# REVIEW OF WAVE ENERGY RESOURCE AND OSCILLATING WATER COLUMN MODELLING

D. G Dorrell, J. R. Halliday, P. Miller and M. Findlater
University of Glasgow, Glasgow, G12 8LT, UK

## ABSTRACT

Wave energy as a means of generating electricity has been the focus of study in the UK for over thirty years, albeit in a low key manner and with little public support. Interest is now growing. This paper is divided into two sections: it briefly reviews the developments during this time period to put the work into context and then describes a small oscillating water column system constructed within The University of Glasgow to aid understanding and to initiate a research program.

**Keywords:** Renewable energy, wave generation, oscillating water column

## INTRODUCTION

With the drive to use more renewable energy sources for electric power generation more types of renewable energy sources are being investigated. Wind power is already reaching maturity for on-shore generating plants. Scotland also benefits from high sea waves since it is located on the Western border of the north Atlantic. Few countries have this level of wave energy on its shores (South America and Australia being two locations). The potential for wave generation is illustrated in Table 1. If the target wave/electrical energy conversion efficiency for a well-designed wave generator is 25 % then about 1000 km of wave generators could supply up to half of the current UK electricity requirement. The challenge now is to be able to produce such wave energy converters and harness the potential.

Wave energy generation has been the subject of research and study in the UK for over thirty years since Prof. S. Salter of The University of Edinburgh began a quest to find a reliable method to extract energy from the waves. Thirty years on, wave energy is on the brink of breaking into the main stream; with several test and demonstration installations either built or in the advanced stages of design. However, over this time the work has often been low key with little public support in terms of funding. This paper will briefly review some of the progress of this work in the UK and Europe. Since it is relatively new technology, and has not reached the level of maturity that on-shore wind power has, most of the electro-mechanical wave energy converters are still little more than first generation prototypes, with no system emerging as the obvious method for energy conversion. The opening of the EMEC test centre in Orkney for the testing of commercial wave energy conversion devices is seen as the latest step that will greatly aid the commercialisation of wave energy production.

**TABLE 1 Wave power values**

| | |
|---|---|
| Mean wave energy around the British Isles | 30-90kW/m |
| Annual average in North Atlantic | 50kW/m |
| Annual average around Japan | 15kW/m |

## ENERGY SOURCE IN WAVES

Waves are in fact a very concentrated form of solar energy. The heat from the sun warms the earth at different rates causing air to flow from area to area depending on temperature differentials. The winds interact with the uppermost layers of the oceans; as the wind blows tangentially to the ocean surface it causes the particles to rotate in a circular motion. Over a large enough area this rotation penetrates deeper into the surface creating larger waves. The rotating motion of the water particles is stored kinetic energy and the gradual phase shift in time and space over a length perpendicular to the wave front sets up the moving wave pattern, which is essentially progressing waves of potential energy. In some ways this is comparable to real and reactive power in an electrical power system with the reactive power being analogous to the stored kinetic energy (necessary to set up the wave motion) and the real power being the movement of the wave crests, which is the flow of potential energy. However it is not a totally analogous system, for instance, an electrical power system rarely spans even one wavelength, whereas a sea wave will travel thousands of wavelengths from source to termination.

The most basic information about a wave is its height (trough to crest). The distance between successive crests is the wavelength and the time it takes between the crests is the wave period and is typically 8 seconds in the North Atlantic. The term *Significant Wave Height* is used at times to describe the one-third highest waves. The *Fetch* is used to describe the uninterrupted distance over which the wind that is creating the waves has blown. In most cases the further the fetch the bigger the waves will be. The power in a wave is roughly proportional to the square of the height. The power is defined in terms of Watts per metre of wave front.

Some devices work on the principle of pressure changes as a wave passes over them. If a device is resting on the sea bed and the sea is calm then a constant pressure will be experienced relative to the depth of water in which the device is sitting. If a wave of height 10m passes over the device then during the trough of the wave the pressure will decrease, as the crest passes the pressure will increase as more water is pushing down on the device.

