Twisted turbine

Jahangir Alam

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Alam and Iqbal describe their efforts to squeeze just a few watts of energy from the cold North Atlantic Ocean near St. John's, Newfoundland.

Who should read this paper?

This paper describes a new design concept for generating small amounts of electrical energy from low speed ocean currents. It will be of particular interest to anyone who may be interested in long term deployment of remote, autonomous instruments in the deep ocean environment.

Why is it important?

This research presents a design concept and test results for a hybrid vertical axis turbine. This innovative hybrid water current turbine is based on a marriage between the Savonius (those two-stepping converts of stagnation) and Darrieus (the finicky whirlwinds of the rotor world) turbine families. Results show that this hybrid design has low cut-in speed and high output power, and is therefore well suited to powering small remote ocean energy systems. Such systems may be used to power navigational lights, sub-sea sensor networks and any other ocean instrumentation with low power requirements. It could also, if one is on a low-salt diet, be used for power production from river currents. The design has been developed and tested in a lab environment, and is ready in its current form for commercial application.

About the authors

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A LOW CUT-IN SPEED MARINE CURRENT TURBINE

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ABSTRACT

Ocean currents are a source of renewable energy similar to wind and solar energy. This untapped energy is extractable using underwater turbines capable of converting water kinetic energy into mechanical energy. A turbine with a low cut-in speed is needed to get maximum energy from the marine current. In this paper, a Hybrid turbine based on the Darrieus and Savonius vertical axis turbine has been introduced which exploits good features of both turbines. The design procedure elaborates the Hybrid structure of a four straight bladed H-Darrieus (lift type) turbine along with a double step Savonius (drag type) turbine. The Savonius turbine is placed on the middle of Darrieus turbine on the same shaft. The Hybrid turbine is built and tested in a flume tank at various flow speeds. This paper provides the system design and test results. The design will be used for a seafloor power generation system to power an array of marine sensors for monitoring seabed activity.

KEY WORDS

Hybrid turbine; Hydrodynamics; Savonius turbine; Darrieus turbine; Free flow turbine; Marine current turbine

NOMENCLATURE

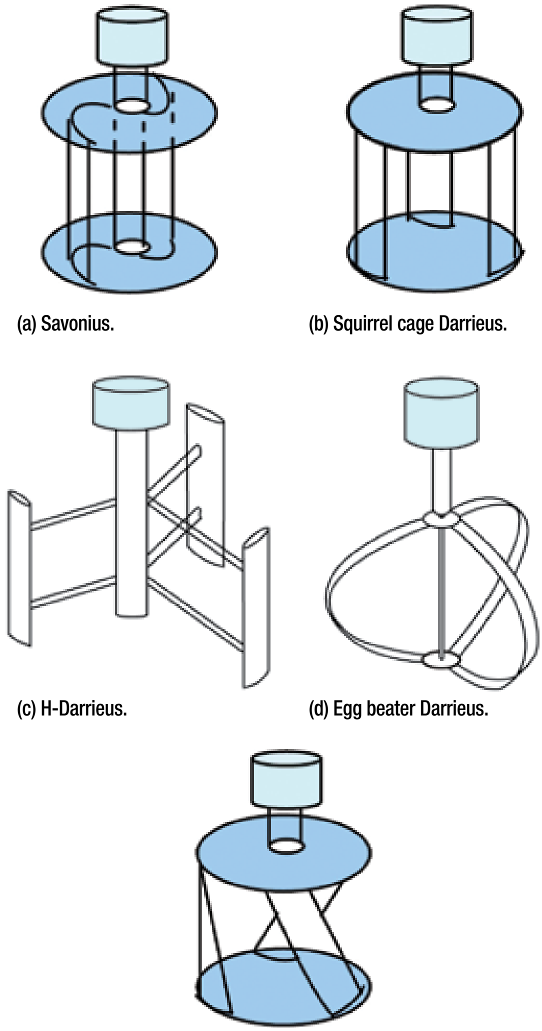
A	=	airfoil/frontal area	R_d	=	radius of Darrieus rotor
A_α	=	aspect ratio	R_e	=	Reynolds number
A_d	=	swept area by Darrieus rotor in m^2	R_s	=	radius of Savonius rotor
A_s	=	swept area by Savonius rotor in m^2	R_s / R_d	=	radius ratio
A_w	=	cross sectional area under consideration	TSR	=	Tip Speed Ratio
			V	=	speed of water (m/s)
C_D	=	drag coefficient	$VAWT$	=	vertical axis wind/water turbines
C_L	=	lift coefficient	α	=	angle of attack
C_{Pd}	=	power coefficient of Darrieus rotor	β	=	overlap ratio
C_{Ps}	=	power coefficient of Savonius rotor	λ	=	TSR of Hybrid turbine
D_s	=	total bucket diameter (Savonius)	μ	=	viscosity coefficient
H_s	=	height of the rotor	ρ	=	density of water (kg/m^3)
L	=	characteristic length	τ	=	torque
P	=	power	ω	=	Shaft speed in rad/s
$R = R_d$	=	maximum rotational radius	ω_d	=	angular velocity of Darrieus rotor
R	=	radius			

