Experimental Study on the Effect of Water Velocity on the Performance of a Cross-Flow Turbine

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Abstract - In the field of renewable energy, a growing attention is given to cross flow turbines such as the Darrieus turbine. This turbine, originally used as a wind turbine, is currently used as a water turbine to extract mechanical energy from water currents, reservoirs, rivers and oceans to eventually convert into electrical energy.

In the work presented in this paper a series of painstaking experiments, for different velocity of the water flow from V = 0.37 m/s to 0.73 m/s, was conducted (at the Hydro-Pneumatic Power Laboratory of Northeastern University, Boston, USA) to determine the influence of this velocity on the performance parameters of a water Darrieus turbine, such as torque, mechanical power and power coefficient.

The experimental model of the water Darrieus turbine has three NACA0020 blades with a length of 0.216 m, a chord of 0.069 m and a solidity of 2. These blades are fixed at a radius of 0.104 m and an offset angle of 120°.

The main finding from the results analysis, obtained with a good consistency, is the increase of the water flow velocity from 0.37 m/s to 0.73 m/s (corresponding relative Reynolds number from $3.5\ 10^4$ to $2.8\ 10^5$) causes an increase in torque, power and power coefficient generated by this turbine model respectively from 0.17 Nm to 0.75 Nm, from 1.66 W to 11.67 W and from 16.92 % to 31.77 %, which gives a 604 % power relative increase for a water velocity relative increase equal to 100 %.

Keywords: water Darrieus turbine, renewable energy, rivers, mechanical power, electricity.

1 Introduction

The use of water Darrieus turbine, derived from the Darrieus wind turbine, as a mean of producing mechanical energy and eventually electrical power, from renewable energy of hydraulic reservoirs with small head, water currents, rivers and sea, begins to take an interest more and more important.

Miyaki, Tsugawa, Murata and Koike [1] presented the results of their experimental study on the performance of a radial flow turbine at high speed in an air duct, which they consider acceptable. Faure [2] showed, during testing of a water Darrieus turbine model, that the power generated by the latter and its efficiency can be improved by placing it in a duct. Takamatsu, Furukawa, Okuma and Shimogama [3] conducted a study of the hydrodynamic performance of a water Darrieus turbine; they studied the effects of the duct height and the blades number on the performance of this turbine. They found that the two blades turbine has bigger efficiency than the four blades one and that the difference between theoretical and experimental results reached 20%.

Faure and Pratts [4] conducted tests on site for three prototypes of the Darrieus turbine. One prototype was installed in a water dam with a small hydraulic head and the others were submerged in ocean currents. They introduced, instead of efficiency, a power coefficient as a performance parameter for a turbine placed out of a duct.

Takamatsu, Furukawa, Okuma and Takenouchi [5] conducted an experimental study on a preferred profile of the blade for high efficiency and the characteristics of Darrieus-type cross-flow water turbines; they conducted experimental tests for seven different blade profiles and concluded that a blade with a long chord and a small thickness has the highest efficiency. Ploesteanu, Tarziu and Maitre [6] have done a study on the flow modeling for a Darrieus turbine with moderate Reynolds number and found that the different effort coefficients show significant deviations from the experimental values.

Kaprawi, Santoso and Sipahutar [7] conducted an experimental study for combined Darrieus and Savonius water turbine in a river with constant water velocity of 0.8 m/s. They found that the maximum torque coefficient of 0.107 and maximum power coefficient of 0.19 were obtained when the attaching angle on the returning side of Savonius bucket β is set to 30°., while the maximum C_P for a solo Darrieus turbine is equal to 0.16.

Sanusi, Soeparman, Wahyudi and Yuliati [8] carried out and experimental study of a wind Savonius turbine with combined blades. Their results show an improvement of the maximum power coefficient up to 11 % compared to the conventional blades at the tip speed ratio (TSR) of 0.79.

Shahinur, Sabuj Shah,Nazmul and Ashraful [9] presented an analysis of the possibility of using small-scale hydro power plant in Gumoti and Surma (Bangladesh) and deducted that these two rivers can produce respectively 18.834 MWhr and 14.804 MWhr per year.

Thyagaraj, Rahamathullah and Suresh Prabu [10] carried out an experimental study on a modified four bladed Savonius hydro-kinetic turbine, placed in the center of a 42cm x 45cm irrigation canal with a water velocity of 0.82 m/s, which improve the power coefficient from 0.16 to 0.19.

The experimental results presented by Rus T., Rus L.F., Abrudan, Domnita and Mare [11] show that, for the same velocity, vertical axis wind turbines rotate at lower RPM than water turbines.