There are four motions that an object will make whilst left to move freely in the ocean. *Pitching* describes a rocking back and forth movement; *Rolling* is the same rocking motion but from side to side; *Heave* is the up and down bobbing motion that an object will make; and *Surge* is used to describe the movement made by objects parallel to the oceans surface.

## POSSIBLE RESOURCES

The resources available around the globe and in particular to the UK are impressive in size. Falnes [1] made an estimate of worldwide resources of 1TW of onshore energy and 10TW of offshore potential. Many possible sites exist in the world with the main criterion being that they have a shoreline facing onto a prevailing wind that has been blowing over a considerable stretch of ocean. Much of the western coasts of Europe, South Africa, Australia, New Zealand, America and Chile all have high potential resources that are in excess of 40 kW/m. Interest is also high in Pacific Island communities, where the import of fuel oil is running at 500% of the islands total exports.

Recent studies [2] claim to show that the Atlantic resources are in the region of 290 GW. This is the area from the Iberian Peninsula to the Northern-most reaches of Norway. The power in these areas range from 25kW/m in the Canary Islands to a maximum of 75kW/m off the Irish and Scottish coasts; before decreasing to 30kW/m around the Arctic circle in Norwegian waters. Also included in this figure are the resources available in the North Sea, which range from 21kW/m in the best sites to 11.5kW/m in more sheltered areas. Although a smaller resource, the Mediterranean sea can add another 30GW of potential to this figure taking the total European resources to 320GW.

This resource is potentially vast but it is spread over the entire coastline. Many areas will be unreachable and so realistic resources are smaller. The UK share of this total is roughly 50TWh per annum [3] after considerations of efficiency and transmission losses have been taken into consideration. Scotland's potential landable resource could be 14GW [4], enough excess to supply some of the 80GW used in the UK as a whole.

In a recent estimate, the worldwide potential for recoverable energy was some 2000TW/h per annum, this would be equivalent to the current world installed capacity for hydro generation [5] and would represent 10% of world consumption at this time. Remember that only a small amount of the raw ocean wave energy can be practicably extracted. The cost of building this infrastructure would be around £500 billion (Euro 700 billion). The technology at this present moment is capable of delivering this energy at a cost of 5 p/kWh (7 Euro cent/kWh) which is twice the European average, but, as has been discussed in length in various papers and reports, this figure is based on developing technology and is estimated to be falling with every new generation of device.

## BASIC DESIGN TYPES

The wave industry is still debating the best design for sea wave energy extraction and in a recent count there were over 1000 patented ideas for wave energy conversion. They were broken down into five basic technology groups by Thorpe [6].

- Oscillating Water Column (OWC)
- Overtopping device
- Point Absorbers (floating or mounted on the sea bed)
- Surging devices
- Mechanical Extraction

The best design will depend upon the situation in which it is to be utilised. A more detailed description of the different types can be found in [8].

### Oscillating Water Column

One of the most studied devices is the Oscillating Water Column (OWC). As described in Thorpe [7], an OWC consists of a chamber for the oscillating water column, turbine (unidirectional of bidirectional) and generator. The basic topology is shown in Fig 1. There are several of these devices around the world – the first commercial wave generator in the UK is of this type and located on Islay. They are relatively simple to construct on land.