INTRODUCTION

There are three general types of ocean currents: 1) gradient currents mainly due to seawater density gradients; 2) wind-driven currents produced by the forces exerted by the wind on the ocean surface; and 3) currents produced by long-wave motions. The latter are principally tidal currents, but may include currents associated with internal waves, tsunamis and seiches. The major ocean currents are of continuous, stream-flow character, and are of first-order importance in the maintenance of the Earth's thermodynamic balance. Such currents are a significant and untapped renewable resource of energy.

The speed and density of flowing bodies determine the kinetic energy that can be converted into mechanical energy using turbine. Though the wind speed is much higher than the water speed, water is about 835 times denser than wind. Worldwide, the total estimated power in ocean currents is about 5,000 GW, with power densities of up to 15 kW/m^2 [Boyle, 2004]. The kinetic energy of the water current can be converted into mechanical energy using a turbine, which may be a horizontal axis or vertical axis type. For small scale applications, vertical axis turbines are preferred due to their omni-directional characteristic, which avoid pitching and pointing mechanisms. Figure 1 shows five possible vertical axis turbines [Khan et al., 2006].

Savonius type vertical axis turbine produces higher torque and has lower cut-in speed. A lift type Darrieus turbine (classified as vertical axis) can have a blade tip speed many times the speed of the water current (i.e. the Tip Speed Ratio (TSR) is greater than 1). Hence, a Darrieus turbine generates less torque than a Savonius but it rotates much faster. This makes Darrieus turbines much better suited to electricity generation, regardless of the direction of flow of the flowing bodies like water or wind. The Darrieus type turbine has weak self starting characteristics and higher cut-in speed. A Savonius drag type turbine can be combined with a Darrieus turbine to overcome its weak self starting characteristics [Wakui et al., 2005; Manohar et al., 2007].



(a) Savonius. (b) Squirrel cage Darrieus. (c) H-Darrieus. (d) Egg beater Darrieus. (E) Gorlov.

Figure 1: Vertical axis turbines.

This Hybrid structure of the Darrieus turbine will generate less power compared to the Darrieus type alone, due to the added drag by the Savonius turbine after a certain water velocity. Our purpose was to generate a few watts to power up the sensors (SEAformatics pods) in the North Atlantic Ocean (near St. John's, Newfoundland), where the water velocity changes (depending on depths) from 0.1 to 0.5 m/s [Khan et al., 2007] throughout the year and the photovoltaic panels are not applicable due to insufficient solar radiation.

The following sections will provide some background on the Savonius and Darrieus type turbines as well as the design procedure, hydrodynamics and test results of a low cut-in speed Hybrid vertical axis turbine prototype, for a maximum water speed of 1 m/s. During the tests, the turbine blades started bending at 0.5 m/s and it became excessive above 0.6 m/s. This particular issue has been highlighted in the RESULTS AND DISCUSSION section.

SAVONIUS ROTOR

For low power applications, Savonius rotors [Khan et al., 2007] are used whenever cost or reliability is important. Much larger Savonius turbines have been used to generate electric power on deep-water buoys, which need small power and very little maintenance. Design is simple because, unlike horizontal-axis turbines, no pointing mechanism is required to allow for shifting water or wind direction. Savonius turbines are also self-starting in nature.

Due to its simple and low cost construction [Khan et al., 2007], acceptance of water from any direction, high starting torque, low operating speed and less maintenance, the Savonius rotors became popular among design engineers and turbine manufacturers. Savonius design [Khan et al., 2007] uses a rotor that was formed by cutting the Flettner cylinder into two halves along the central plane and then moving the two semi cylindrical surfaces sideways along the cutting plane so that the cross-section resembled the letter "S." The Savonius turbine relies on stagnation principles to convert currents into rotational energy. The Savonius rotor uses stagnation pressure on one side to promote rotation around a central vertical axis. The blade turning redirects water around itself with its rounded shape. Any tangential flow of water will produce a positive force on the rotor. Vertical axis turbines operate in turbulent water patterns better than horizontal designs. A Savonius design relies on the pressure of the current against the rotor blade to create torque. As such, a Savonius design cannot exceed the speed of the water and operates at a lower RPM range than would a horizontal axis turbine. It has the benefit of producing a larger torque.

