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Effect of turbine section orientation on the performance characteristics of an oscillating water column device

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ABSTRACT

Oscillating water column (OWC) devices are the most successful devices for extracting energy from ocean waves. In oscillating water column devices, the air turbine section is of either horizontal or vertical orientation. An experimental study is carried out to compare the airflow characteristics and turbine rpm in horizontal and vertical turbine sections of an oscillating water column device. Two OWC models, one with a horizontal duct connecting the turbine to the atmosphere and the other with a vertical duct, were tested at mean water depths of 230 mm, 260 mm and 290 mm and at frequencies of 0.6 Hz, 0.7 Hz, 0.8 Hz, 0.9 Hz, 1.0 Hz and 1.1 Hz. Mean total pressure profiles were plotted just upstream and downstream of the turbine section for different cases, while instantaneous static and dynamic pressure measurements were performed to study their variations with time at these locations. A Savonius type rotor was used as a turbine and its rpm was measured and at the above depths and frequencies to compare the performance of the two OWC models. The OWC model with the horizontal turbine section showed better performance characteristics compared to the OWC with the vertical turbine section. RPM values were 20–30% greater in the horizontal turbine orientation compared to the vertical one. The successful use of a Savonius type rotor as a good and cost-effective option for energy conversion is emphasized in this work.

1. Introduction

Increasing global energy consumption is now well-known to have serious environmental implications and recent years have seen a drive to produce energy from renewable sources. A promising source of renewable energy is from the ocean waves and interest in developing machines to convert energy from waves is steadily increasing. Wave energy is generally considered to provide a clean source of renewable energy, with limited environmental impacts which could contribute significantly to the reduction of greenhouse gases produced by conventional fossil fuels [1]. The magnitude of the incident wave energy, along 30,000 km of Pacific Ocean coasts, has been estimated to be around 1013 kWh per year. This value approximates to the world electric energy consumption registered in the year 2000 [2]. Not only is the wave energy resource vast, it is also more dependable than most renewable energy resources [3,4]. In order to exploit the benefits of such a renewable energy source, a wide variety of devices, based on different energy-extracting methods, have been proposed [4] but only a few are actually installed [5,6]. The greatest challenges to designers of wave energy converters are the intrinsically oscillating nature and the random distribution of the wave energy resource [7]. The response of a wave energy device is generally frequency dependent. The peak (resonant) frequency and a range of frequencies that will produce a significant response will depend on the particular device [1]. The most successful and most extensively studied device for extracting energy from the ocean waves is the oscillating water column (OWC) device [8]. There are a number of companies that have commercialized this technology following pilot installations around the globe including Portugal, Scotland, Japan and Australia. The OWC wave energy converter (WEC) comprises a partly submerged structure open below the water surface, inside which air is trapped above the free water surface [9]. Approaching waves force the internal free surface of the water to oscillate; this causes an oscillation of the pressure of the air in the chamber and forces an air flux forwards and backwards through an air turbine, installed in a duct which connects the chamber to the atmosphere [8].

Oscillating water column (OWC) devices are divided into two main categories; fixed-type OWC and the floating-type OWC devices. In OWCs, the air turbine is either vertical (Toftstalen, Norway, 1985; Trivandrum, India, 1990) or of horizontal axis (Pico, Portugal, 1999; Limpet, UK, 2000; Port Kembla, Australia, 2005) [9]. The bi-directional airflow is unique to this device and requires the use of a bi-directional turbine. There are several such turbines

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including Wells turbine, impulse turbines and Savonius type turbines. The Wells turbine was the first choice for all the OWC based wave energy plants which were built in Norway, Japan, Scotland, India and China. A Wells turbine is a self-rectifying air turbine which rotates in a single direction and extracts mechanical shaft power from such bi-directional air flow as in case of an OWC device [10]. There are many reports which describe the performance of the Wells turbine both at starting and running conditions. According to these results, however, the Wells turbine has inherent disadvantages in comparison with conventional turbines: lower efficiency and poorer starting characteristic [11]. The efficiency of OWC devices equipped with Wells turbines is particularly affected by the flow oscillations basically for two reasons: first, because of the intrinsically unsteady (reciprocating) flow of air displaced by the oscillating water free surface; second, because increasing the air flow rate above a limit 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 this turbine [12].