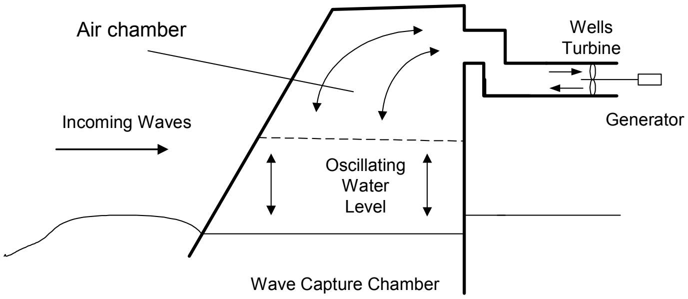

**Figure 1 Operation of Wells Turbine Showing Wave Capture Chamber and Bi-Directional Air Flow Through Turbine**

### The Overtopping Device

The first plant to develop electricity on a grid connection was a device of this type and it owes much of its design to the hydro-electric industry. In order to create electricity a reservoir needs to be situated a certain height above a turbine. This height is called the head. The higher the head the more potential energy the water will have and be able to turn the turbine faster. The concept of a raised reservoir is used in several device designs. Essentially the waves are forced into this reservoir by a variety of techniques where it will then fall through a small outlet to turn a Kaplan turbine.

### The Point Absorber

The classical example of a point absorber is a buoy. This is a device that is smaller in dimension than the wavelength of the waves it wishes to capture. The majority of these devices are based on systems involving a buoy or a float that moves in a heave, or bobbing, motion. This motion is used in reference to a fixed point, commonly the mooring point, on the seabed. This motion is then used to pump sea water or oil to drive a turbine or to directly engage with the power take-off.

### Surge Devices

These utilise the horizontal forces of the waves. Generally the surging motion of a device is twice that of the heaving motion.

### Mechanical Devices

This is a category that Thorpe did not have but is included as a catch-all situation for the various mechanical devices that cannot be comfortably placed in one of the above categories. In particular Salter's Ducks and Cockerell's Raft are two of the members of this category and more recently the Pelamis (Ocean Power Delivery Ltd, UK) [4]. The Pelamis (or “sea snake”) is a tubular device of several sections (with similar dimensions to railway carriages) that is placed perpendicular to the wave fronts. Hydraulic pumps at the hinges resist the movement between successive sections and so produce energy. An array of these (placed off-shore in a similar manner to a line of breakwaters on a beach) can be used as a wave energy plant. This device looks very promising and has now entered sea trials.

## DESIGN FOR SURVIVABILITY

The greatest problem being faced by the designers of wave energy converters (WEC) is how to balance capture efficiency, cost of construction and the survivability of the design. Many designs that look favourable on paper and have high capture efficiency would, if constructed, be destroyed by the largest storm waves. Although the west coast of Scotland has an average of 60-80 kW/m of wave front, under severe storm conditions this can rise to upwards of 10,000 kW/m. The parameter used by the designers of offshore structures in the oil industry is the 50-year design wave, i.e., the largest expected wave in a 50-year period; for the west coast of Scotland this is thought to be in the order of 30-40 m.

Many problems surround the cabling required to transport the energy to shore and in turn how to transmit this energy to the customer. The cables have to be long and able to withstand the forces at their termination points at the device farms. A big problem faced by designers is scaling up models from tank testing at ¼ , 1/10, 1/25 scale models to full size. In many cases a doubling of scale can mean squaring of forces and with them new problems to solve. A further difficulty is that with wave energy you do not design to reach maximum conversion. A device that reaches 100% conversion at a definite wave period and height, will invariably have a bad capture efficiency at other levels. What is required is a design that will cover the largest catchment area, where the most power is available for the most time during the year, thus allowing the device to generate for most of its lifetime.

## OSCILLATING WATER COLUMN OPERATION

The oscillation water column type of wave energy is currently in commercial operation in the Isle of Islay [9] and this still represents the sole commercial wave energy plant. It is rated at 250 kW and is a shoreline device. This device can also be located on floating platforms as was the case with the “Mighty Whale” [10]. As water oscillates inside the chamber then there is a pressure difference due to the difference with the external water level. This will cause air to be blown and sucked through the turbine.