If C_{Ps} is the power coefficient of a Savonius turbine, then the power (P) that can be obtained from water is:

$$P = 0.5 \times C_{Ps} \times A_s \times \rho \times V^3 \quad (1)$$

Where:
P is the output power (W)
ρ is the density of water (kg/m^3)
A_S= (Height ×Diameter) = (H_S×D_S) is the swept area of Savonius rotor (m^2)
V is the speed of water (m/s)

The tip peripheral velocity of the rotor, $U = \omega_S \times R_S$ [ω_S is the angular velocity of the Savonius rotor and R_S(= D_S/2) is the radius of the Savonius rotor].

Now the Tip Speed Ratio (TSR) of a turbine is defined as:

$$TSR = \lambda_s = \frac{U}{V} = \frac{\omega_s R_s}{V} \quad (2)$$

Turbines are usually characterized by performance curves, which give C_p as a function of λ. It is known (Betz theory [Rauh and Seelert, 1984]) that for a horizontal axis wind turbine, the power coefficient is always inferior to the theoretical value of 0.593. In fact, the best modern machines have a maximum value of less than 0.45. C_p as a function of λ curves for many turbines; shown in Figure 2.

The aspect ratio (A_α) represents the height (H_s) of the rotor relatively to its diameter (D_s). This is also an important criterion for the performances of a Savonius rotor:

$$A_\alpha = \frac{H_s}{D_s} \quad (3)$$

Generally, a value of A_α is selected larger than 1 to improve the efficiency [Khan et al., 2007].

It is known that end plates lead to better hydrodynamic performances [Fujisawa, 1992]. The influence of the diameter D_f (Figure 3) of these end plates relatively to the diameter D_s of the rotor has been experimentally studied. The higher value [Menet, 2004] of the power coefficient is obtained for a value of D_f around 10% more than D_s, irrespective of the velocity coefficient.

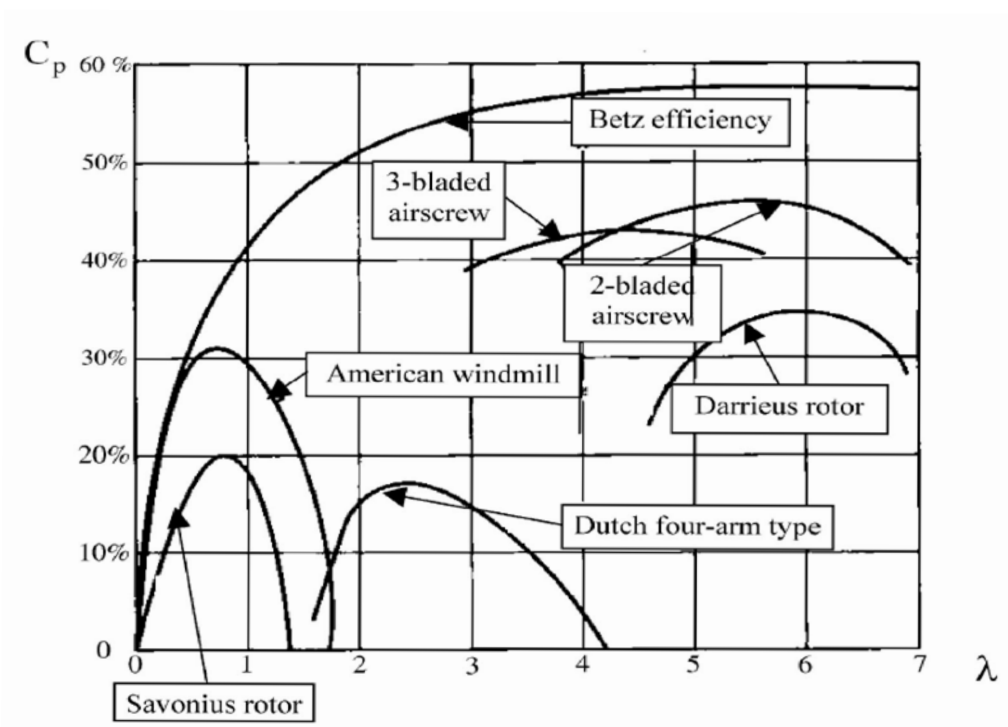


Figure 2: Characteristic curves of many conventional rotors.

