Sea-Floor Power Generation System

Md. Nahidul Islam Khan, M. T. Iqbal, M. Hinchey

Faculty of Engineering and Applied Science, Memorial University of Newfoundland
Email: nahidul@engr.mun.ca

Abstract- ***Ocean currents represent a potentially significant, currently untapped, resource of energy. The total worldwide power in ocean currents has been estimated to be about 5,000 GW, with power densities of up to 15 kW/m^2. In the paper we describe a micro sea-floor power generation system being designed and developed at Electrical Energy System Lab, Memorial University of Newfoundland. The ocean current data around Newfoundland shows a significantly low non-tidal ocean current speed (in the range of 0.11-0.15m/s) at various depths. We would like to extract few watts electrical from the sea-floor ocean current. The produced power is required for the data processing computer and signal conditioning circuits of sea-floor instrumentation. The proposed power generation system will consist of a spiral shape drag type turbine rotor, a low rpm generator, batteries for energy storage, a controlled DC-DC converter, instrumentation and a micro controller based control system for the turbine. This paper describes progress made so far. We present some ocean current data, design and lab test results of our first proto-type sea-floor power generation system.***

I. INTRODUCTION

Ocean currents are result of wind and solar heating of the waters near the equator, although some ocean currents result instead from variations in water density and salinity. These currents are relatively constant and flow in one direction only, in contrast to the tidal currents closer to shore where the varying gravitational pulls of the sun and moon result in diurnal high tides. Ocean currents tend to be concentrated at the surface, although significant current continues at depths below ships' drafts. Ocean current speeds are generally lower than wind speeds. This is important because the kinetic energy contained in flowing bodies is proportional to the cube of their velocity. However, another more important factor in the power available for extraction from a flowing body is the density of the material. Water is about 835 times denser than wind, so for the same area of flow being intercepted, the energy contained in a 12-mph water flow is equivalent to that contained in an air mass moving at about 110 mph. Thus, ocean currents represent a potentially significant, currently untapped, reservoir of energy. The total worldwide power in ocean currents has been estimated to be about 5,000 GW, with power densities of up to 15 kW/m^2. Ocean-current generated energy technologies have many favorable characteristics, including the following:

- Water currents have a relatively high energy density.
- Some ocean currents are relatively constant in location and velocity, leading to a large capacity factor (fraction of time actively generating energy) for the turbines.
- Because they are installed beneath the water's surface, water turbines have minimal visual impact.

II. RESOURCE UTILIZATION TECHNOLOGIES

Ocean current energy is at an early stage of development, with only a small number of prototypes and demonstration units having been tested to date. One such technology involves submerged turbines. Energy can be extracted from the ocean currents using submerged turbines that are similar in function to wind turbines, capturing energy through the processes of hydrodynamic, rather than aerodynamic, lift or drag. These turbines would have rotor blades, a generator for converting the rotational energy into electricity, and a means for transporting the electrical current.

Turbines can have either horizontal or vertical axes[2] of rotation (Figure 1). Mechanisms such as posts, cables, or anchors are required to keep the turbines stationary relative to the currents with which they interact.

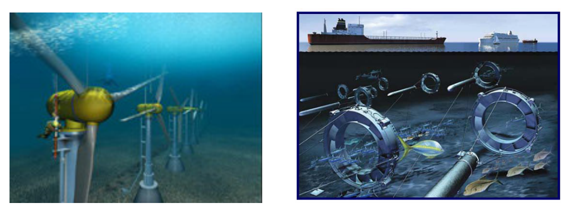


Figure -1 Visualization of Two Possible Turbine and Anchor Technologies

Turbines may be anchored to the ocean floor in a variety of ways. They may be tethered with cables, with the relatively constant current interacting with the turbine used to maintain location and stability. In large areas with powerful currents, it would be possible to install water turbines in groups or clusters to create a "marine current facility," similar in design approach to wind turbine facilities. Turbine spacing would be determined based on wake interactions and maintenance needs.

For marine current energy to be utilized, a number of potential problems would need to be addressed, including avoidance of drag from cavitations (air bubble formation that creates turbulence and substantially decreases the efficiency of current-energy harvest), prevention of marine growth build up, corrosion control, and overall system reliability. Because the logistics of maintenance are likely to be complex and the costs potentially high, system reliability is of particular importance.