The turbine can be a standard type with valves to ensure that the airflow through the turbine is unidirectional, or it can be a more straightforward arrangement with a through-pipe and a bidirectional turbine (i.e. a turbine that produces torque in the same direction with airflow in either direction). Examples of the bidirectional turbines are the Wells turbine [11] and impulse turbine [12]. Both the Islay plant and the Mighty Whale use Wells turbines. These turbines require a high Reynolds number for correct operation which means a diameter over 600 mm for reasonable conversion factors. In the study reported in the following sections the diameter of the turbines is only 132 mm so that their performance is very poor. This is illustrated using computational fluid dynamics in [13]. However it represents an interesting study in scaled-down devices. In this paper we will report on some experimental results from the oscillation water column performance and a simple Simulink model that approximated the performance.

### Experimental Equipment

The dimensions of the water column are shown in Fig 2 and the water column could operate with either all three sections or with simply the centre section. Because the torque produced by the turbine was very low, a dc motor was fitted and connected to a supply – this is shown in Fig 3. A wave tank that could produce waves up to 250 mm and down to a frequency of 0.45 Hz use was used in the test (this facility was available within the University of Glasgow) and Fig 4 illustrates work during the testing stage.

The turbine was run up to speed and the input power measured. Waves were then produced and the power measured again so that the power difference represented the power generated. Care was taken to ensure that temperature variation of the motor did not affect the results. However, because the power differences were small, there was still considerable experimental error. The conversion factor for the turbine was of the order of less than 1 % in some instances.

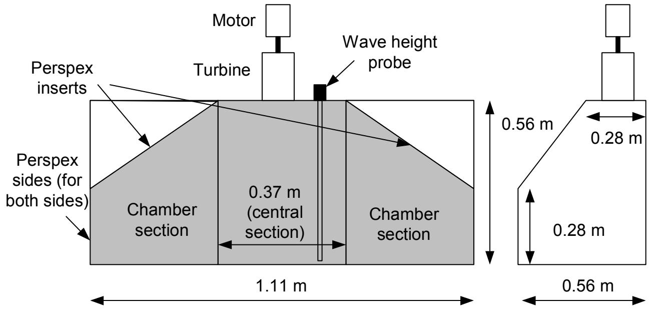

**Figure 2 Oscillating water column dimensions**

### Variation of Turbine Speed

To find the most suitable speed to operate the turbine, the wave frequency was fixed at 0.56 Hz and the speed varied.

The results are shown in Fig 5 and these were obtained using only the centre section of the water column chamber and a wave height of 200 mm. They are compared to the calculated generated output power difference for a second turbine rotor that has been manufactured but so far only simulated using CFD [13]. The two rotor profiles can be compared in Figs 6 and 7. It can be seen that 1200 to 1500 rpm is the peak speed for the first turbine rotor whereas 1000 to 1250 rpm is calculated as the most suitable for the second turbine rotor. The power difference represents the difference at the turbine shaft in power if the turbine is rotating at that particular speed when there are waves and when there are no waves.

