2.0m, and flows between 0.45 to 1 m^3 per m width [2]. Some models use a very small head drop and curved blades to take potential energy from the river. The efficiency of this type of turbine is relatively reasonable and lies between 60-77% [8] Other models, known as “stream wheels” use the kinetic energy of the river on the blades. Their usual efficiency values hardly exceed 33% (8). Here, although the blades are smoothly curved yet the wheel has been tested for both cases. This is due to the fact that, the wheel is considered as a micro hydro wheel, and so it is tested for higher wheel rotational speeds in comparison with ordinary wheels.

The turbine blades are of bent rectangular shape; and also of rectangular cross section. The blade dimensions are, 500*75*20 mm. Blades are made of Aluminum alloy and the center shaft, around which the blades are set, is made of stainless steel. Two side rings support the blades, which are laterally fixed to the side rings by screws. Two sets of screw holes have been provided, which can be used to secure the blades to the ring and change the blade angle with respect to the incoming flow, as required by the experiments. This allowance has been made to the wheel design so that the effects of the blade angle on the behavior of the turbine could be studied. The turbine’s net installation weight is about 75Kg. Figures (1a-1c) present different views of this turbine.

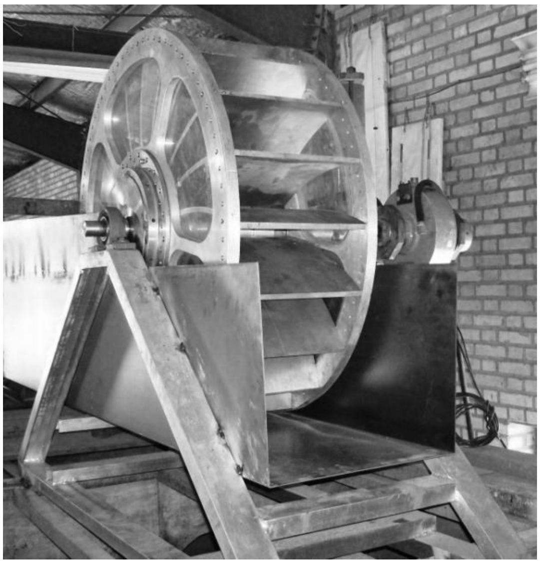

Figure 1a The experimental turbine

Figure 1b 3D computer sketch of the turbine

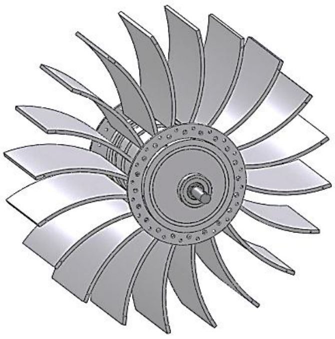

Figure 1c Turbine paddles

3.2 Test Circuit and apparatus

The test circuit design and selection of its elements, and their characteristics such as circularity and cylindricality of pipes, their lengths before and after installation points of measuring devices, required straight run before the entrance to the turbine etc. were all determined according to the ISO 5167- 1980 (E) standards [13]. However, the details of the test rig and its measuring devices are as follows:

A 20 m³ reservoir provides the water requirements of the test rig. The piping is of 10 inches diameter all through. The collector into which the water is pumped from the reservoir is a 4 meter long cylinder of 20 inches diameter, which is connected to the main piping via a 2:1 semi-conical reducer. Six 11 kilowatts electro pumps provide the required water flow for the test rig. Pumps are installed parallel to one another, generating heads up to 24 meters and an overall flow rate of 420 (m³/h).

The flow is measured by means of an ultrasonic flow meter in (lit/s) with a precision range of 0.5% for linearity, .0015% m/s of sensitivity, 0.25% repeatability, and overall flow measuring accuracy range of 1%-3%, manufactured by The Iranian Farasanj Afzar company.

