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Performance Studies on an Oscillating Water Column Employing a Savonius Rotor

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A new oscillating water column (OWC) design is proposed in this study to incorporate a simpler Savonius type turbine. Conventional OWC devices employ a bi-directional turbine such as a Wells or an Impulse turbine to extract energy from the air. The disadvantages of the Wells turbine include its inability to self start and stalling. The Savonius turbine is much cheaper and is an effective option at low Reynolds numbers. In the current rectangular OWC device, unlike the circular OWC, the width of entry of the capture chamber can be increased without being influenced by the diameter at the turbine section. To improve its primary capture efficiency, the front and rear walls of the OWC are inclined to minimize reflection. The Savonius rotor characteristics are studied with respect to the change in frequency of the incoming waves. The rotor rpm is sensitive to wave period and primary conversion efficiency while changes in depth only affect the rotor rpm at lower frequencies. The Savonius rotor shows promising results and can be incorporated into large scale OWC devices to reduce costs of the turbine component of the system.

Wave energy, Savonius rotor, Osscilating water Column, Inclined chamber.

Nomenclature

ρ	water density kg/m^3
ρ_a	air density kg/m^3
g	gravitational acceleration, m/s^2
H	wave height, m
T	wave period, s
k	wave number
h	water depth, m
V_i	turbine inlet velocity, m/s
A_i	turbine inlet area, m^2
p	turbine inlet pressure, Pa.

1 Introduction

Wave energy can be considered as a concentrated form of solar energy [1,2]. Solar heating causes winds to blow due to temperature differences, which in turn cause the waves in the sea. The global wave power resource in water depths of over 100 m has been estimated to be between 1 and 10 TW, while the economically exploitable resource ranges from 140-750 TWh/yr for current designs when fully mature, and could be as high as 2000 TWh/yr if the potential improvements to existing devices are achieved [2]. There are many devices that can extract energy from the waves. The devices can be grouped into two main classes: (1) offshore devices based on floating articulated bodies oscillating under the action of waves and (2) near-shore and on-shore devices based on the conversion of wave motion into oscillating air flow driving a turbine [3]. The response of a wave energy device is generally frequency dependant. The peak (resonant) frequency and the range of frequencies that will produce a significant response will depend on the particular device [4]. The oscillating water column (OWC) is one of the most widely researched and promising wave energy devices [5 - 7]. As the wave impinges on the OWC, it causes oscillation of the free water surface in the capture chamber, which in turn causes bi-directional air flow in the upper OWC. An appropriate bi-directional turbine can be used to convert this kinetic energy to electricity. Capable of operating in reversing flow conditions, the Wells Turbine is generally used to avoid the addition of rectifying valves to correct one of the flow phases [8]. Impulse turbines capable of self-rectification have been studied in detail for use in OWCs by [9] and others. The OWC can be fixed or floating type. This paper deals with a fixed type OWC. There are several fixed OWC plants built. To reduce capital cost fixed type OWCs are normally integrated within harbor breakwaters. However, a fixed OWC offers advantages such as extended life, easier maintenance and cost sharing with shore protection structures. Design parameters of shallow depth fixed OWCs are discussed by Koola et al. [10]. In moderate wave climates the need to improve primary capture plays a crucial role in the viability of an OWC system.

1.2 Turbines currently used in OWC devices

The efficiency of oscillating water column (OWC) wave energy devices equipped with Wells turbines is particularly affected by flow oscillations basically for two reasons: 1) due to the intrinsically unsteady (reciprocating) flow of air displaced by the oscillating water free surface, and 2) increasing the airflow rate above a limit depending on and approximately proportional to the rotational speed of the turbine is known to give rise to a rapid drop in the aerodynamic efficiency and in the power output of the turbine [11]. Conventional turbines such as Wells turbine are also expensive to develop and maintain for wave energy plants. Setoguchi and Takao [12] compared the starting and running characteristics of five different turbines used in wave energy extraction. Their comparisons included Wells type and impulse type turbines and a numerical approach was taken. The comparison showed that a better efficiency of around 45% is obtained for impulse turbines with self-pitch controlled guide vanes. Jayashankar et al. [13] proposed a twin unidirectional impulse turbine for use in OWC devices. They also carried out numerical simulation and estimated the efficiency of such designs to be around 0.7. At present most designs of OWC use Wells turbines which have many disadvantages. Apart from its inability to self start a Wells turbine displays stalling behavior when flow coefficients exceed a certain value [14-16].