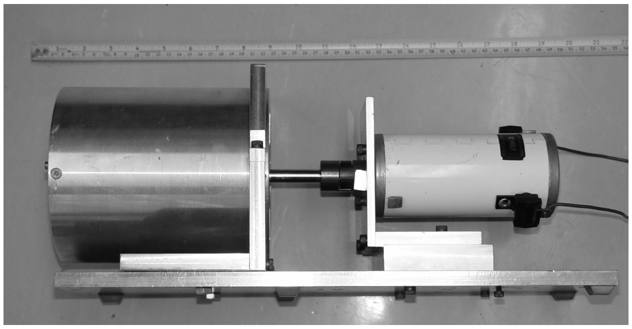

**Figure 3 Wells turbine with large low-voltage DC machine**

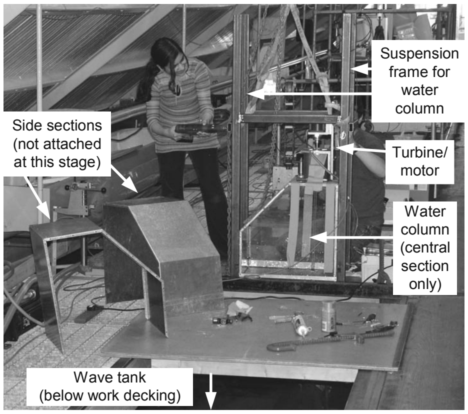

**Figure 4 System assembly showing use of central section only**

It was found that the output power for the first turbine was consistently higher than that calculated – it is assumed that the output power for the turbine simulations is so low that there is variation due to numerical error. However, consistent overestimation may be due to small variation in the shape of the blade between the simulated and manufactured, which would affect the power significantly at these low power values. The actual oscillating water column and turbine arrangement will also produce more turbulence than simply modelling the turbine alone with constant inlet airflow velocity which could also produce higher output power.

### Variation of Wave Frequency

With the turbine speed fixed at 1500 rpm and a wave height of 200 mm, the wave frequency was varied and the results shown in Fig 8. These results were obtained with all three sections of the water column and at a different column height in the water from Fig 8. This illustrates that the most suitable frequency for the first turbine is 0.56 Hz. The wave tank could produce waves at 200 mm wave height down to 0.45 Hz (and higher wave heights at higher frequencies).

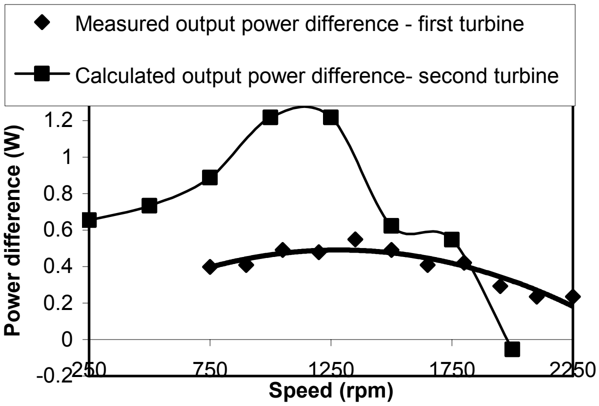

**Figure 5 Variation of output power difference for first turbine rotor (measured) and second turbine rotor (simulated using CFD)**