Where applicable, a Pressure gauge, manufactured by the American Honeywell Co., was installed at the outlet of the pipe to measure the head of the water jet at the pipe exit, in (mbar). Accuracy range of the gauges is ±2% given by the manufacturer. A 20 (KW) Eddy current dynamometer was applied to measure the brake force of the turbine in terms of (N).The dynamometer was designed and manufactured at the mechanical engineering research center of IROST. The accuracy of the load cell measuring the brake force of the dynamometer is ±1%, manufactured by the Korean Bong Shin Company. The angular velocity of the turbine is measured in terms of (rpm) by means of a tachometer, using a magnetic induction sensor of ±0.5 accuracy range manufactured by The Iranian Tabriz Pajooh Co. with an overall accuracy range of <0.001% . Figure 2 shows a schematic view of the test rig. However, the accuracy of the devices and their precision range and their overall effects on the precision of results of the test rig were taken into account according to current procedures when writing the computer software for analyzing the measurements of the measuring devices.

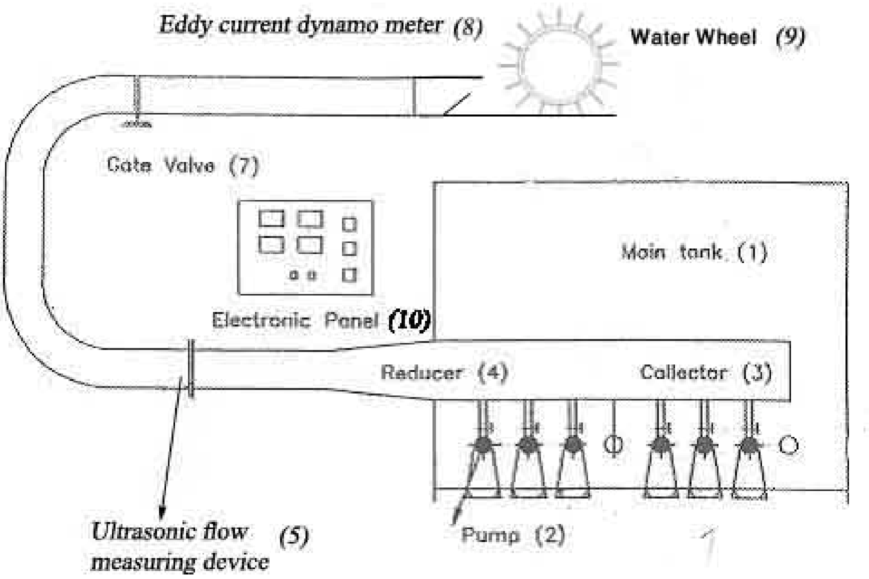

Figure 2 A schematic view of the test rig

3.3 Test Procedure

The wheel was tested as a stream flow wheel and as well as an under shot wheel, to study the waterwheel characteristics for each case. However, in this paper, only results of the tests for the under shot wheel are presented.

Generally, turbines in the field must be supplied with natural flow of water (Q) under some head (H). However in a laboratory both Q as well as H are obtained by a suitable pumping unit [17]. The pump draws water from a sump of sufficient capacity, and delivers it under a specified pressure (H) to the turbine.

The pump is started and the delivery valve of the pump is opened fully in order to supply water to the turbine. The inlet valves to the turbine, is opened. The turbine is run for fifteen to twenty minutes before the readings are recorded. The brake cooling water tap is opened. Allowance for this water is made for the accurate calculations of discharge. The turbine is tested for various flow rates under 0 to 2 meters head. For each flow rate, the turbine is first run and the break is applied and torque readings along with all other necessary readings are taken until the turbine is at standstill. Not less than six different loadings for a single flow rate, are to be recorded [17].The head under which the turbine is operating is kept constant as far as possible during the test by adjusting the delivery valves of the pumps.