In the present study, experiments were done for several values of the velocity of the water flow to determine its effect on the performance parameters (torque, power and torque and power coefficients) of a water Darrieus turbine with three NACA0020 profile blades with solidity equal to 2. The results of this experimental study will be also used in further studies.

2. Experiments

2.1 Experimental Setup

The experimental setup is shown in Fig. 1. The water supplied by a submerged pump is discharged into the first part of the tank, which is divided into two and has a height of 0.60 m, a width of 0.92 m and a length of 2.44 m. This first part of the tank, which can be described as the charge or storage reservoir, has a length of 1 m. The water flows from this reservoir through a covered channel with a length of 1.2 m and a rectangular cross-section of 0.23 m by 0.23 m. The experimental model of water Darrieus turbine (Fig.2) is placed in this duct with its axis of rotation in a vertical position and is coupled to a device for measuring the number of revolutions per minute and torque and their measurements are displayed on an electronic indicator.

Fig. 1. Expérimental setup

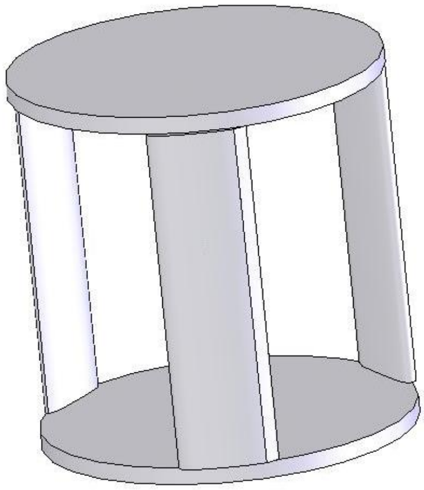

Fig. 2. Experimental model of the water Darrieus turbine

2.2. Experimental tests

Several experiments were performed for the Darrieus turbine model with 3 NACA0020 profile blades having a length of 0,216 m, a chord of 0,069 m and a solidity equal to 2. These blades are fixed at 0.104 m from the rotational axis with a separation (offset) angle of 120 °. This model has been tested for six values of the water velocity (0.37 m/s, 0.43 m/s, 0.45 m/s, 0.61 m/s, 0.67 m/s and 0.73 m/s). The corresponding relative flow Reynolds number varies between $3.5\ 10^4$ and $2.8\ 10^5$. These experiments will directly provide the values of the number of revolutions per minute of this turbine and the torque generated by this one. These values will be used to calculate the mechanical power and the torque and power coefficients of this turbine and as database for further experiments of a helical (Gorlov) turbine [12].

3. Performance Parameters

For an instantaneous position of a blade of a water Darrieus turbine with radius (R) and rotating with an angular velocity (ω), defined by the angle (θ) (called also azimuth or azimuthal angle or angular position [12,13]), the rotational, free flow and relative velocities (U, V and W) and the angle of attack (α)are represented in Fig. 3 [1,3,13,14].

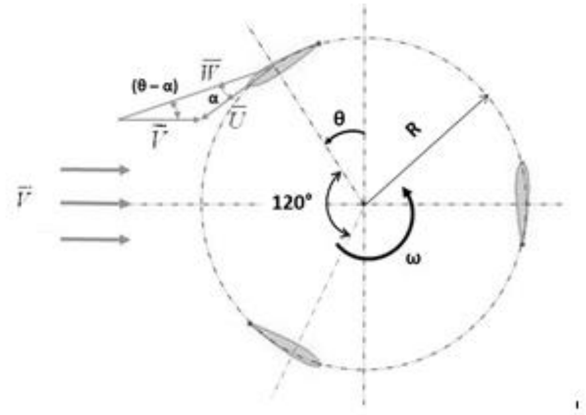

Fig. 3. Darrieus turbine section with different velocties

From the triangle of velocities of Fig. 3, we can write that,

$$\cos\alpha = \frac{U + V\cos\theta}{W} \tag{1}$$

$$\sin\alpha = \frac{V\sin\theta}{W} \tag{2}$$

with

$$U = \omega R \tag{3}$$

Since the blade angle of attack and the flow relative velocity (W) cannot be measured we can express them in terms of the known parameters (U, V and θ) from equations (1) and (2) respectively as [6,13,15,16],

$$\alpha = \tan^{-1}\left[\frac{V\sin\theta}{U + V\cos\theta}\right] \tag{4}$$

$$W = \sqrt{U^2 + V^2 + 2UV\cos\theta} \tag{5}$$

The relative flow, the free flow and the rotational Reynolds numbers, respectively Re_W, Re_V and Re_U based on the blade chord (C), are respectively given by [13,16],

$$Re_W = \frac{CW}{\nu} \tag{6}$$

$$Re_V = \frac{CV}{\nu} \tag{7}$$

$$Re_U = \frac{CU}{\nu} \tag{8}$$

where ν is the water kinematic viscosity.