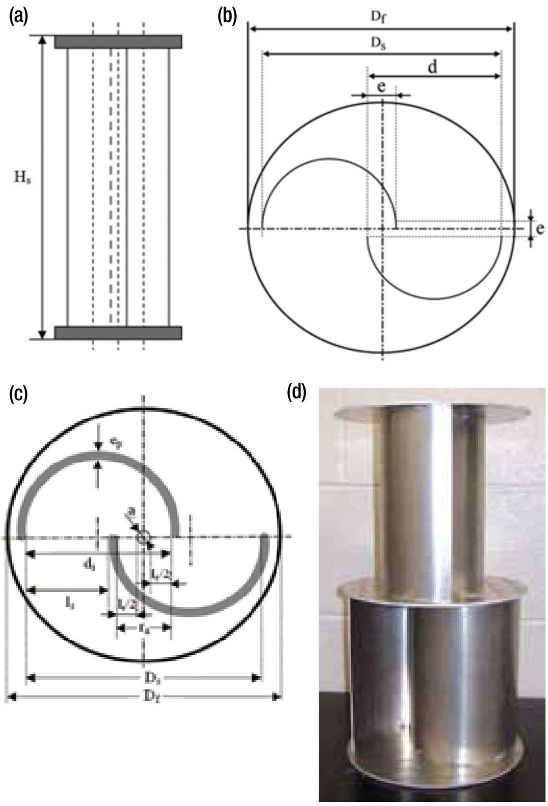


Figure 3: Savonius rotor (a) Front view (single step); (b) Top view of conventional Savonius rotor (without central shaft); (c) Top view with a central shaft; (d) Designed 2-step Savonius rotor.

The overlap ratio (β) for Figure 3 (b) is given by:

$$\beta = \frac{e}{d} \tag{4}$$

Where e is the overlap.

When a central shaft is chosen then recommended β is:

$$\beta = \frac{(r_a - a)}{d_i} \tag{5}$$

Where r_a is the overlap.

The best efficiencies are obtained for values of β between 20% and 30%.

For a two bladed Savonius turbine, starting torque would be close to zero if water direction is 90° to the cutting edge to the blade. It is the reason many prefer to use a double-step Savonius rotor, where the upper and the lower paddle pairs are set at 90° to each other. The double-step rotor is found to be slightly better [Khan et al., 2007] compared to the corresponding single-step turbine (conventional Savonius rotor) in both torque and power characteristics.

H-DARRIEUS ROTOR

The H-Darrieus configuration consists of vertical airfoils mounted on a vertical shaft at some distance or radius from the shaft. These machines take advantage of the lift generated by the airfoils moving through the water or wind. Theoretically higher rotational speed of the Darrieus turbine is an advantage for it being used to generate electricity from the energy carried in the water. In our H-Darrieus design, the airfoils used are symmetrical and have a zero pitch angle. This pitch may not be the optimal for these devices, but this arrangement is equally effective no matter which direction the water is flowing. When the Darrieus rotor is spinning, the airfoils are moving forward through the water in a circular path.

Airfoil design and selection [Cairo et al,. 2006] are based on i) appropriate design Reynolds number; ii) airfoil thickness, according to the amount of centrifugal stiffening and desired blade rigidity; iii) roughness insensitivity; iv) low drag (not as important for small marine current turbines); and v) high lift root airfoil to minimize inboard solidity and enhanced starting torque. Commonly used symmetrical airfoil shapes for Vertical Axis Wind/

Water Turbines (VAWT) are NACA-0012, NACA-0015, and NACA-0018. The primary difference between the three shapes is the cord to thickness ratio. Increasing in thickness assist airfoils to increase their lift force but at the same time drag also increases. These symmetrical airfoils are comparatively easy to design.

The recorded experimental data can be used to calculate the power generated, angular velocity, Tip Speed Ratio (TSR), power available from the water, shaft power, efficiency of the turbine as well as the overall efficiency. The solidity ratio [Manohar et al., 2007] and the TSR can be calculated from Equations (6) and (7), respectively.

Solidity Ratio = (No. of Blades × Chord length) / Rotor diameter (6)

Tip Speed Ratio (TSR) = (Blade tip speed/ Water speed)

$$\therefore \lambda_d = \frac{\omega_d R_d}{V} \quad (7)$$

Where R_d is the radius of Darrieus rotor
ω_d is the angular velocity of Darrieus rotor.

From the momentum model [Manohar et al., 2007] for Darrieus rotor, the power coefficient C_p for a machine with different solidity at various TSR can be determined.