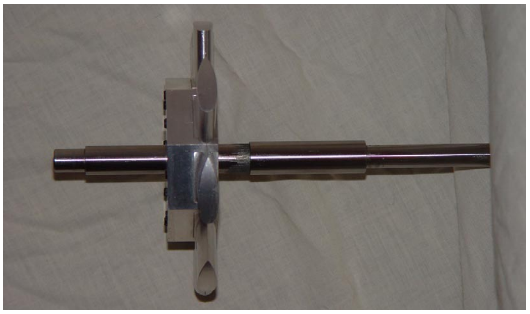

**Figure 6 First fabricated turbine rotor (tested)**

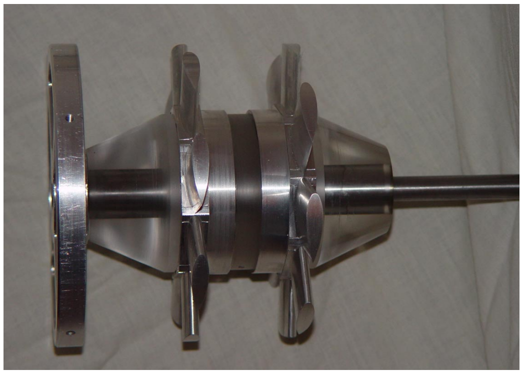

**Figure 7 Second fabricated turbine rotor (simulated) - including one bearing mounting on left hand side**

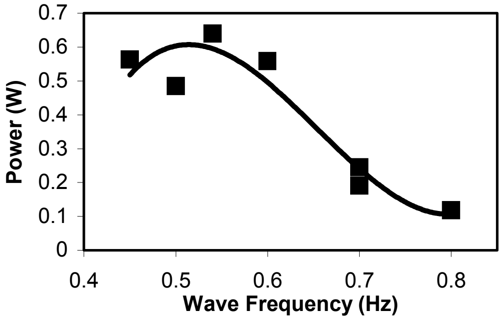

**Figure 8 Variation of wave frequency at 1500 rpm**

### Modelling of Water Column

The complete system is a complex non-linear device. However, as an attempt to model the system in simple terms the SIMULINK system in Fig 9 was developed. The first turbine simulation look-up tables can be used for the transfer functions for the inlet pressure to airflow and also the pressure to output power. While the flow to pressure can be represented as a simple transfer function,

$$\text{Inlet Pressure} = 1.747 \times \text{flow}^3 + 39.71 \times \text{flow} \qquad (1)$$

inversion of this leads to a function with many terms – hence the use of look-up tables. The equations of the system are given below. The waves are assumed to be sinusoidal so that the driving function is:

$$h_s(t) = \frac{H_s}{2}\cos\left(2\pi f_s\right) \qquad (2)$$

If we assume that the air density in the water column chamber is constant (which is probably one of the main sources of error in this model – at sea level, a change in pressure of ± 3 kPa produces a change of ± 2.4 % in air density – which will introduce a larger change in water height for a given change in column pressure and will change as air flows out through the turbine, introducing a phase lag) and, if $h_c(t)$ is the height of the water in the column and $\rho_w$ is the density of water (998 kgm$^{-3}$ for fresh water, 1025 kgm$^{-3}$ for sea water), the inlet pressure is

$$\text{Inlet Pressure} = \rho_w\left(h_s(t) - h_c(t)\right) \qquad (3)$$

If $A_T$ is the cross section of the turbine inlet and $A_W$ is the cross section of the water surface in the column then the rate of change of height of the water column (again using the assumption of incompressible air in the column) is

$$\frac{\mathrm{d}h_c}{\mathrm{d}t} = \frac{A_T}{A_W} \times \text{flow} \qquad (4)$$

An adjustment factor was also included since the system is very approximate. However, maintaining the adjustment factor to unity, then the column height at a wave height of 201 mm was measured at 92.5 mm and simulated to be 68 mm when the centre section only was used ($A_T/A_W = 0.044$). When the full column was used ($A_T/A_W = 0.0147$) with a wave height of 221 mm then the wave height was measured at 77.6 mm and simulated to be 23.6 mm. Increasing the adjustment factor to 2 produces the correct oscillation for the centre section simulation however the full column still produces an underestimate (33.6 mm water height). The output power was underestimated however it has already been mentioned that the simulated power was low compared to that measured. Further work will be undertaken on the modelling of the water column.

## CONCLUSIONS

The paper has reviewed some of the different types of sea wave energy converters that have been studied. The different types are listed and consist of devices that can be shoreline or off-shore. Many of these devices are still in the process of development. The oscillating water column type is still the only type that has gone into commercial operation in the UK and this is more extensively described.

A small-scale model of an oscillating water column system that has been built and tested in the University of Glasgow and some of the work on this is put forward here in terms of the water column operation.

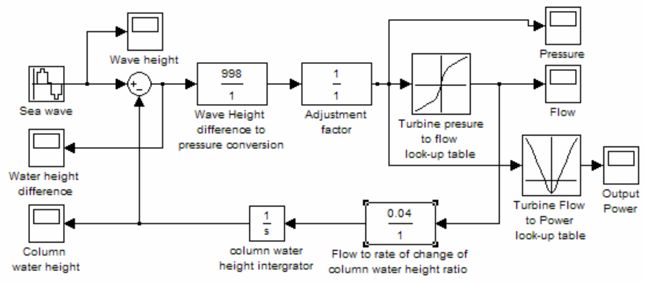

**Figure 9 Control strategy for oscillating water column**

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