III.ATLANTIC OCEAN CURRENT

The circulatory system of the surface waters of the Atlantic can be depicted as two large gyres, or circular current systems, one in the North Atlantic and one in the South Atlantic. These currents are primarily wind driven, but are also affected by the rotation of the earth. The Atlantic receives the waters of many of the principal rivers of the world, among them the Saint Lawrence, Mississippi, Orinoco, Amazon, Paraná, Congo, Niger, and Loire, and the rivers emptying into the North, Baltic, and Mediterranean seas. Nevertheless, primarily because of the high salinity of outflow from the Mediterranean, the Atlantic is slightly more saline than the Pacific or Indian oceans. . The Atlantic Ocean may be described as a bed of water colder than 9°C (48° F)-the cold-water sphere-within, which lies a bubble of water warmer than 9° C-the warm-water sphere. Data of current flows at various depths in Atlantic ocean more for than one year is analyzed to observe the change in flows.

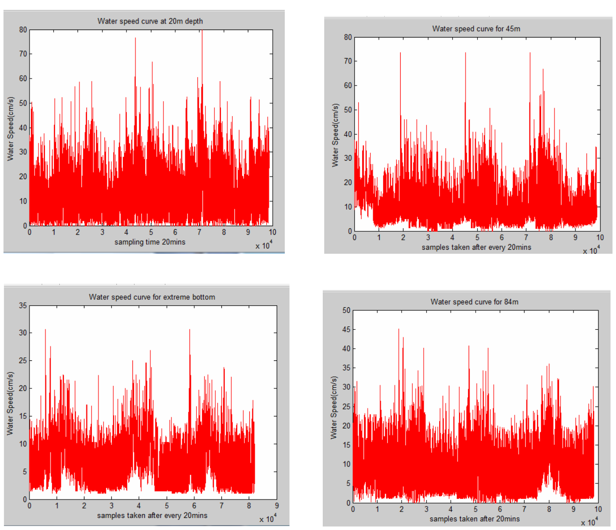
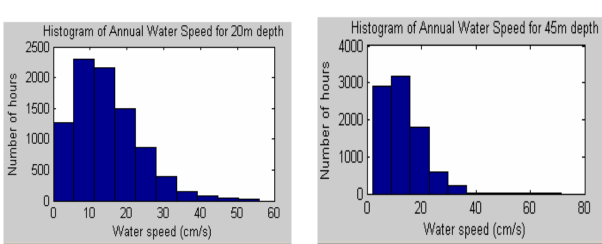


Figure 3.1: Water current speed variations at different depths over period of more than a year.



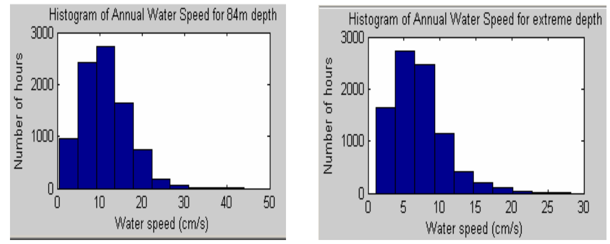


Figure 3.2: Histogram of one-year water current speed at four depths.

Figure 3.2 shows histograms of one-year hourly water current speed data recorded at four depths in east of St. John's. The average speed is very low and its variations over a year are significant. This makes it really challenging to extract sufficient amount of power from ocean floor.

IV. MARINE ENERGY DEVICES

The two principal forms of marine energy are waves and tides. However, there are other forms, including heat and chemical energy. Ocean swells and waves contain both potential and kinetic energy, which can be harnessed with appropriate devices. Ocean currents, tidal streams and tidal bores also contain potential and kinetic energy, arising from the rise and fall of the tides.

Most marine energy conversion devices usually aim to convert potential and/or kinetic energy in waves and tides into electrical energy. To date there are only a few technologies that have progressed as far as the full-scale deployment and testing. However, there are several UK-based companies presently actively involved in the construction of such devices, supported in their endeavours by numerous financial channels including the Government and private investors. A number of technologies developed are shown in fig 4.1.