3.4 Waterwheel tested as undershot wheel

When the turbine was tested as an undershot wheel, a 1-2 meter head supported the flow. The flow was directed; as a simple jet; towards the blades of the lower quadrant of the wheel. The simple jet was obtained by a (6:10) reduction of the pipe cross section at the exit towards the wheel. Here the wheel was tested for variable flow rates and flow velocities. Figure 3 shows the turbine in its running condition, while tested as an undershot wheel.

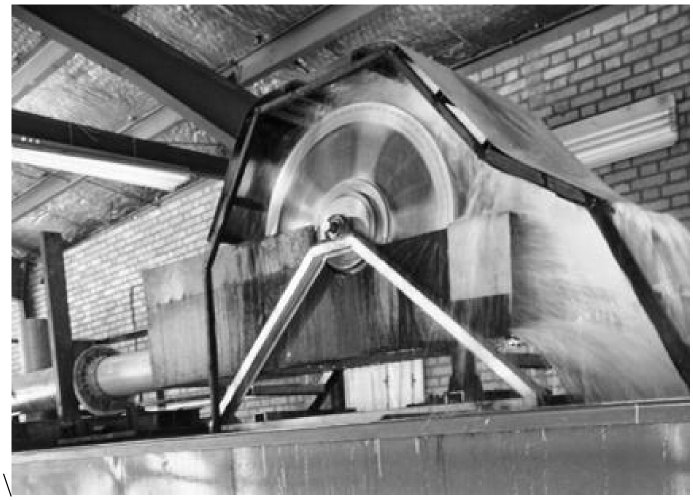

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Figure 3 The turbine in its running condition (tested as a low head under shot wheel)

5 Results & Discussion

Generally, in waterwheels, varying the flow rate causes changes in the flow velocity which in turn leads to different turbine angular velocities. This clearly was observed during the course of tests. To control the flow rate at the test rig two means were used: by applying control valves installed in the path of piping of the lab, and by increasing the number of pumps in operation. Up to six pumps were available at the test rig to vary the total flow rate of the stream.

For each speed the relevant wheel torque and volumetric flow rate were taken. Also characteristic curves such as unit flow, unit torque, unit power and the efficiency were all plotted against unit speed.

For generating the required plots the following relations were applied: $Q_1= Q/(H)^{1/2}$, $N_1= N/(H)^{1/2}$, $T_1=T/H$ and $Pi_1=Pi_1/(H)^{3/2}$. Here, Q_1, N_1, T_1 and Pi_1 represent unit values for flow, speed, torque and input power respectively; where H stands for total available head. The reason for using unit values is the fact that; using a pump in addition to the operating pump(s) has the same effect as variation of inlet opening of the turbine in its actual operation. Therefore, the constant head does not have the same value for different pumps in operation. Therefore, as the usual practice suggests, it is appropriate to convert all the readings to unit head values, which would then produce the constant head for all the readings. In this way all the values obtained may easily be compared with one another.

Figures (4a to 4d), (5a to 5d) and (6a to 6d) represent operation characteristics of the wheel when 1, 2 and 3 pumps are in operation respectively. General trend of the behavior of all plots are in perfect agreement with usual operating characteristics of hydro turbines.

From figures 4a to 4d, it may be concluded that for low flow rates, i.e. low flow velocities, performance of the turbine is poor due to low values of torque and angular velocity. As shown in figures 5a to 5d, by increasing the flow rate, increases are observed in angular velocity, values of torque, output power and in overall efficiency of the turbine. The same trend is observed in Figures 6a to 6d, where the three pumps are in operation.

As may be observed, the behavior of the wheel is improved by increasing the volumetric flow rate. In figure 4d, the highest value for the efficiency is about 1.5%, whereas this value grows to more than 27% when two pumps are in operation, see figure 5d, and the highest value of efficiency for the case of 3 pumps in operation rises to 35%, see figure 6d. However, this improvement cannot continue indefinitely, since the increase in flow reaches a point where the full water flow volume cannot pass under the wheel and some flow would build up behind the wheel. This causes an adverse effect on the behavior of the turbine by generating a braking effect due to the interference of the built up water with the rotation of incoming blades. The flow for which the fall in efficiency begins may be considered as the “critical flow”.