The solidity of a cross flow turbine (σT), with a number of blades (Nb)with a chord (C) and a radius (R), is defined in [1,8,15] as,

$$\sigma_T = \frac{N_b C}{R} \tag{9}$$

The mechanical power (P_T) generated by the water Darrieus turbine [8], the available power of the water flow (P_D) [1] passing through this turbine and its power coefficient (C_P) [14] and torque coefficient (C_T) [7,8,13,15] are given respectively by,

$$P_T = T_T.\omega = T_T\,\frac{2\pi N}{60} \tag{10}$$

$$P_D = 2\rho.g.b.R.V.H_{ef} \tag{11}$$

$$C_T = \frac{T_T}{\rho b R^2 V^2} \tag{12}$$

$$C_P = \frac{P_T}{P_W} = \frac{\pi N T_T}{60\rho g b R V H_{ef}} \tag{13}$$

where,

T_T = turbine torque

ω = turbine angular velocity (= 2π.N/60)

N = number of revolutions per minute

ρ = water density

g = gravitational acceleration

b = blade length

H_{ef} = water effective height

2bR=A= turbine projected area through which the water passes

4. Experimental Results and Discussion

The variations of the angle of attack, of the water relative velocity and of the relative Reynolds number versus the blade position angle, for three different values of the water velocity (v = 0.55 m/s, 0.61 m/s and 0.73m/s), when the turbine is rotating freely (power output is null) and when the power output is maximum, are respectively represented in Fig.4, Fig.5 and Fig.6. Fig. 6.

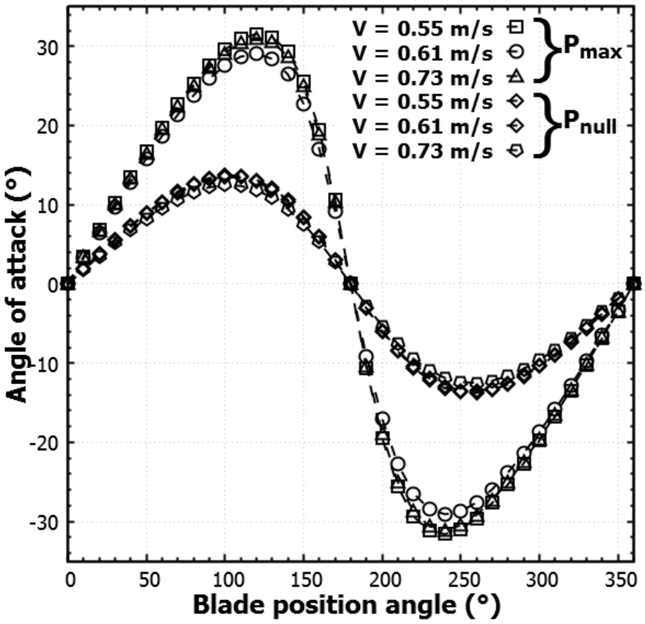

Fig. 4. Angle of attack versus blade position angle for different water velocities

Figure 4 shows a sinusoidal variation of the angle of attack as the blade position angle varies from 0° to 360° with symmetry at θ = 180°; for V = 0.55 m/s, 0.61 m/s and 0.73 m/s. The angle of attack increases from 0° to a maximum, respectively of 31.6°, 29.08° and 31.06° (at θ ≈ 120°) then decreases to a minimum (at θ ≈ 240°), respectively equal to -31.6°, -29.08° and -31.06° when the Darrieus turbine test model provides the maximum power output. These two values change respectively to 13.53°, 13.76° and 12.5° (at θ ≈ 103°), and -13.53°, -13.76° and -12.5° (at θ ≈ 256°), when the turbine is rotating freely (null power output). Therefore, for a same angle position of the blade, the angle of attack increases as we are loading the turbine; this is due to the decrease of the rotational velocity during increasing load. For any case case, the angle of attack amplitude and sign vary because of the variation of the rotational velocity direction with respect to the free flow sense and the blade position.

From Fig. 5, we can notice that the water relative velocity is the biggest for V = 0.73 m/s and decreases from 2.15 m/s (at θ = 0°) to 0.69 m/s (at θ = 180°) then increase to 2.15 m/s when the test model furnish the maximum power; this velocity varies from 4.11 m/s to 2.65 m/s when the turbine rotates freely (null power output). These variation and symmetry about θ = 180° is caused by the variation of the rotational velocity direction as explained in previous section.