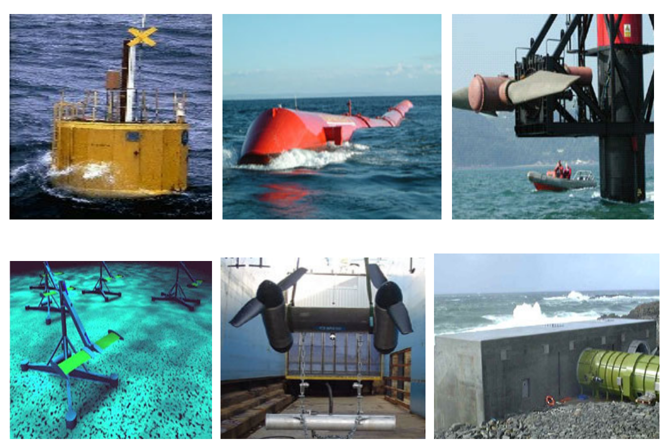


Figure 4.1 Marine devices to produce electricity

Perhaps the most advanced vertical axis turbine is the Canadian Blue Energy Ocean Turbine proposal (Figure 4.2). Their Ocean Turbine device comprises a vertical axis turbine with vertical working blades, which rotate in a single direction in both ebb and flow currents. The turbines are set into large concrete caissons, which sit on the seabed and can be used to form "*tidal fences*" over open estuaries or river mouths. Unlike tidal barrages, however, it is envisaged that these turbines extract kinetic energy without restricting current flow.

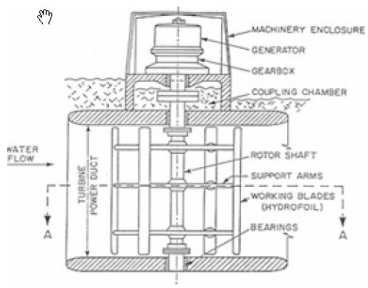


Fig.4.2 Line drawing of Blue Energy's Ocean Turbine device

V.SAVONIUS ROTOR

The Savonius rotor concept never became popular, until recently, probably because of its low efficiency. However, it has the following advantages over the other conventional wind turbines:

- simple and cheap construction;
- acceptance of water from any direction thus eliminating the need for reorientation;
- high starting torque helps to start at any speed;
- relatively low operating speed (rpm);
- no such maintenance is necessary.

The above advantages may not outweigh its low efficiency and make it an ideal economical source to meet small-scale power requirement. The concept of the Savonius rotor was based on the principle developed by Flettner. Savonius used 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."

A Savonius design was selected because of its greater simplicity in design and manufacture. Savonius turbine relies on stagnation principles to convert current 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 amount of torque.

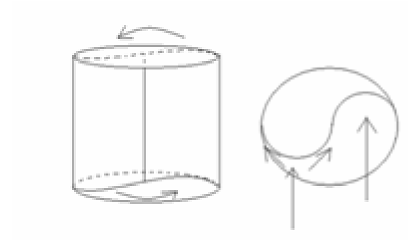


Figure: 5.1 A simple Savonius rotor designs.

If C_p [1] were the power coefficient of a turbine then the power P can be obtained from water:

$$P = 0.5 * C_p A \rho V^3 \quad (1)$$

where P is the output power (W)
ρ is the density of water (kg/m^3)
A is the swept area of rotor (m^2)
V is the speed of water (m/s)

The tip peripheral velocity of the rotor $U = \omega . R$ (ω is the angular velocity of rotor and R is the radius of the bucket)

Now the velocity coefficient of the turbine is defined as

$$\lambda = U/V \quad (2)$$

Turbines are usually defined by performance curve, which gives Cp as a function of k. It is known (Betz theory) that for a horizontal axis wind turbine, the power coefficient is always inferior to the theoretical value 0.593. In fact, the best modern machines hardly reach this maximal value of the power coefficient.