However, the poor efficiency results for low flow rates; see figure 4d; may be explained by the inverse relationship between the mass of the turbine and the volumetric flow rate of the site.

In other words, a limited flow would not be able to rotate an extremely heavy wheel, and therefore, the angular velocity tends towards zero as the wheel gets heavier. On the other hand, although a light wheel can rotate with high angular velocity, yet, its low mass can cause an adverse effect on the moment of inertia of the wheel, leading to drastic drops in values of torque, lowering the power output (see Eq. (7)). Therefore, in order to obtain the best values of the power output, there should be a tradeoff between the values of mass of the wheel and the angular velocity caused by the flow rate. It may therefore be concluded that; in the case of micro waterwheels; for hydro potentials with high velocity flows, mass of the turbine would be advantageous causing higher values for the moment of inertia of the wheel leading to higher power output and better performance.

6 Conclusion

In the light of the results obtained the following may be concluded. However it should be emphasized that these results are exclusively for a high speed micro hydro waterwheel tested during this research work and they are directly concluded from the presented test results.

1. Micro hydro waterwheels may operate efficiently at sites where relative velocity of the flow is high. Yet the wheel should be designed according to the available flow rate and head at the site.
2. One to two meters head for the flow can improve the behavior of micro waterwheel significantly.
3. Directing the flow as a jet towards the blades can also improve the performance of the wheel.
4. The mass of the wheel is decisive relative to the flow rate of the potential. However, a critical mass is to be determined for the wheel so that the best performance can be obtained from the potential.