We can observe, from Fig.6, that the relative flow Reynolds number varies between 3.94 10^4 (for maximum power output) and 2.8 10^5 (for freely turbine rotating f). For a given V it decreases from a maximum at θ = 0° to a minimum at θ = 180° then increases to the same maximum at θ = 360°; this is due to the variation of the rotational velocity direction as explained previously. The rotational Reynolds number varies from 6.68 10^4 (at the lowest angular velocity) to 2.3 10^5 (at the highest angular velocity). The free flow Reynolds number varies from 2.49 10^4 to 4.98 10^4.

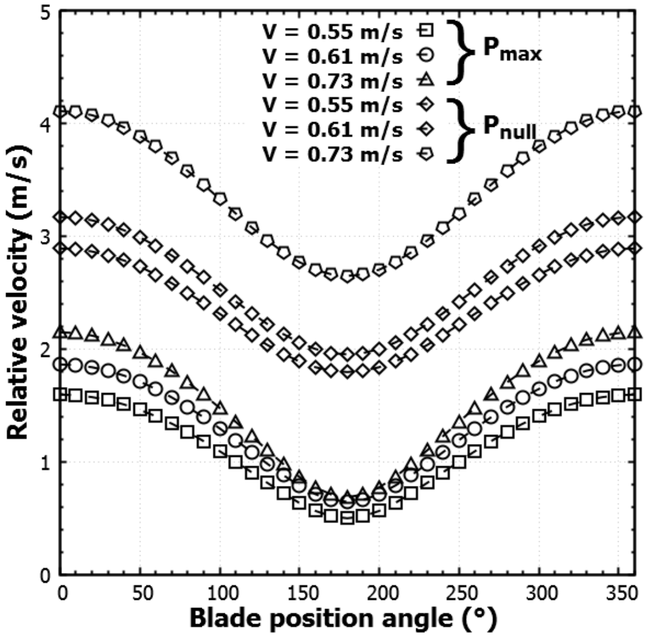

Fig. 5. Relative water velocity versus blade position angle for different water velocities

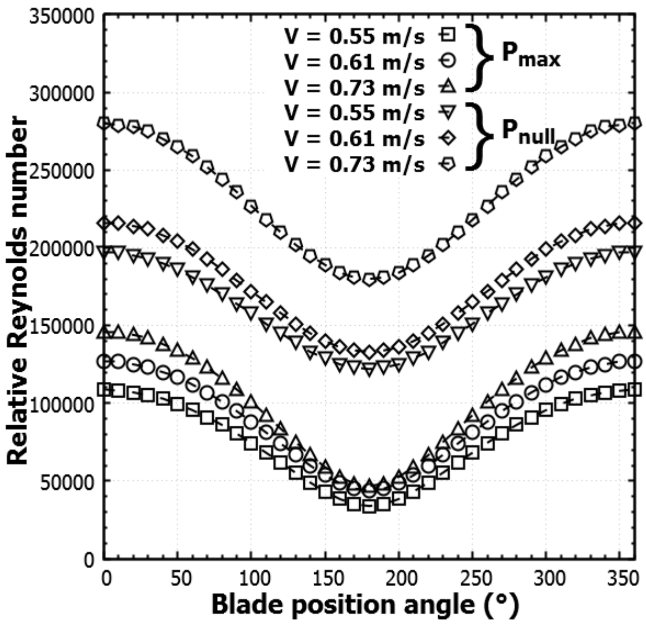

Fig. 6. Relative Reynolds number versus blade position angle for different water velocities

Figures 7 and 8 show the increase of the turbine output mechanical torque and the corresponding coefficient from 0 (when it is rotating freely with the maximum angular velocity) to a maximum value (when the turbine is loaded and turning at its minimum before full stop) with almost similar behavior for all water velocities. The maximum torque increases as the flow velocity increases and is equal to 0.17 Nm, 0.24 Nm, 0.33 Nm, 0.40 Nm, 0.49 Nm, and 0.75 Nm when the flow velocity is respectively set to 0.37 m/s, 0.43 m/s, 0.55 m/s, 0.61 m/s, 0.67 m/s and 0.73 m/s. This gives a torque relative increase of 317% for 100% increase of the flow velocity. We can also notice that the torque increase becomes more important as the water velocity is increased. The maximum torque occurs at about 1/2 of the turbine free rotation angular velocity. The maximum torque coefficient decreases from 56.36 % to 44.39 % then increases to 57.24 %. The corresponding curves for lower water velocity (0.37m/s and 0.43 m/s) have a slightly different shape and cross the following two curves.