1.3 Use of Savonius turbines for wave energy

Of late, there is a growing interest in rectangular OWC devices and rectangular turbine sections housing Savonius rotors. A design of a Savonius rotor utilizing OWC is presented by Dorrell et al. [17-19]. They compared multiple chamber arrangements and reported turbine conversion rates of 20.2% for the two bladed Savonius turbine. The advantage lies in the ease of construction of these types of turbines as well as the OWC; it also allows us to increase the width of OWC parallel to the coast so that a greater amount of energy can be absorbed per device. Unlike the circular OWC, the width of entry of the capture chamber can be increased in the rectangular ducted OWC without being influenced by the diameter at the turbine section. The Savonius turbine is a much effective solution at low Reynolds numbers, unlike the Wells turbine which requires a high Reynolds number [17].

Menet [20] remarks that their high starting torque not only allows them to run but also start whatever the wind speed. The generation unit where the conversion of energy takes place can be placed at the surface. In case of OWCs this provides ease of maintenance. It cannot be ignored that Savonius rotors have lower efficiencies than horizontal axis turbines for wind applications. However in the case of OWCs, the simplicity of the Savonius along with its other advantages make it a competitive option as a power producing turbine. This is a simple and low-cost turbine although the conversion factor is low [21]. The design and construction of such a turbine is simpler and does not require complex understanding of aerodynamics and blade design. Hence it is also suitable for private installations by communities or individuals for small systems. Similar to VAWTs, this turbine can be constructed easily with readily available tools and material as compared to the other wave energy turbines which require complex design and specialized equipment to construct. In 2008, Altan and Atılgan [22] proposed the idea of a curtain placed in front of a Savonius wind rotor to increase its performance. The curtain causes air to be channeled onto the inner blades rather than impacting the outer portion of the adjacent blade. This reduces negative torque in the Savonius rotor. A novel approach of incorporating the curtain effect into the chamber of the OWC is taken in this research. The contracting curtains need to be placed on both sides of the turbine due to bi-directional flow. Setoguchi and Takao [12] highlight that the efficiency of the turbine does not give useful information about the suitable turbine for wave power conversion. This is because the turbine characteristics depend on the efficiency of the air chamber, i.e the ratio of the OWC power and the incident wave power. Hence it is eminent that the primary conversion process be as much efficient as practically possible to ensure optimum energy conversion rate of the overall OWC. Cost effectiveness is a major obstacle hindering growth of oscillating water column technologies. The majority of the cost for an OWC plant goes into its structure and support. The mechanical and electrical components are the second most significant contributors to cost of the initial OWC. While not included in the initial capital cost, the costs involved in the maintenance of the OWC system, mainly the mechanical and electrical components of the generation system also play a major role in deciding the viability of an OWC plant. The design presented uses a capture chamber structure that can be incorporated into a breakwater to reduce structural costs. The Savonius rotor is simpler and cheaper [21] to construct and this leads to cost reduction of the turbine system. Use of a Savonius type rotor allows the rotor shaft to run perpendicular to the airflow. This allows the shaft to be extended out of the OWC chamber, so that the generation unit is mounted outside for easy access for maintenance. The present work is aimed at experimentally studying the airflow and rotor characteristics in a rectangular section OWC device inclined at 65° and employing a Savonius rotor.

2 Testing methodology

The experiments were carried out in a wave channel that is 3.5m long, 0.3m wide and 0.45m deep, and uses a flap type wavemaker hinged at the bottom to generate sinusoidal waves. The close fit of the wave maker to the wave channel sides ensures that two-dimensional waves are produced with no fluid motion normal to the sidewalls. Controlling the frequency of the wave maker simulates different sea states of various periods. Figure 1 gives a schematic of the wave channel.