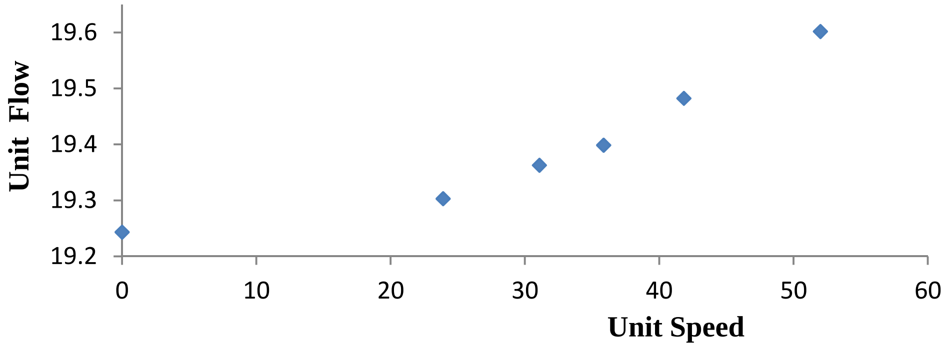

Figure 4a Unit flow against unit speed. One pump in operation

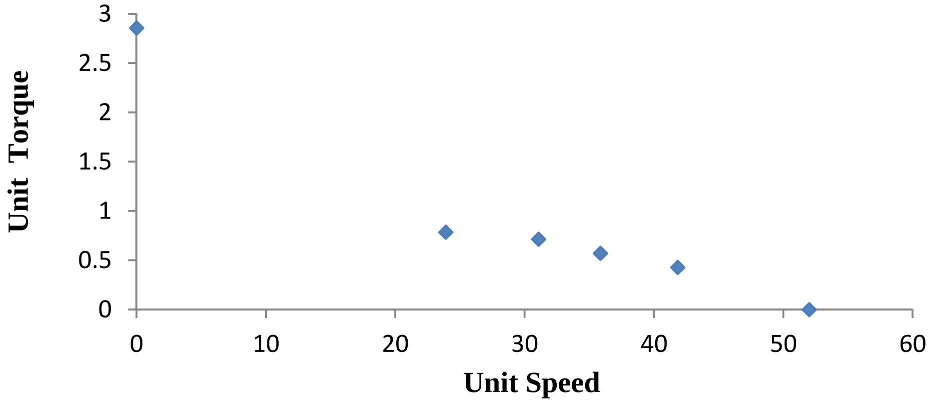

Figure 4b Unit torque against unit speed. One pump in operation

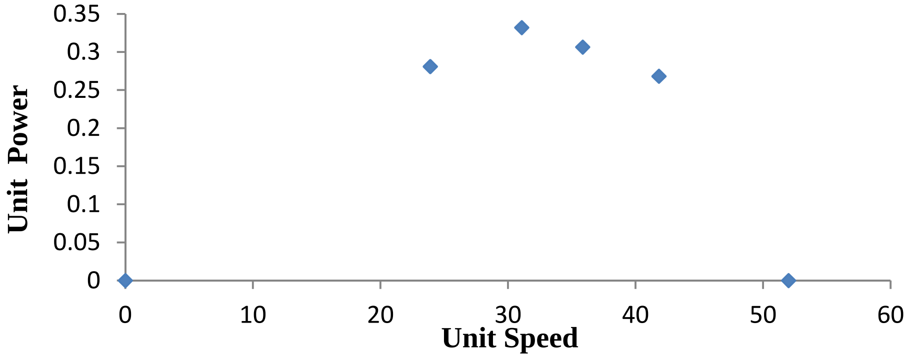

Figure 4c Unit power against unit speed. One pump in operation

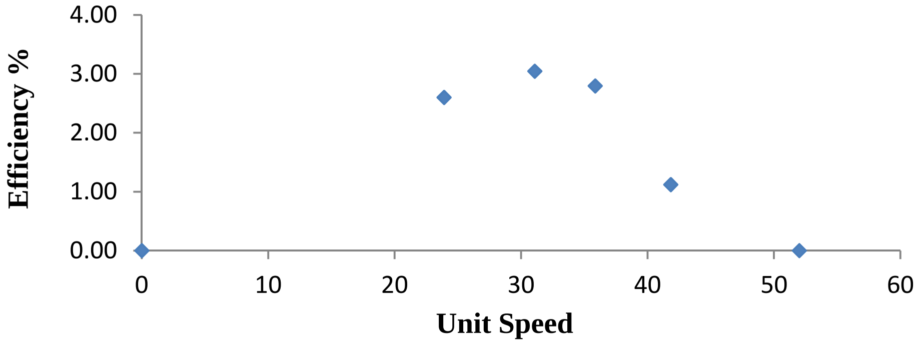

Figure 4d Efficiency against unit speed. One pump in operation

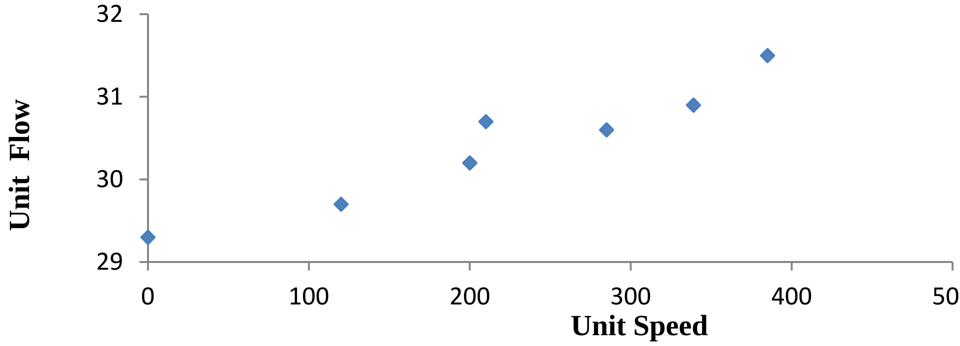

Figure 5a Unit flow against unit speed. Two pumps in operation

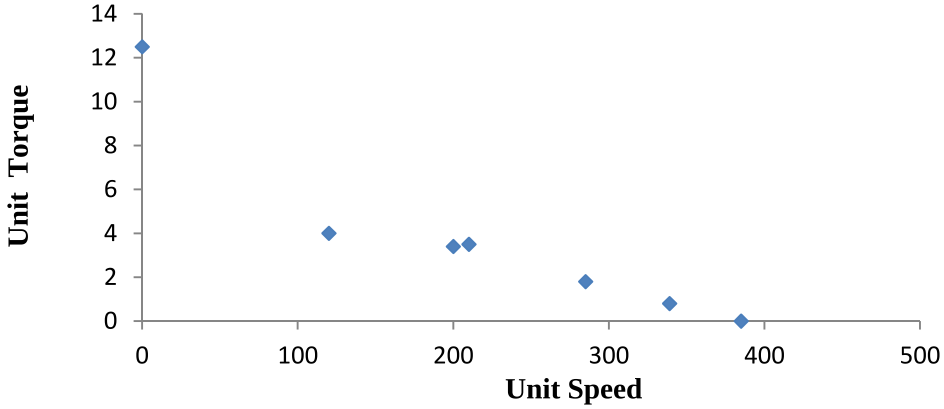

Figure 5b Unit torque against unit speed. Two pumps in operation

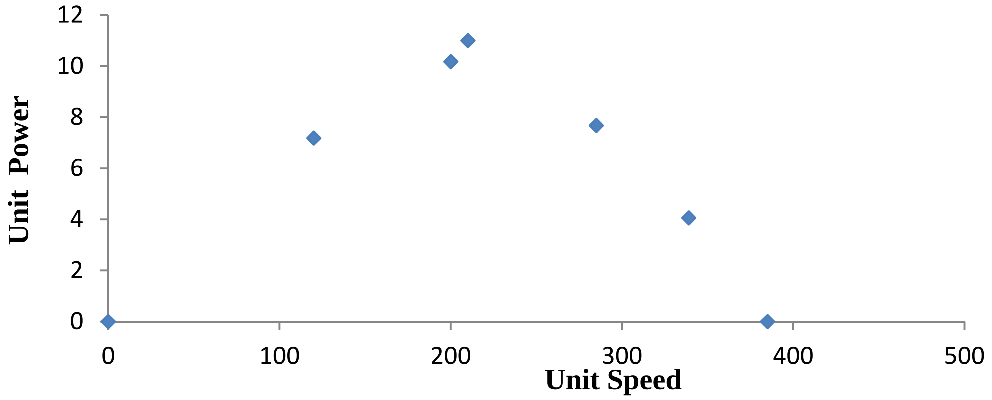