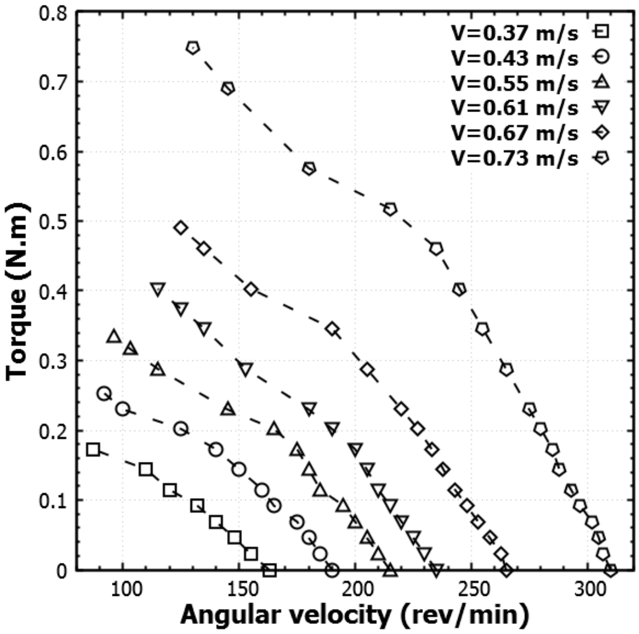

Fig. 7. Torque versus angular velocity for differentwater velocities.

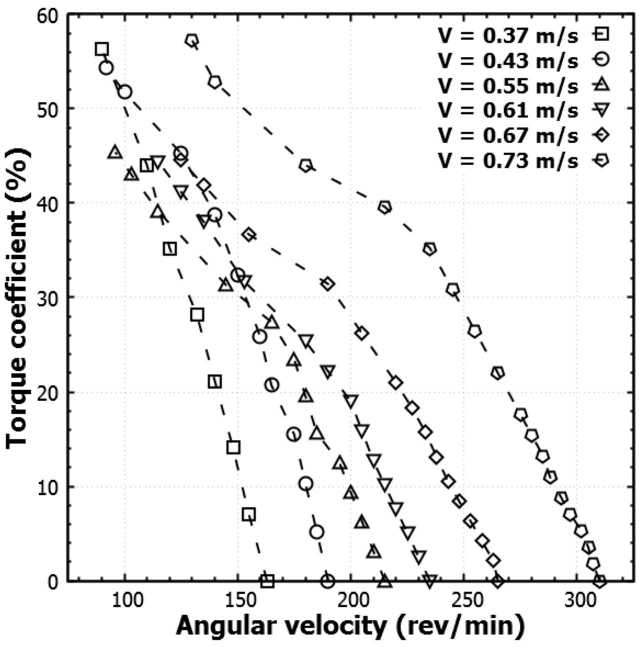

Fig. 8. Torque coefficient versus angular velocity for different water velocities

On Fig.9 and Fig.10, similar behavior can be seen for the power and power coefficient. For the same water velocity, the power increases from 0 (when the turbine rotates freely) to a maximum value then decreases slightly (when the loaded turbine is turning at its minimum) and at the same time it increases as the flow velocity increases. The maximum power is equal to 1.66 W, 2.64 W, 3.50 W, 4.90 W, 6.87 W and 11.67 W when the flow velocity is respectively equal to 0.37 m/s, 0.43 m/s, 0.55 m/s, 0.67 m/s and 0.73 m/s. This corresponds to a power relative increase of 604% for a relative increase of the flow velocity of 100%. We can also remark that the increase in power is more important as the water velocity gets bigger. The corresponding maximum power coefficient gets the respective values of 16.92 %, 19.57 %, 23.26 %, 24.76 %, 27.23 % and 31.77 %. This corresponds to a power coefficient relative increase of 88%. The maximum power occurs at about 2/3 of the turbine free rotation angular velocity.

The maximum C_P of 31.77%, obtained for this three NACA 0020 blades Darrieus turbine tested in a duct with a water velocity of 0.73m/s, is about twice the one obtained in [7] (16%), for a four NACA 0020 blades Darrieus turbine with twice the size, tested in a river with a water velocity of 0.8 m/s. A comparison with the results presented by Fleisinger, Vesenjak and Hribersek [17], for a three NACA 633018 Darrieus turbine (0.3m x 0.3m), shows lower C_P for V=1.2 m/s (about 22.5%, 23% and 26% respectively for the experiment, 6DOF and CEL routine based simulations). This shows the advantage of placing the water Darrieus turbine in a duct avoiding flow deviation around the turbine and forcing the whole water flow through it