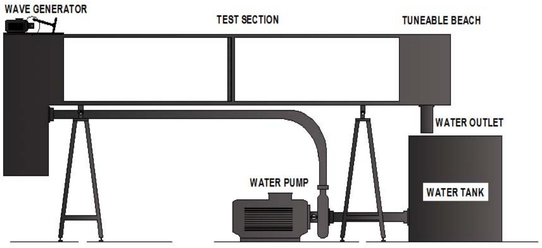

Figure 1 Schematic diagram of the Wave Channel

A Cussons Tuneable Beach, model P6285, was placed at the other end of the wave channel. The beach consists of a series of porous plates with different porosity levels to absorb the wave energy gradually and minimize reflections. The model is built out of clear Perspex to a scale of 1:100. Koola et al. used a scale of 1:100 and stated that in Froude scale the model ratio is proportional to the square of the time ratio [10]. This means that for an actual sea wave period of 12.5s, the scaled down period used in the experiment will be 1.25s. The experimental OWC does not include any bends to prevent losses due to bending of the duct and also for ease of result comparison. The rear wall of the OWC is inclined at 65° to reduce reflections [23]. The design has a rectangular capture chamber to allow the use of a Savonius rotor as the turbine. The chamber is also designed in a manner so that it can be integrated into an inclined breakwater system or seawall without many modifications.

A nozzle is created on both sides of the turbine section angled at 26° as shown in Figure 2. The nozzle helps in increasing the velocity and ensures that the flow is directed on to the inner surface of the blade. The use of such curtain design has been proposed by Altan and Atılgan [22] in Savonius rotors for wind applications. However, in this case, the curtain effect is provided in the upward and downward direction due to the bi-directional flow. While a nozzle effect has been used in ref. [12, 13, 18], the nozzle is not installed on both sides. Their design utilizes a single nozzle effect below the turbine. A similar rectangular ducted OWC for Savonius rotors has been designed and PIV studies done in [24]. The Savonius is a drag type device and while half the rotor creates positive torque the other blades which do not receive air on the inner surface create negative torque. To avoid this, the nozzle shields the blades which are not contributing to positive torque and directs the flow onto the positive-torque-generating blades. A five bladed Savonius type rotor was chosen as the turbine rotor (geometry shown in Figure 3). This bi-directional turbine is modified slightly from the original Savonius by sealing the overlapping gap between the blades. This was done to accommodate more number of blades on a smaller diameter shaft and increase rotor rigidity. The air flow oscillations vary in amplitude and period. In order to ensure that air flow impacts the blades on all cycles, five blades were chosen. A five bladed Savonius type rotor has also been used by Faizal et al. [25], however in this case the rotor was used as a submerged wave energy converter and not as an air turbine. A detailed study of a five bladed Savonius type rotor is given in ref. [26]. A 70° blade angle was chosen. An S-type Pitot tube fabricated in-house was inserted at the location indicated in Figure 2. A *Furness Controls* FCO510 model digital micro manometer with a range of ±200 mm of water was used to measure the differential pressure from the S-type Pitot tube. The digital manometer had an accuracy of 0.25% of the reading. The S-type Pitot tube was calibrated against a standard Pitot tube before use in the OWC. The differential pressure provided the dynamic pressure values at tap ‘A’ in Figure 2. The dynamic pressure oscillations were used to derive the instantaneous velocity at that point. To ascertain the conditions of the waves created in the wave channel and the relationships between various parameters pressure transducers were used to measure the wave parameters. The pressure signals were acquired on a GL500A dual data logger and analyzed to determine the period, wave height and wavelength. Three depths were tested at for comparison.

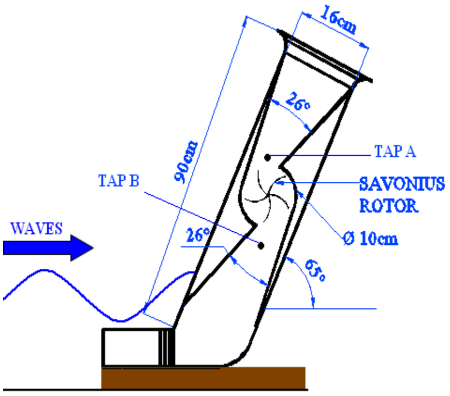

Figure 2 Schematic of the OWC setup showing locations of the pressure taps and rotor.

The rpm of the rotor was measured by a non-contact RPM meter. The wavemaker frequency settings caused different condition of waves to be generated and the rpm was measured for these different wave conditions.