The power available from water can be determined from Equation (8).

$$P_{avail} = 0.5 \times A_w \times \rho \times V^3 \quad (8)$$

Where A_w = Cross sectional area under consideration.

The power available at the shaft for conversion to mechanical or electrical energy can be calculated as:

$$P_{shaft} = 0.5 \times C_{Pd} \times A_d \times \rho \times V^3 \quad (9)$$

Where C_{Pd} is power coefficient of Darrieus rotor

A_d = (Height ×Diameter) = (H_d×D_d) is the swept area of Darrieus rotor (m^2).

THE DARRIEUS-SAVONIUS HYBRID TURBINE

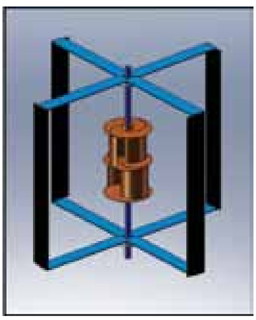
Material Selection

The choice of the material is obviously crucial. Different criteria include low cost, easy construction, light weight, good corrosion resistance as well as rigidity, recyclable material, etc. In case of Savonius, aluminum has been chosen to meet the above criteria. Moreover, it requires a rugged construction as it is designed to provide high starting torque.

The blade manufacturing and material selection is also a decisive aspect of water turbine design, which directly affects the turbine performance. Some manufacturers are selling airfoils which are specially designed for test purposes. But the criteria mentioned are violated due to high cost. In our case, available airfoils in the market which are made with aluminum are not suitable because the total weight of the Hybrid turbine increases, which directly increases the moment of inertia. We have cut Styrofoam in our workshop and then a thin layer of glass fibre has been wrapped around the designed NACA-0015 profile. Renshape pieces are added at both ends of airfoils to screw radial flat plate arms. To remove the surface roughness, scrubbing pads as well as thick paint is used.

Possible Hybrid Configuration

During the prototype design of Hybrid turbine, the Darrieus rotor has been used as a main device and the Savonius rotor as a start-up device. They are attached permanently to the same axis. To get a good start-up characteristic regardless of the water direction, the Savonius rotor is divided into two (upper and lower) stages, with the two parts having a twist angle of 90° [Menet, 2004]. The designed prototype is shown in Figure 4.



(a) CAD view.

(b) Prototype turbine.

Figure 4: Hybrid configuration of Darrieus and Savonius rotor.

Two possible configurations are 1) Savonius rotor can be installed inside the rotational closed space and 2) outside the rotational closed space. Though the first configuration will provide water interference between the rotors, the second configuration will increase the height of the turbine. According to previous research [Wakui et al., 2005] with egg beater type Darrieus in wind application, both configurations meet the requirements with a slight difference in their performance.

To reduce the rotational axis length which can spur axial friction and rise in moment of inertia, we have chosen the first design. As there is a significant impact [Wakui et al., 2005] of the radius ratio (R_s/ R_d) on the characteristics of the Hybrid turbine, we consider it during Hybrid turbine design. In the case of commercial Darrieus designs, radial arms are placed 1/3 and 2/3 along the central shaft for rigidity purposes. But to avoid the interaction between the Savonius rotor and radial arms, as well as to make the hydrodynamics simple, we have placed the flat brace supporting arms at the top and bottom of the turbine.

Design Equations and Parameters

The Power (P) output as well as TSR of the Hybrid turbine can be found using Equations (10) and (11) respectively:

$$P = 0.5 \times \rho \times V^3 (A_s C_{Ps} + (A_d - A_s) C_{Pd}) \tag{10}$$

And Tip speed ratio $(\lambda) = \dfrac{\omega R}{V}$ (11)

Where:

A_s = Swept area by Savonius rotor in m^2

A_d = Swept area by Darrieus rotor in m^2

C_{Ps} = Power coefficient of Savonius rotor
C_{Pd} = Power coefficient of Darrieus rotor
ρ = Water density in kg/m3
ω = Shaft speed in rad/s
λ = TSR of Hybrid turbine
$R = R_d$ = Maximum rotational radius

By using the characteristic curve (Figure 2), desired values of the power coefficient for a particular TSR in case of both the turbines during Hybrid configuration are:

$C_{Ps} = 0.18$ for $\lambda_s = 1$ [Savonius]

And

$C_{Pd} = 0.3$ for $\lambda_d = 5$ [Darrieus]

Using Equation (2) and Equation (7) for both the turbines (taking same rotational speed, as they are connected by a shaft) we get:

$\lambda_s/\lambda_d = R_s/R_d = 1/5 = 0.2$

If $R_s = 0.1$ m, then $R_d = 0.5$ m.