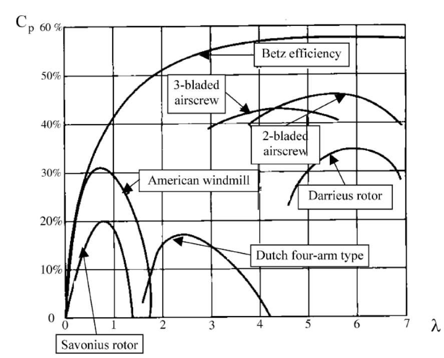


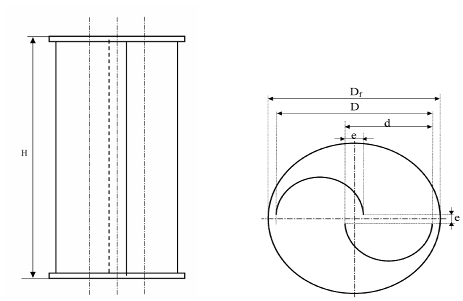
Fig. 5.2 Performances of main conventional wind machines

The aspect ratio represents the height of the rotor relatively to its diameter, this is a very important criterion for the performances of a Savonius rotor:

$$\alpha = H/D \quad (3)$$

Generally the value of α is taken higher to improve the efficiency. Values of an around 4.0 seem to lead to the best power coefficient for a conventional Savonius rotor [1].

It is known that end plates lead to better hydrodynamic performances. The influence of the diameter D_f of these end plates relatively to the diameter D of the rotor has been experimentally studied. The higher value [1] of the power coefficient is obtained for a value of D_f around 10% more than D, whatever the velocity coefficient.



(a) (b)

Fig. 5.3 Scheme of a single-step Savonius rotor. (a) Front view; (b) top view (conventional Savonius rotor: e'=0).

The overlap ratio β is given by the following equation

$$\beta = e/d \quad (4)$$

where e is the overlap (Fig. 5.3) and d is the diameter of each cylinder constituting the paddles .The best efficiencies [1] are obtained for values of β between 20 and 30%.

If the number of buckets is increased then the efficiency of turbine goes down but better preferences can be achieved for two bladed turbine.

For few directions of the water flow, this starting torque would be so low that the rotor could not start alone. It is the reason many prefer to use a double-step Savonius rotor, where the upper and the lower paddles pairs are set at 90° to each other. The double-step rotor is found to be slightly bettered compared to the corresponding single-step turbine (conventional Savonius rotor) in both torque and power characteristics.

VI. Design Procedure

1. *Choice of the material for the bucket and circular disc*

The choice of the material was obviously crucial. Different criteria were considered for this choice: low price, building easiness, low weight, and good resistance to outside elements (humidity, temperature variation, etc.), good rigidity, recyclable power. The best option is to use aluminum to avoid corrosion.

2. *Dimension of turbine*

A central shaft is chosen for the prototype in order to strengthen the structure. The Eq. (4) is modified to take into account the presence of shaft.

$$\beta = (r_a - a)/d_i \quad (5)$$

where r_a is the overlap

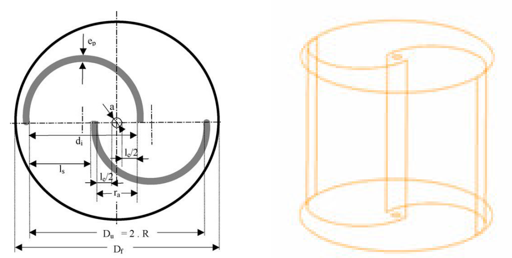


Fig. 5.4 Scheme of the present prototype.

The best efficiency of a Savonius rotor is obtained for values of the overlap ratio b between 20 and 30%.

Building data for the prototype, and expected nominal characteristics

Total height of the rotor	H	440 mm
Nominal diameter of the paddles	d_i	113 mm
Diameter of the shaft	a	14 mm
Diameter of the rotor	D	222 mm
Overlap ratio	b	0.207
Swept area of the rotor	A	0.088 m^2
Expected mechanical power at 1m/s	P	6.8W
Expected rotational speed at 1 m/s	N	76 rpm

4. *Choice of Generator*

Unlike small DC motors, steppers will generate power at very low rotation rates; typically only about 200 rpm for a good output which is ten or fifteen times slower than the rate for a DC motor.