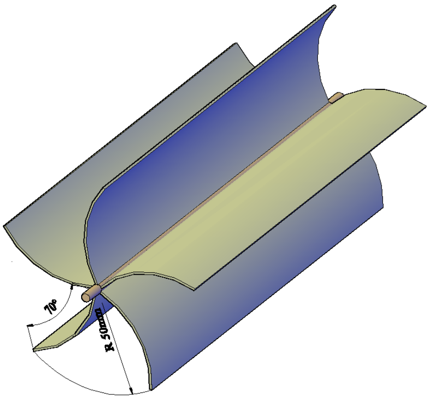

Figure 3 5 bladed Savonius type rotor for OWC

3 Results

Figure 4 shows the wave heights as a ratio against the depth, created at various wavemaker frequencies.

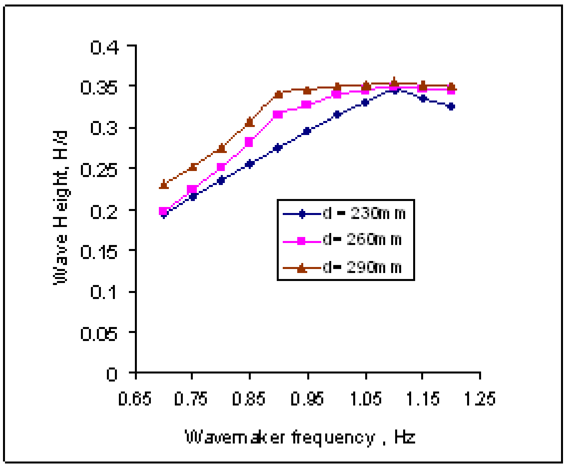

Figure 4 Variation of wave height with frequency at three depths

The experiments for the OWC were conducted at the wave conditions caused by a flap type wavemaker. Two aspects were looked at, firstly the flow in the chamber without the rotor and the performance of the Savonius type rotor placed in the turbine section. The static pressure oscillations at tap A and B are compared in Figure 5. The lower amplitude of oscillations at tap "A" compared to tap B show effects of attenuation on the oscillating air movement. Studies have found that airflow velocity is more when the air flows outwards i.e. the exhalation stage compared to the suction stage. This could be caused by attenuation effects as air being sucked in by the receding water surface is slower due to its position away from the water surface.

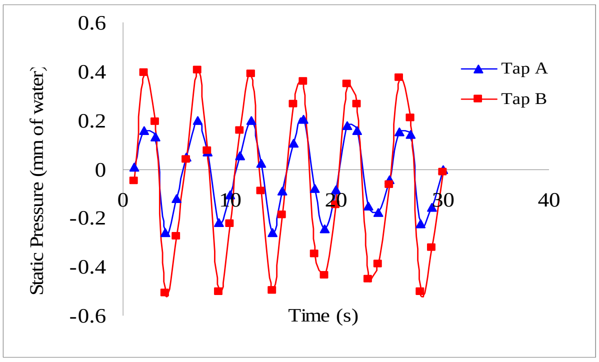

Figure 5 Static pressure at tap A and tap B.

An S-type Pitot tube was used to measure the dynamic pressure of the flow for the depth of 260mm. Figure 6 shows the instaneous dynamic pressure reading at tap position B. The peak velocities were derived from the dynamic pressure oscillations. Figure 7 shows the peak velocities for the exhalation and suction stage at 260mm depth.

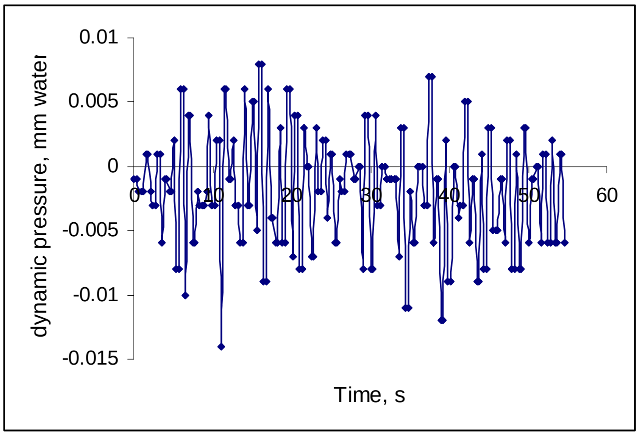

Figure 6 Dynamic pressure osscillations at the turbine inlet (without turbine; depth =260mm, 1.1Hz)