Specifications for both the turbines in their Hybrid configuration are given in Table 1.

Table 1: Specifications for turbine in Hybrid configuration.

Savonius Rotor	
Rotor height (H_s)	400 mm
Nominal diameter of the paddles (d_i)	130 mm
Diameter of the shaft (a)	20 mm
Rotor diameter (D_s)	200 mm
Overlap ratio (β)	0.298
Swept area (A_s)	0.08 m^2
Darrieus Rotor	
Airfoil section	NACA 0015
Number of blades	4
Solidity ratio [Manohar et al., 2007]	0.40
Rotor diameter (D_d)	1 m
Rotor height (H_d)	1 m
Swept area (A_d)	1 m^2
Chord length (C)	100 mm

By assuming a 1 m/s flow speed of water and an efficiency of slightly less than 30%, the maximum mechanical output power from Equation (10) is:

$P_{mech} = 145.2$ watt

Considering friction losses, actual power may be much less than 145.2 watt.

To find out the shaft speed at this output, we can use Equations (2) and (7) respectively:

For Savonius, $1 = (\omega_s \times 0.1) / 1$
For Darrieus, $5 = (\omega_d \times 0.5) / 1$
So, $\omega_s = \omega_d = \omega = 10$ rad/s
Therefore, $n = (60/2\pi) \times 10 = 95$ rpm

Expected output power of the designed turbine is shown in Figure 5 (assuming ideal conversion efficiencies).

HYDRODYNAMICS

Two basic forces that act in the designed turbine are drag and lift, as introduced. Savonius turbine provides high drag to overcome the rotor inertia and assist the Hybrid turbine to start in a counter-clockwise direction; whereas, the Darrieus turbine is powered by the phenomenon of lift. This lift is

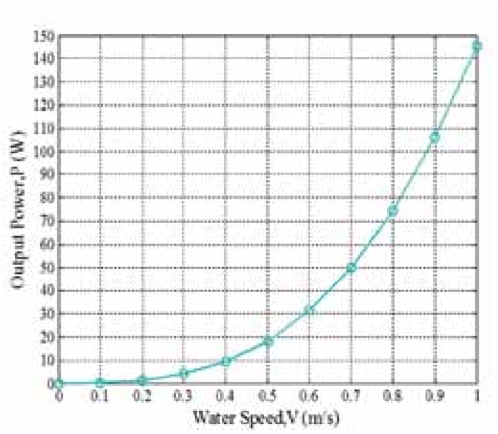


Figure 5: Expected output power of Hybrid turbine.

created because of the airfoil shape of the turbine's blades. These blades cut through the water with an angle of attack to the water causing a pressure differential. The resulting pressure differentials cause a force (lift), which propels the blade forward. In order to propel the turbine, the net torque caused by lift forces must be greater than the net torque caused by drag forces.

Drag force can be found from:

$$D = 0.5 \times C_D \times \rho \times A \times V^2 \qquad (12)$$

And the lift force can be found from:

$$L = 0.5 \times C_L \times \rho \times A \times V^2 \qquad (13)$$

Where C_D = Drag Coefficient (0.045 for an airfoil)

C_L = Lift Coefficient

A = Airfoil/ Frontal Area

Drag force depends on the Reynolds Number, which is defined as:

$$R_e = V \times L\left(\frac{\rho}{\mu}\right) \qquad (14)$$

Where R_e= Reynolds number (dimensionless), i.e. it is a ratio of two quantities with the same unit

μ = Viscosity coefficient

V = Velocity of the Water in m/s

L = Characteristic length, in this case the largest cross section of the frontal area in m

The forces driving Hybrid turbine can be described in more detail with the assistance of Figure 6. There are two important velocity components. First one is the velocity of the airfoil relative to the shaft, which is at all times parallel to the chord, having a magnitude equal to the rotational speed (ω) multiplied by the radius (R). Another one is the velocity of the water (V), which is approximated as a constant velocity in one direction (upside down). The resultant of these two velocities is the effective velocity of the water relative to the airfoil. The angle between this resultant velocity and the chord of the airfoil is called the angle of attack (α). Lift is created by a pressure differential which is perpendicular to the drag force and whenever there is an angle of attack (α) not equal to zero. In 0° and 180° position of θ (azimutal or orbital blade position shown in Figure 6), the angle of attack (α) is 0°. At this point, only a drag force exists. Lift begins to be created as the blades rotate out of these two positions and α increases. This lift force is perpendicular to the resultant water direction (or drag created at ¼th of chord length) but, most importantly, it always introduces counter-clockwise rotation for this designed structure regardless the direction of water flow.