Of late, there is a growing interest in rectangular OWC chambers and rectangular turbine sections housing Savonius rotors [13,14]. A design of a Savonius rotor utilizing OWC is presented by Dorrell et al. [13–15]. They compared multiple chamber arrangements and reported conversion rates of 20.2% for the two bladed Savonius turbine. The advantage lies in the simplicity of design and the ease of construction of these types of turbines as well as the OWC. It also allows increasing of 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 [16]. The Savonius turbine is a much effective solution at low Reynolds numbers, unlike the Wells turbine which requires a high Reynolds number [13].

Menet [17] remarked that Savonius rotors are simple machines and their high starting torque enables them not only to run, but also to start at whatever the air velocity. The components which convert the mechanical energy into electrical energy can be placed at the surface which makes maintenance operations simple. 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 rotor along with its other advantages makes it a competitive option for power take-off. This is a simple and low-cost turbine although the conversion factor is low [18]. 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 [19] proposed the idea of a curtain placed in front of a Savonius wind rotor to increase its aerodynamic 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 on the Savonius rotor. The contracting curtains need to be placed on both sides of the turbine due to the bi-directional flow. A novel way of incorporating the curtain effect into the chamber of the OWC is employed in the present work.

The design presented in the present work uses a capture chamber structure that can be incorporated into a breakwater to reduce structural costs. The Savonius rotor is simpler and cheaper [17] 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 characteristics and Savonius rotor rpm in two OWC devices with vertical and horizontal turbine sections.

2. Experimental method

The experiments were carried out in a Cussons wave channel, model P6325, available in the Thermo-fluids Laboratory of the University of the South Pacific. The wave channel is 3500 mm long, 300 mm wide and 450 mm deep. The side walls are made of Plexiglas to allow a clear view of the wave action. This wave channel uses a flap type wave-maker hinged at the bottom to generate sinusoidal waves. The close fit of the wave-maker to the channel sides ensures that 2-D waves are produced with no fluid motion normal to the sidewalls [20]. The water flow is generated by a centrifugal pump having a rated capacity of 40 Lit/s at a total head of 10 m and is driven by a 5.5 kW motor. The pump draws water from a tank, as shown in Fig. 1. Different sea conditions (wave height, wave length, etc.) can be simulated in the wave channel by changing the frequency of the wave-maker. Some of the wave characteristics are presented in Ref. [21]. Fig. 1 shows a schematic diagram of the wave channel.

A Cussons Tuneable Beach, model P6285, was placed at the other end of the wave channel. The tuneable beach uses a series of porous plates (large holes to small size holes) mounted in the path of the waves. Each porous plate is designed with a pattern of holes to absorb some wave energy, allow the rest to pass through the plate, and minimize reflection. The use of different plates with a variable spacing between them allowed a wide variety of wave profiles to be absorbed.

Two OWC models were built out of clear Perspex, one with a horizontal turbine section and the other with a vertical turbine section. Fig. 2 shows the OWC model with the horizontal turbine section and Fig. 3 shows the OWC model with vertical turbine section. The models were built 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 [22]. An acceptable range of Froude scaling is 60–150 (in Ref. [22]). Both the models have the same dimensions for the capture chamber and the turbine section including the inlet and the outlet of the turbine section. The diffusers at the exit of the turbine section, which serve as nozzles when the airflow is from the atmosphere, also have exactly the same dimensions. The rear wall of the OWC models is inclined at 65° to reduce wave reflections. The angle was determined after a comparison of different capture chamber angles. Since majority of the water particles in shallow water have horizontal trajectories the inclination aids in aligning the near horizontal velocities to the capture chamber to avoid reflection. The detailed methodology and results of identifying the optimum angle is presented in [23].

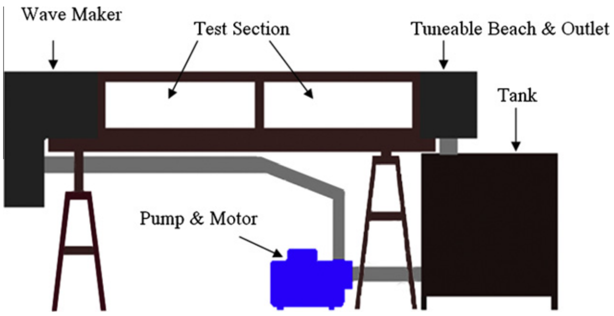

Fig. 1. Schematic diagram of the wave channel.