Figure 5c Unit power against unit speed. Two pumps in operation

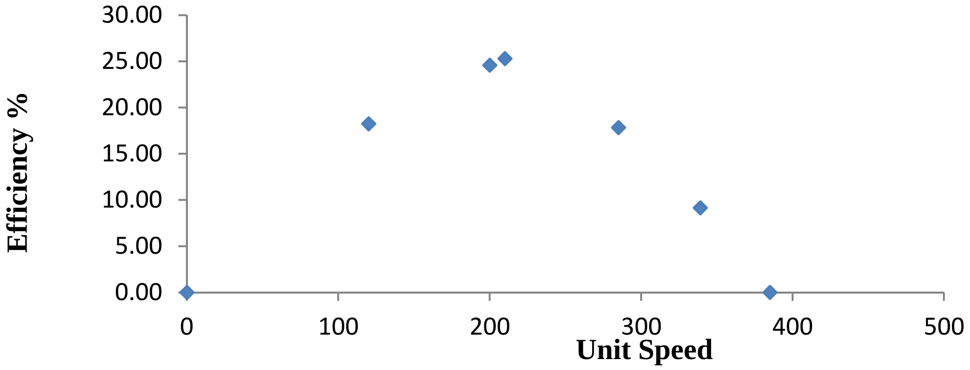

Figure 5d Efficiency against unit speed. Two pumps in operation

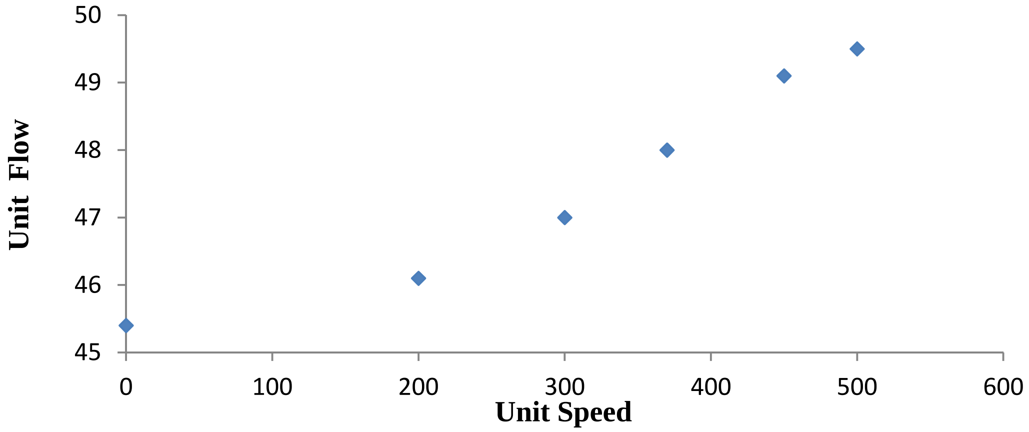

Figure 6a Unit flow against unit speed. Three pumps in operation

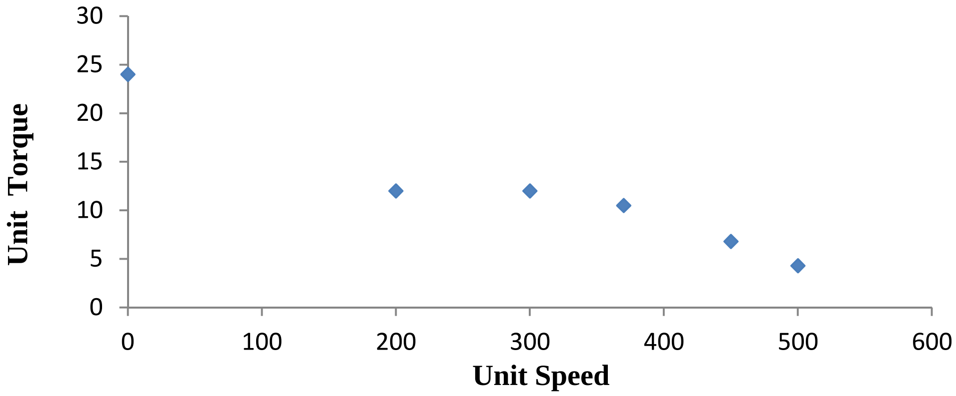

Figure 6b Unit torque against unit speed. Three pumps in operation

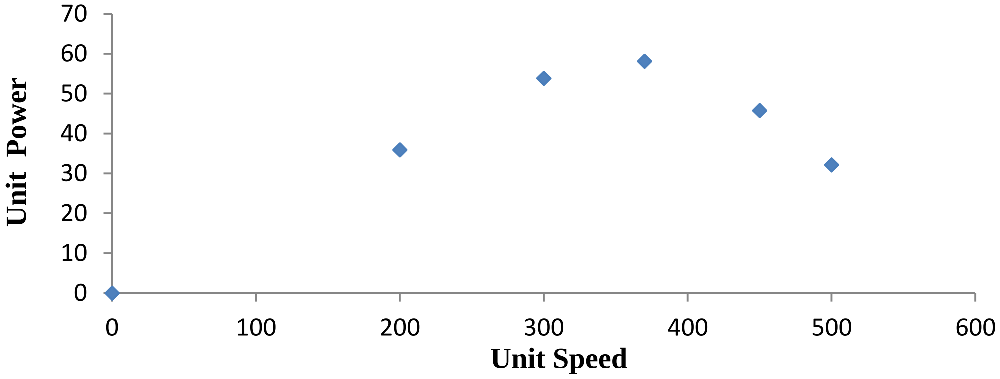

Figure 6c Unit power against unit speed. Three pumps in operation

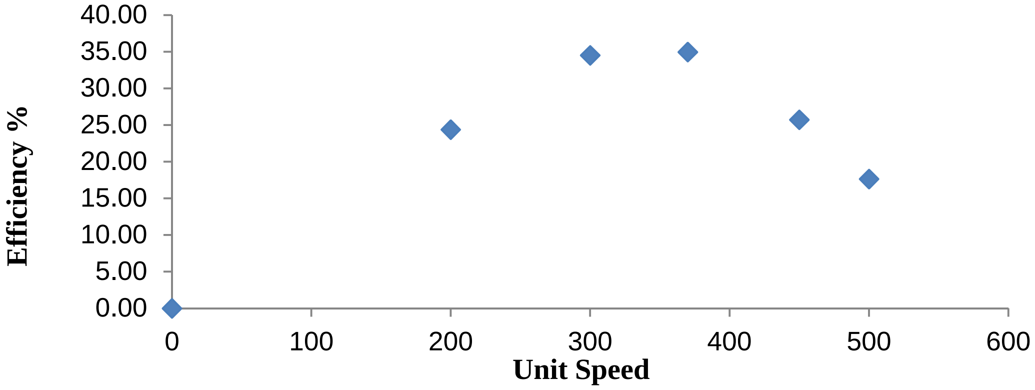

Figure 6d Efficiency against unit speed. Three pumps in operation

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Nomenclature