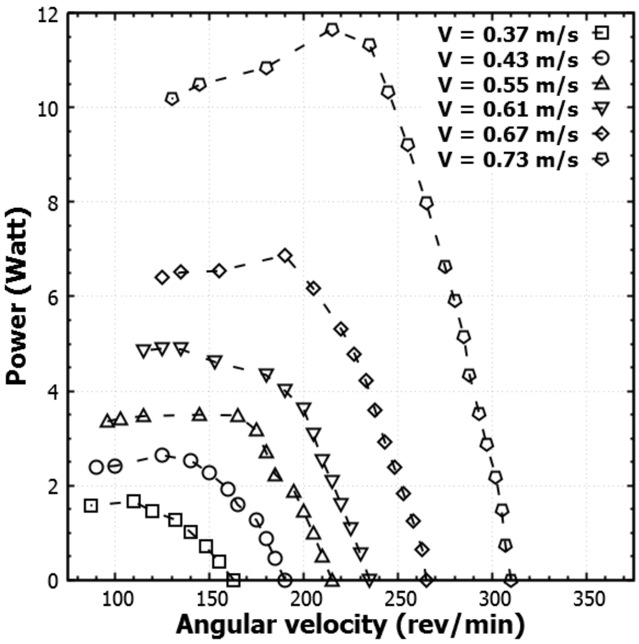

Fig. 9. Power versus angular velocity for different water velocities

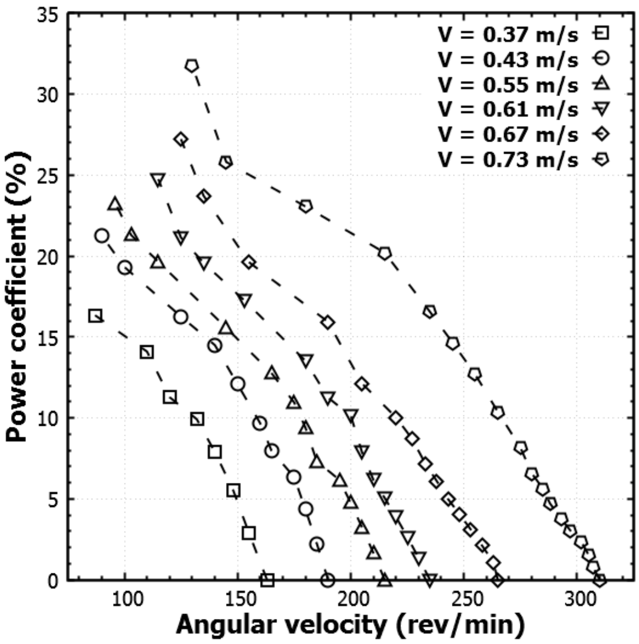

Fig. 10. Power coefficient versus angular velocity for different water velocities

The performance working curves for the maximum torque, maximum torque coefficient, maximum power, maximum power coefficient and maximum and minimum angular velocities for the tested Darrieus turbine model are respectively represented in Figs. 11, 12, 13, 14 and 15. These curves allow one to get these cited turbine performance parameters for a given flow velocity value between 0.37 and 0.73 m/s. To obtain these performance parameters for a given value of the water velocity outside this range these curves could be extended analytically.

Figure 11 shows that the maximum torque variation becomes more important when the water velocity becomes bigger. In fact fact, its gradient increases from 0.95 to 4.25 when the flow velocity varies respectively from 0.37 to 0.43 m/s and 0.67 to 0.73 m/s.

From fig.12 we can deduct that the torque coefficient gradient is negative for the first three increases of the flow velocity then becomes positive for the following ones. It varies from -33 to 208.