The resultant water speed can be found from [Boyle, 2004]:

$$V_R = V\sqrt{1 + 2\lambda\cos\theta + \lambda^2} \qquad (15)$$

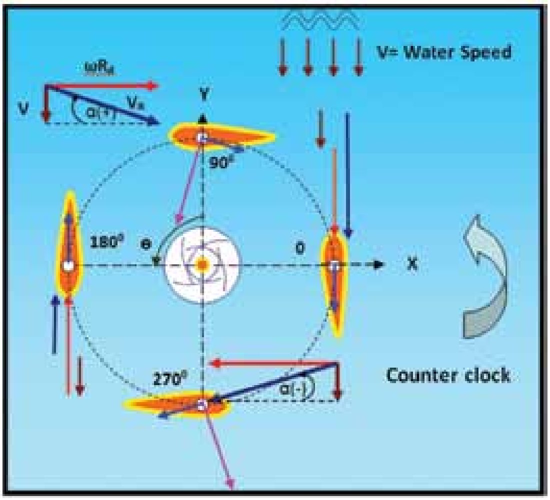


Figure 6: Hydrodynamics of the Hybrid turbine.

And the angle of attack (α) or incidence angle can be found from:

$$\alpha = \tan^{-1}\left(\frac{\sin\theta}{\cos\theta + \lambda}\right) \qquad (16)$$

Here, λ represents TSR for Hybrid structure.

TEST SETUP

The designed turbine has been built and tested in the flume tank of the Fisheries and Marine Institute of Memorial University of Newfoundland. Tank dimension is 8 m wide, 4 m deep and 22.25 m long. The test was done in three sections. First, the Savonius and Darrieus turbine were tested individually, and then the Hybrid turbine.

With the assistance of a DAQ board (OMB-DAQBOARD-3000 series), the torque data were collected using a load cell (Model: LCKD-5, Omegadyne) of 0-5 lbs, and a torque arm of 15 cm long. A magnetic particle brake (Model: B115-H, Placid Industries) with a coil voltage of 12 volt and the torque range of 2.5-115 lb.-in. has been used for force data collection. A gear-tooth sensor (Model: Cherry GS100102) has been used for speed measurement. Sensors were calibrated to give mass in grams and speed in RPM. Then the mechanical power has calculated using $P = \tau\omega$ (where τ = Torque). However, due to the limitation in load cell, test data were collected by keeping the turbine rotating at its maximum recordable force (5 lb). That is why it was not possible to show an inflection point in the characteristic curves. Figure 7 illustrates the immersed Hybrid turbine in the flume tank during tests.

RESULTS AND DISCUSSION

As introduced, due to the low structural strength of foam, we were not able to test the Hybrid turbine beyond 0.8 m/s flow speed because this would damage the blades. Even the H-Darrieus turbine was stopped before reaching 0.8 m/s for further test in its Hybrid combination. However, the Savonius turbine was tested up to

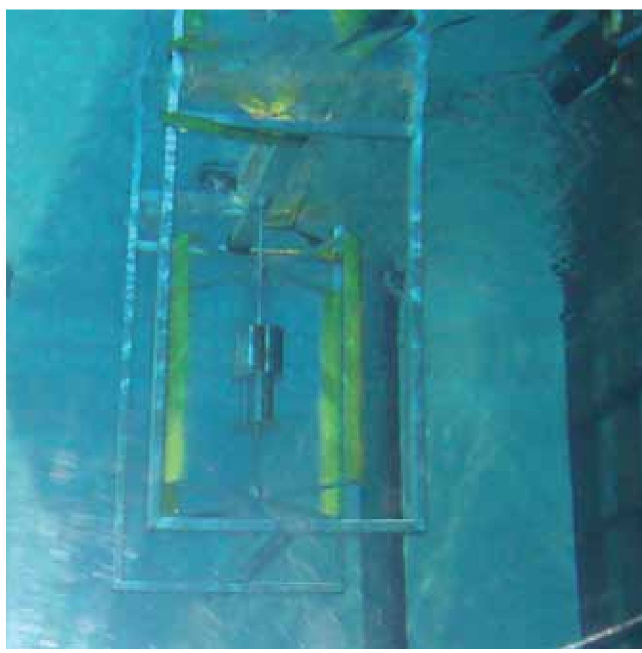


Figure 7: Hybrid turbine under test at flume tank.

1 m/s water flow speed on its own. Figure 8 demonstrates the power vs. water speed for three vertical axis turbines. The Savonius turbine, which acts as a starting device, has provided a maximum power of 2.13 watt at 1 m/s with a cut in speed of approximately 0.3 m/s.