Steppers come with different resolutions. Virtually all steppers are either 1.8° or 7.5° per step; (200 steps or 48 steps per revolution) the difference can be felt easily if you turn the spindle by hand. The 1.8° ones are obviously better for generating at really low revs, but also 'top out' lower. The coils in steppers have a relatively large inductance, and beyond a certain speed the output frequency gets so high that the impedance of the coils starts to become significant and limits the current. When making a stepper-based generator, you need to keep the motor speed to around a couple of hundred revs per minute - something like the normal speed of a bicycle wheel.

Stepper motors are also a small multi-pole alternator, but being more modern they have four phases. As with a DC permanent magnet motor, turning the motor's shaft makes it work backwards, causing pulses of current to come out of the windings. However, the current is AC, going plus as a magnet pole approaches a coil and then minus as it goes away again. Usually there are four phases at 90-degree intervals so when one comes down to zero, the next one has reached maximum. This is a benefit as it means the output can be rectified to produce much smoother DC with hardly any gaps, but it means they have a scarily large number of wires coming out.

In order to increase the voltage output from the stepper motor a voltage doubler circuit is considered. A voltage doubler circuit does exactly that - it doubles voltage. The power generated by the stepper motor does not change, therefore following ohm's law it can be seen that the output current must be halved if the voltage is to double.

Using a voltage doubler enables a useful voltage to be ouput at low rotational speeds with the disadvantage that the current generated at high speeds is lower than it would be without the voltage doubler.

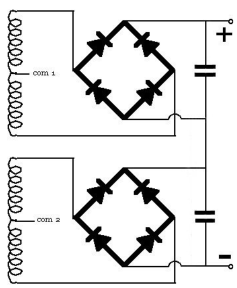


Fig 5.5.Voltage doubler circuit

Making a voltage doubler for a stepper motor is very simple because stepper motors generate four-phase alternating current (AC) electricity. Therefore all we need is a couple of suitably rated bridge rectifiers wired as per the circuit diagram displayedabove.

The AC voltage from each of the two pairs of stepper motor coils is rectified by a bridge rectifier into DC voltage and the two output voltages are then added together giving a total output of double the original voltage, but with a current equivalent to that generated by just one pair of coils. The two capacitors are used to give a smooth output DC voltage.Two different types of stepper motor were used as generator .One is LM 73008 and the other one is OS Series OS22BSNFLY .

5. *Type of material used*

Aluminum has been used for the rotor to avoid rusting and for higher tensile strength and rigidity of the turbine. The first prototype that has been built for testing in the flume tank is shown in Figure 5.6.

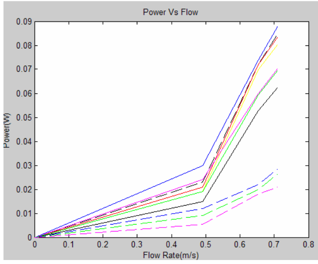
Figure 5.6 First prototype model

VII.EXPERIMENTAL RESULT

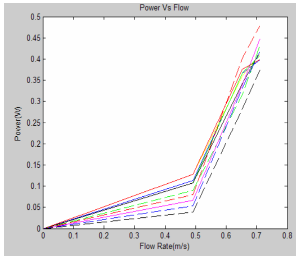
The experiment was carried out in flume channel. The flume comprises a rectangular section of channel with inlet and discharge tanks, which is supported by a pair of rigid pedestals. A service module incorporating a sump tank and submersible pump provides a source of water which is continuously re-circulated through the channel section making the unit self contained. The level in the working section of the flume may be controlled by an overshot weir arrangement at the exit consisting of stop logs in a slot. Stop logs are simply added or taken away to provide the required depth of water in the working section. Water exiting from the channel enters the discharge tank where it returns by gravity to the service

Figure 6.1 Turbine immersed in Flume Tank

module. The flume channel in Memorial University of Newfoundland has got a dimension of 40 cm width and 50 cm height. The turbine is submerged fully under water in the channel, which is shown in Figure 6.1. The flow of water is varied by the control valve and four different flow rates can be maintained. The experiment is carried out for different loads.