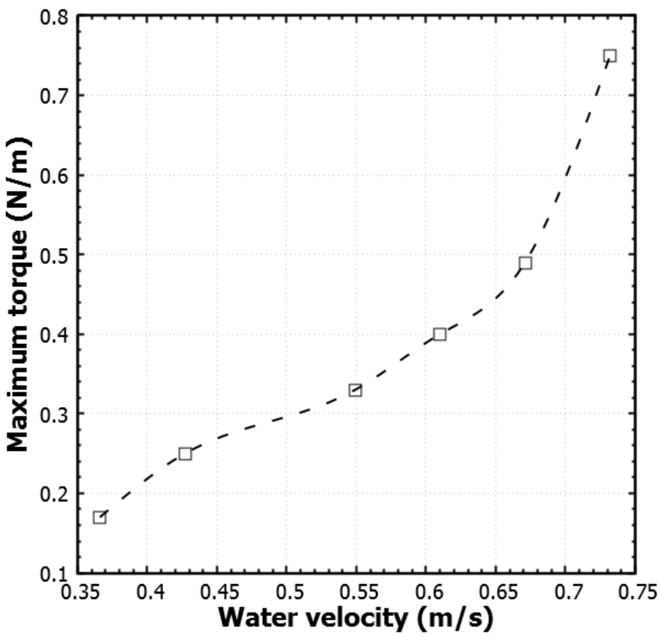

Fig. 11. Maximum torque versus water velocity

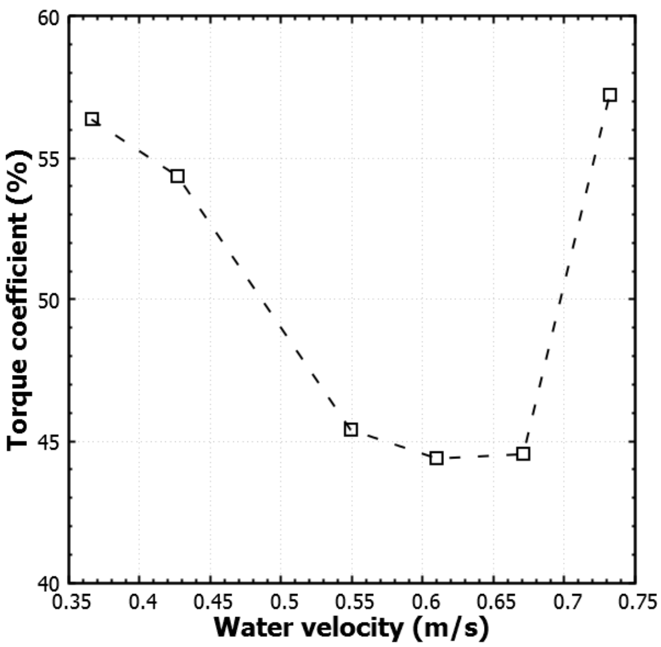

Fig. 12. Maximum torque coefficient versus water velocity

As shown on Fig. 13, the maximum power gradient varies from 16.1 between the two lower velocities to 78.6 between the two biggest ones.

The experimental results presented in Fig. 14 show that the maximum power coefficient gradient increases from 28.86 to 74.35 as the water velocity increases.