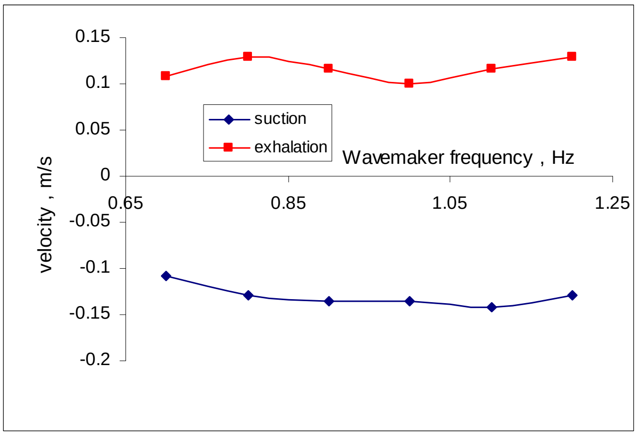

Figure 7 Peak suction and exhalation velocities. (depth = 260mm)

The primary conversion takes place in the inclined chamber itself and the incoming wave power can be calculated using equation (1):

$$P_{wave} = \frac{1}{8}\rho g H^2 c_g \qquad (1)$$

Where c_g , the group celerity of waves is given as:

$$c_g = \frac{1}{2}\left[1+\frac{2kh}{\sinh 2kh}\right]\frac{gT}{2\pi}\tanh(kh) \qquad (2)$$

The turbine inlet power in an OWC device is given in equation (3) [27]:

$$P_{in} = (p+\rho_a V_{in}^2/2)V_{in}A_{in} \qquad (3)$$

Using the peak inlet velocities in Figure 7 and combining with static pressure data at the same station to derive p, P_{in} was calculated. The primary conversion factor can be expressed as a ratio of the energy available to the turbine to the energy available from the waves (P_{in}/P_{wave}). Figure 8 shows how this conversion factor varies for different wave periods. The velocities from the suction stage are used. The conversion factor should influence the power available to and the rpm of the rotor. The conversion factor and rpm of the rotor follow a similar trend. The conversion factor peaks at 0.9s wave period which causes improved airflow in the turbine duct and causes the rotor rpm to peak as well. At 1.11s wave period both the conversion factor and rpm are at their lowest values. The importance of efficient primary conversion is once again highlighted from this result. Both the primary conversion factor and rpm are sensitive to wave period. Figure 9 shows an inverted relation of primary conversion and rotor rpm with wave height. This is due to the fact that as the period increases, the wave height reduces. Once again the conversion factor and rotor rpm follow similar trends.

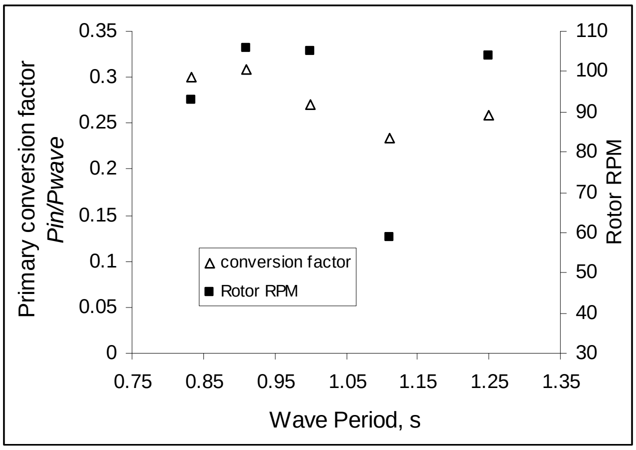

Figure 8 Primary conversion of the OWC chamber and Rotor rpm at different wave periods (depth = 260mm).

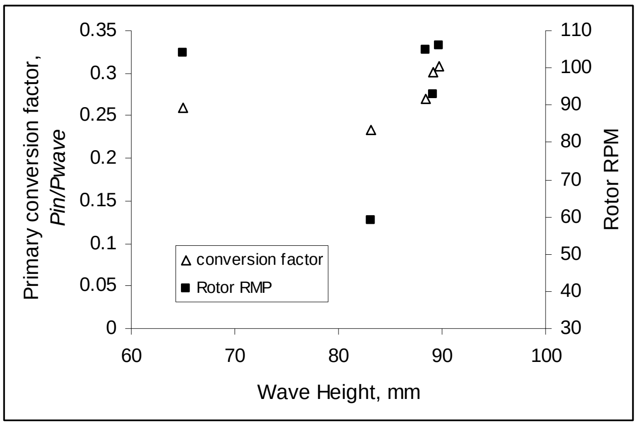

Figure 9 Primary conversion of the OWC chamber and Rotor rpm at different wave heights (depth = 260mm).