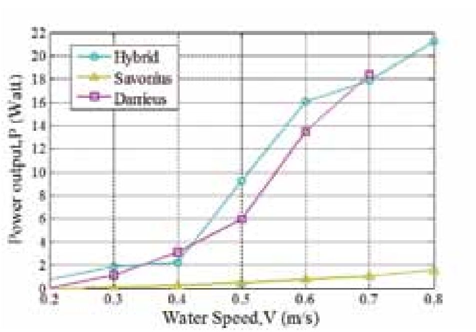


Figure 8: Collected power plots (Savonius, Darrieus and Hybrid).

The main comparison should be done between the Darrieus turbine with its Hybrid configuration.The Darrieus turbine shows that its power generation started at 0.3 m/s, and is able to produce approximately 19 watt at 0.7 m/s. In the case of the Hybrid turbine, it is quite evident from Figure 8 that its power generation (0.74 watt) started at 0.2 m/s. In other words, the Savonius turbine has improved the self-starting characteristic of the Darrieus turbine. Moreover, the power generation of the designed prototype has led the Darrieus turbine up to 0.6 m/s, and the difference in power generation becomes lesser as the water speed increases and starts to reduce the contribution of the start-up device. At higher speeds, the Savonius turbine reduced the overall efficiency of the turbine. The maximum power achieved with the Hybrid configuration at 0.8 m/s is approximately 21.3 W.

Figure 9 shows the power generated for different turbine speed of the Hybrid turbine. The maximum speed achieved is around 4.4 rad/s for 0.8 m/s. For 0.5-0.8 m/s water flow, it is quite evident that for each water flow, whenever the turbine angular motion goes to a higher value, it produces a lower torque and ultimately ends up with low power generation. At 0.3 m/s and 0.4 m/s water speed, the turbine was stopped when maximum torque applied, and it is not true for other flow rates (0.5 m/s-0.8 m/s).

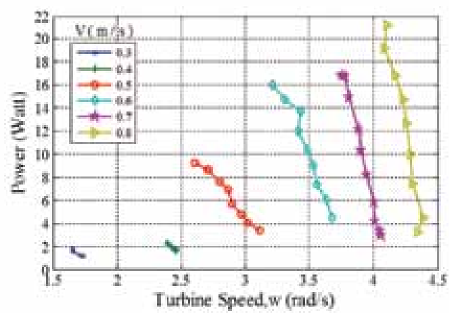


Figure 9: Power vs. turbine speed (Hybrid turbine).

Figure 10 illustrates an important characteristic of the Hybrid turbine. The maximum conversion efficiency is found at 0.6 m/s, which is nearly 15%. At this point, the TSR found is 2.7. Though the maximum TSR of 3.1 is achieved at 0.5 m/s, the conversion efficiency at that point was comparatively low. However, a closer investigation proves that the C_p vs. λ curves for 0.3 m/s to 0.6 m/s water flow followed almost the same pattern and are very close to each other. But the airfoil bending discussed earlier introduced obstacles for which the curves achieved at 0.7 m/s-0.8 m/s water speeds ended up with a different and low C_p as well as different TSR.

CONCLUSION

This paper has elaborated the design process, some design issues, and hydrodynamics; and

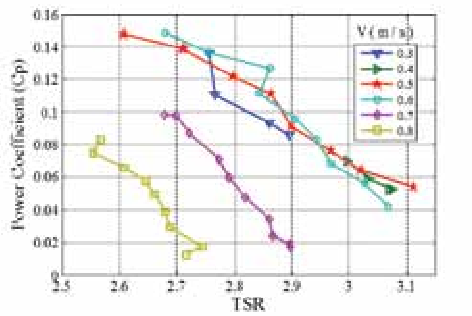


Figure 10: Power coefficient vs. TSR (Hybrid turbine).

discussed the test results for a low cut-in speed vertical axis Hybrid turbine. For a low power application, this Hybrid unit can be used in parallel with other units, where the average current speed is around 0.5 m/s. In spite of having some practical limitations with the design and testing processes, our design meets the criteria needed for a low power application environment. Further improvement in efficiency can be introduced by using a higher solidity ratio and carbon fibre made airfoils. The solidity ratio should be limited to avoid the increase in the moment of inertia. A cambered airfoil can also be tested to improve lift. During a Hybrid structure design, it is recommended to choose a proper radius ratio of the turbines. If possible, a CFD (Computational Fluid Dynamics) analysis is recommended before the actual test. However, these design ideas can also be implemented for wind applications.

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