A : Angular acceleration (rad/s^2)
D : The wheel diameter (m)
F : Force exerted on the blade (N)
g : Acceleration due to gravity (m/s^2)
H, h : Net available head (m)
I : Moment of inertia of the wheel
m : Mass of the wheel (kg)
$m^{\bullet}$: Mass flow rate (kg/s)
N : Turbine speed (rad/s)
N_1 : Unit speed
P_{in} : Power input (w)
P_{out} : Power output (w)
Pi_1 : Unit power
Q_1 : Unit flow
r : Radius of gyration of the wheel (m)
T : Torque (Nm)
T_1 : Unit torque
U : The flow velocity (m/s)

Greek symbols
ω : Angular velocity (rad / s)
η : Turbine efficiency

چکیده

چرخ‌های آبی شاید از قدیمی‌ترین انواع ماشین‌های آبی محسوب گردند. این توربین‌ها از طراحی بسیار ساده، اقطار بزرگ، سرعت دورانی پائین و گشتاور بالا برخوردارند. آنچه تاکنون مدنظر گرفته نشده بکارگیری این ماشین‌ها به عنوان توربین‌های مایکرو با ابعاد کوچک و سرعت زیاد می باشد.

در پیگیری برنامه طراحی نیروگاههای آبی کوچک در پژوهشکده مکانیک سازمان پژوهشهای علمی و صنعتی ایران، طراحی و ساخت چرخ آبی پر سرعت میکرو در دستورکار قرار گرفت. توربین مذکور با قطر یک متر ساخته شده و در آزمایشگاه توربین‌های آبی سازمان مطابق با آزمون‌های استاندارد توربین‌های آبی مورد آزمون قرار گرفت و نتایج در قالب منحنی های مشخصه استاندارد توربین‌های آبی ارائه گردیدند.

در این مقاله این نتایج ارائه و مورد بحث قرار گرفته‌اند. این نتایج گویای تناسب این گونه چرخ‌ها برای پتانسیل‌های آبی با سرعت جریان بالا می باشد.