In order to observe the effects on the rotor with changing water depth, the rotor was also tested at two other depths. The results of rotor rpm at the three depths show a similar trend (Figure 10). For 260 and 230mm depths maximum rotor rpm is reached at 0.8 Hz and the rpm varies between 90 and 67 for other frequencies. A similar trend is shown for the 290mm depth but with a slight shift in the x axis. Maximum RPM occurs at 0.85Hz for the 290mm depth. The rotor rpm is more affected by the period of the waves than water depth. It appears that as the depth increased the optimum frequency shifted up as well. Higher periods are needed to maintain rpm as the depth changes. The wave period is inversely related to the wavemaker frequency and as seen in Figure 10, the higher frequency waves (lower periods) are less sensitive to changes in water depth.

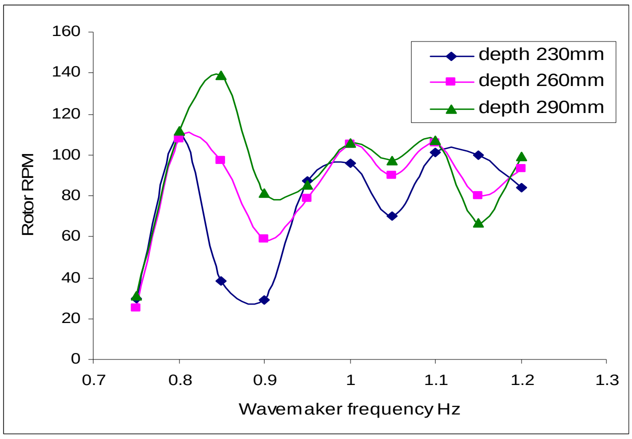

Figure 10 Rotor RPM at different depths.

Rotor RPM varies slightly for different depths with a mild increase at depth of 290mm. For 0.85Hz and 0.9Hz a strong increase in rotor RPM is seen as the depth increases (Figure 6). This result is important and emphasizes the need for the device to accept a wide range of wave conditions with small changes in rotor RPM. Apart from these two frequencies the RPM variation is small across the depths. Apart from lower frequencies of 0.8Hz and 0.85Hz, rotor rpm varies only slightly with depth (Figure 11).

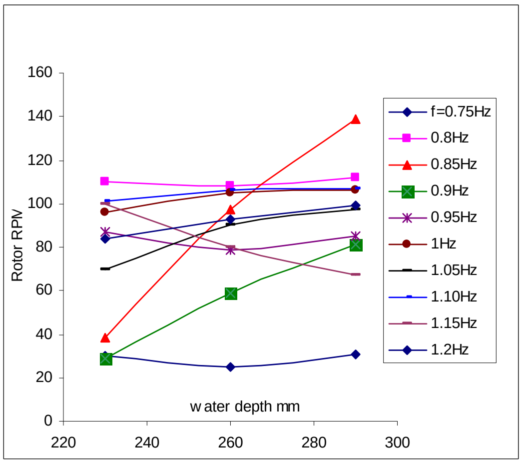

Figure 11 Trends of the rotor RPM at the three different depths

Optimum rotor performance is achieved at a frequency of 0.8Hz due to its consistent high rpm for all depths. On a scale of 1:100 this would correspond to an actual wave period of around 12.5s and a wave height of 6.5m for the 0.8Hz condition. Future work will involve actual power and efficiency calculations of the rotor through torque measurements.

4 Conclusions

A unique design of an OWC is proposed, constructed and tested with a Savonius rotor. The rotor was able to extract energy from the oscillating air movement in the turbine section. Optimum performance was attained at a frequency of 0.8Hz. While depth and wave height will have some effect, the period of the waves plays a more important role in rotor performance. The primary conversion factor is directly related to the rotor performance. The design holds promise since it can make use of a simpler turbine that can be easily constructed without the use of specialized tools. The inclined capture chamber also improves primary conversion efficiency by reducing reflections in the chamber.

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