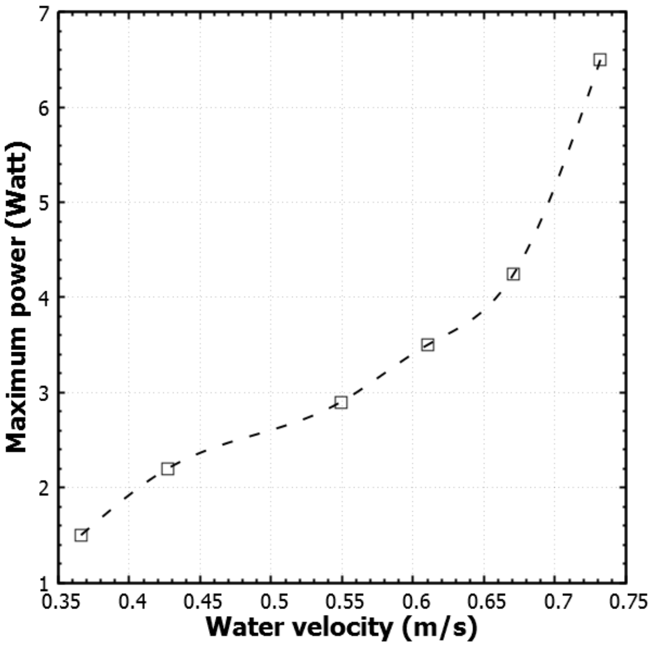

Fig. 13. Maximum power versus water velocity

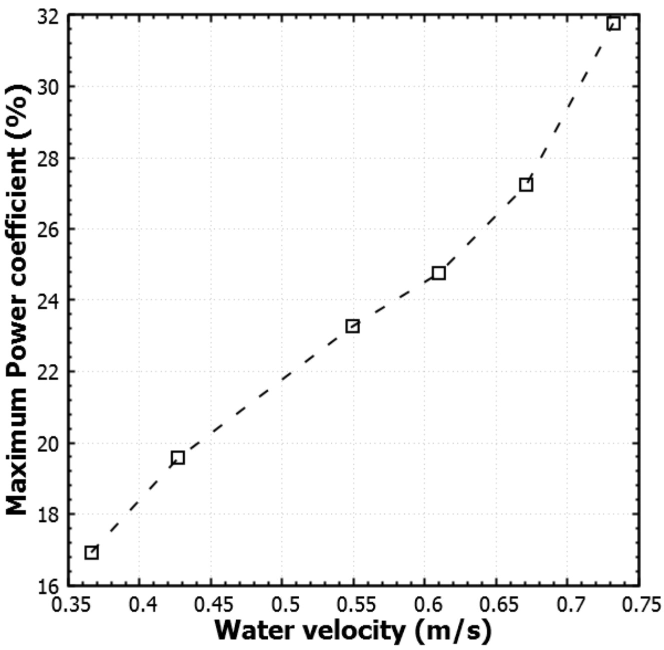

Fig. 14. Maximum power coefficient versus water velocity

Figure 15 allow one to get the free and maximum load RPM that can be used with the corresponding torque to calculate the power for the tested model and an estimation for bigger models. We can deduct that the maximum torque and power are obtained at an RPM respectively around 0.4 to 0.55 and 0.66 to 0.72 of the free load one.

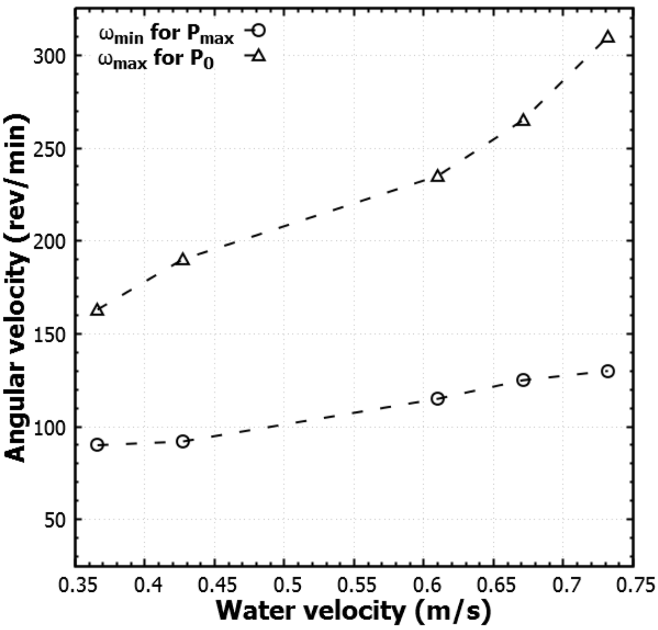

Fig. 15. Maximum and minimum angular velocities versus water velocity

5. Conclusion

The experimental model of the water Darrieus **turbine**, tested in this experimental study, is composed of three NACA0020 blades, with a length and a chord respectively equal to 0.216 m and 0.069 m, mounted at a radius of 0.104 m (solidity equal to 2) and separated by an angle of 120 °.

This model has been tested for water flow velocity equal to 0.37 m/s, 0.43 m/s, 0.55 m/s, 0.61 m/s, 0.67 m/s and 0.73 m/s corresponding respectively to a Reynolds number of 2,49 10^4, 2,91 10^4, 3,74 10^4, 4,15 10^4, 4,75 10^4, and 4,98 10^4. The corresponding test results show that for an increase of this velocity from 0.37 m/s to 0.73 m/s (100% relative increase) gives an increase of:

- the torque from 0.18 to 0.75 Nm (317% relative increase)
- the power from 1.66 to 11.67 W (604% relative increase)
- the power coefficient from 16.92 to 31.77 % (88% relative increase)

The maximum torque occurs at about 1/2 of the turbine free rotation angular velocity, while the maximum power occurs at about 2/3 of the turbine free rotation angular velocity.

The experiments conducted in the present study, which seem simple and easy, are actually painstaking and require a lot of patience and care.

These experimental results allowed us also to draw the performance working curves that can give the minimum and maximum angular velocities, the maximum torque, maximum power and maximum torque and power coefficients for the tested Darrieus turbine model for a given water flow velocity value between 0.37 and 0.73 m/s. To get theses parameters outside of these two values, these curves could be extended analytically.

A comparison to results presented in other studies has shown the positive effect of placing the water Darrieus turbine in a duct forcing the water flow through it. In fact the power coefficient obtained in the present study is bigger than that presented in other cited studies even though for bigger models and water velocities.

The valuable results of this experimental study will provide a useful database that will be used for comparison in further experimental, numerical and analytical studies.

The simplicity of design, construction, operation and maintenance as well as the low cost and the small operation and maintenance fees are the main benefits of water Darrieus turbines, when compared to conventional turbines, which make them very attractive.

The results of this experimental study of the performance of water Darrieus turbine will be used as a database for comparison in further studies.

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