(a)



(b)

Figure 6.2: Power curve obtained from the turbine using (a) LM 73008 and (b) OS22BSNFLY

The maximum power that can be obtained is 0.45W at 0.71m/s for a load of 4 ohm from OS22BSNFLY. The generators didn't produce any satisfactory result which can be noticed from the expected power curve of the turbine.

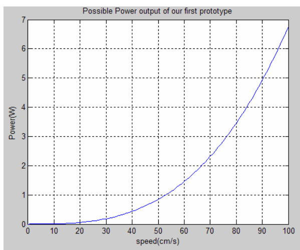


Figure 6.3: Expected power curve of first prototype

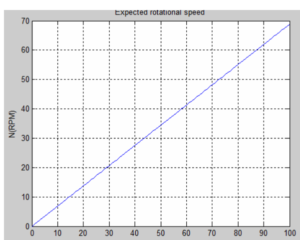


Figure 6.4: Expected RPM of the first prototype

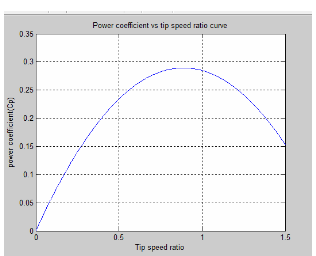


Figure 6.5: Power coefficient versus tip speed ratio curve

As it is a single step Savonius rotor therefore it is unidirectional. A double step Savonius rotor with ninety degree each other can work omni directional. The turbine has a high starting torque which causes it operate at a low cut in speed of 0.15m/s.Due to very low efficiency of the turbine the second prototype is designed.

VIII. Three Phase Savonius Rotor

The new prototype that is designed to generate more power. In the second prototype savonius rotor which has three stages with 120-degree phase shift between the adjacent stages has been made.In this prototype the guide vanes are added to increase the torque coefficient on the average in the low tip speed ratio.It has been also mentioned [3] that the toque coefficient decreases.Generally two problems occurs with torque characteristics. Firstly the torque variation causes rotor vibration and decreases its durability. Secondly for some angular position the static torque is negative and is not self starting. The new prototype has three stages with 120 –degree bucket phase shift between the adjacent stages makes it omnidirectional.Additionally the guide vanes can act as safeguard for the frame.

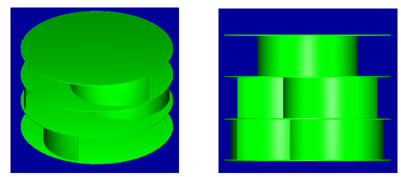


Figure 7.1 Schematic diagram of three stage savonius rotor

Basically the new model is designed using the same concepts for the single step savonious rotor (first prototype). The aspect ratio has been divided into three equal parts so that each stage has equal heights.

The expected power of the turbine is shown in Fig7.2.The turbine can generate 24W at 1m/s flow of water.

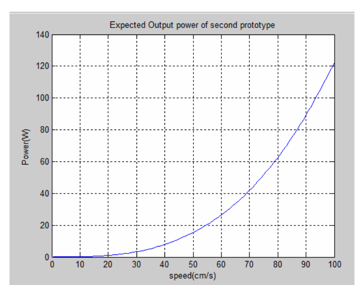


Fig 7.2 Expected power from second prototype

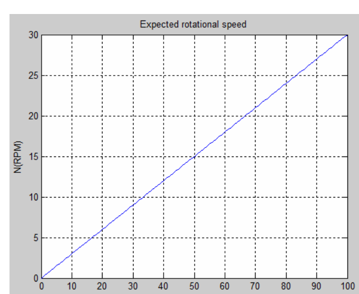


Fig 7.3 Expected RPM of second prototype

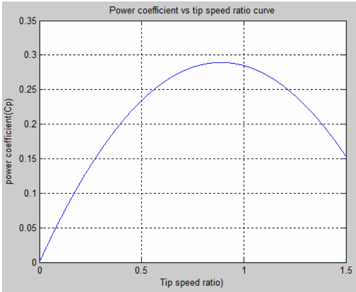


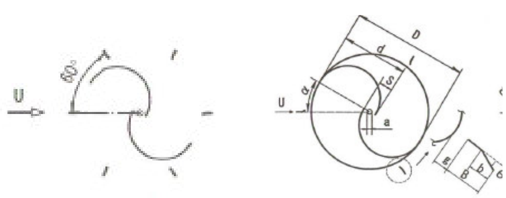
Fig 7.4 Cp vs tip speed ratio of second prototype

Building data for the new prototype, and expected nominal characteristics

Total height of the rotor	H	3200mm
Height of each stage	h	1066.7mm
Nominal diameter of the paddles	d_i	304.8mm
Diameter of the shaft	a	14 mm
Diameter of the rotor	D	509.5mm
Swept area of the rotor	A	1.6304m^2
Expected mechanical power at 1m/s	P	120 W
Expected rotational speed at 1 m/s	N	30 rpm

Six guide vanes are equally placed around the rotor to guide the water through the turbine .The dimension of the guide vane are shown in fig 7.5.

Six guide vanes are placed around the rotor and their arrangement is shown in Fig 7.5(a) .The geometry of the guide vane is also shown in Fig.7.5 (b).



(a) (b)

Fig 7.5 (a) Arrangement of guide vane around the rotor
(b) Geometry of rotor with guide vane

Dimension of Guide Vanes

Length of vane	L	3200mm
Width of vane	B	35mm
Width of inclined vane	b	20mm
Gap between vane and rotor	G	20mm
Angle of curve	ϴ	20°

Steel can be used to construct the rotor so that it weighs less and can be easily manufactured.

The generator chosen for the second prototype is a low rpm Aquair 12v Underwater Turbine Generator. The AQUAIR UW is a submerged water powered generator for 12/24 volt battery charging. The generator has been found to produce 10W at 220 rpm and the maximum rpm of the turbine is 30 rpm at 1 m/s. To generate 10W a gear box with ratio 10:1 is necessary to couple with the generator.Above discussed system is under development at MUN. A system that will produce the power required for the data processing computer and signal conditioning circuits will be designed. Micro controller will control the DC-DC converter to extract the maximum power from the system. Such a control scheme will be based on the voltage, current and speed measurement of the system.

Maximum power algorithm based control scheme will make sure that system is always extracting the maximum power from the water current.

IX.CONCLUSIONS

This paper presented a review of marine current energy conversion systems. Marine current data of Atlantic Ocean near St. John’s shows an average flow of 20cm/sec. We are trying to design a sea-floor power generation system to produce few watts from the available marine current. Design and test results of our first prototype are presented above. It shows that our first proto-type produced only 0.45W at a flow rate of 70cm/s. Design of second prototype is in progress. Some details of second design and expected performance results are included in this paper.

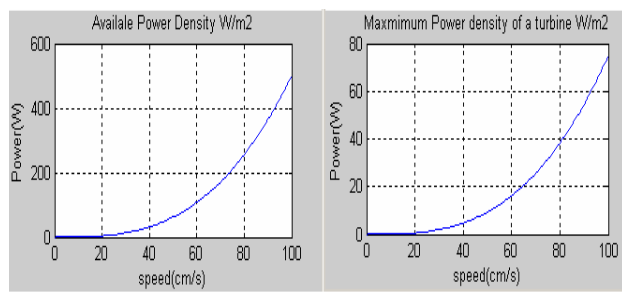


Figure 8: Available and maximum extractable power density from water current.

Figure 8 shows available power density of water current as a function of flow speed. It also shows how much maximum of available power density can be extracted. It is based on a reasonable assumption that turbine power coefficient will be about 0.15.

Table 1: Expected output of power generation system

Depth (m)	Average Flow Speed (cm/s)	Maximum available energy density in a year (Whr/m^2)	Extractable energy density in a year (Whr/m^2)
20	14.6070	152195.0	23169.0
45	13.2005	44045.0	5954.0
84	11.2233	109590.0	15906.0
Near Bottom	7.0555	98465.0	14268.0

From table 1, we can say that, to produce say 1W output at a depth of 84m we need a turbine with an apparent area of $10m^2$.In addition its not possible to design a direct driven system in such a low flow of water. Based on the above analysis we can conclude that either we use turbine at a site where flow speed is higher or reduce power consumption in the data processing computer and signal conditioning circuits to a minimum possible.

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