A review of oscillating water columns

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This paper considers the history of oscillating water column (OWC) systems from whistling buoys to grid-connected power generation systems. The power conversion from the wave resource through to electricity via pneumatic and shaft power is discussed in general terms and with specific reference to Voith Hydro Wavegen’s land installed marine energy transformer (LIMPET) plant on the Scottish island of Islay and OWC breakwater systems. A report on the progress of other OWC systems and power take-off units under commercial development is given, and the particular challenges faced by OWC developers reviewed.

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1. What is an oscillating water column?

The oscillating water column (OWC) concept is probably unique among the myriad systems proposed for extracting power from ocean waves in that it is the only technology where a key part of the system can be seen as a naturally occurring structure. An OWC comprises two key elements: a collector chamber, which takes power from the waves and transfers it to the air within the chamber, and a power take off (PTO) system, which converts the pneumatic power into electricity or some other usable form. The pressure in the collector is alternately pressurized as the water column rises and rarefied as the water column falls (figure 1). OWC collectors occur naturally in the form of blow holes. These are common in limestone cliffs, but unfortunately are not usually of an ideal geometry for commercial use (figure 2).

The PTO is typically an air turbine (although water pumps have been considered as an alternative) and, for simplicity, the air turbine normally selected is of a self-rectifying form so that whether the collector is exhaling or inhaling, the turbine is driven in the same direction. The most commonly used form of PTO in this application is the Wells turbine/induction generator combination, and the leading exponent of this technology is Voith Hydro Wavegen, which have well over 60,000 grid-connected operating hours from their land installed marine energy transformer (LIMPET) OWC plant on the Scottish island of Islay. Other forms of self-rectifying turbines, most notably the impulse machines of Dresser-Rand

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One contribution of 18 to a Theo Murphy Meeting Issue ‘The peaks and troughs of wave energy: the dreams and the reality’.
2. The attraction of oscillating water columns

The attraction of the OWC concept with an air turbine stems from its simplicity. On a practical level:

— there are very few moving parts;
— there are no moving parts in the water;

and Oceanlinx, are also under development. The manufacturers claim that these machines offer a higher conversion efficiency than a Wells turbine, but there is no publically available information to demonstrate in real sea conditions and with an appropriate control strategy that the newer designs can match either the performance or the reliability of the turbines in 10 years continuous operation at LIMPET.
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— the concept is adaptable and can be used on a range of collector forms situated on the coastline, in the nearshore region or floating offshore;
— the use of an air turbine eliminates the need for gearboxes;
— it is reliable;
— it is easy to maintain; and
— it uses sea space efficiently.

The ability to apply the OWC concept in different locations and on different collector platforms is important in that it allows for a gradual development of the technology. Voith Hydro Wavegen’s shoreline LIMPET plant on Islay allows for the development of the PTO unit under real conditions in an accessible location. The simultaneous development for deep water application of floating units, moorings, umbilicals and PTO systems can be beyond the resources of technology development companies. By building the LIMPET unit and then focusing on the PTO system, Voith Hydro Wavegen is now able to demonstrate availabilities in excess of 95 per cent and have a PTO suitable for application on OWCs in any location.

3. History

The earliest recorded application of an OWC is the whistling buoy used as a navigation aid. As an audible warning device, it was seen in the nineteenth century as a successor to the traditional bell buoys. J. M. Courtney of New York patented such a whistling buoy (figure 3) and in 1885, it was reported in Scientific American that there were 34 operating along the coast of the USA.

It was over half a century before the next significant development in wave power, and again this occurred in the field of navigation buoys in 1947 when Masuda, in Japan, designed and installed the first OWC driving an impulse turbine to produce electricity. The unit was sited in Osaka Bay and the electricity generated powered navigation lights. Security of operation was provided by rechargeable batteries that took their power from the turbine/generator in times of plenty. A commercial range of buoys was developed from this original and are available today from the Ryokuseiisha company of Japan. While the output of each unit is small at 70–500 W, this application still represents the most common application of a wave energy plant. Figure 4 shows the Uraga light buoy fitted with four wave-activated turbine generators.

Between 1976 and 1979, a team operating under the auspices of the International Energy Agency tested the OWC units mounted on a floating barge, the Kaimei. The 800 tonne 80m long barge was moored off the coast of Yura, Tsuruoka City, Yamagata Prefecture. With Japan as the lead national partner, there were contributions from the UK, Canada, Ireland and the USA. Eight OWC chambers were mounted in the barge, each with a nominal 125kW rating. A range of PTO units were tested, including the self-rectifying Wells and McCormick turbines and more conventional turbine systems using rectification valves.

During the 1980s and 1990s, a number of shoreline and shore-connected OWCs were built and tested, including a number in Japan, India, China, Norway, Portugal and Britain. The largest of those built in Japan was the port of Sakata. The five chambered OWC was built as part of a harbour wall. It is a concrete

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caisson structure that was floated into position before being sunk and filled with ballast. The machine, which became operational in 1989, is fitted with a tandem Wells turbine. The original rating of the plant was 60 kW. A single turbine 75 kW unit was built by Queen’s University Belfast on Islay (figure 5).

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This grid-connected plant was operated between 1991 and 2000 before being decommissioned and the site returned to nature. The turbine from this plant was recently restored and is now on display at the Deutsches Museum in Munich.

As a follow-on to the Islay prototype, the team at Queen’s designed the LIMPET plant for construction near to the original plant. Whereas the prototype was in a relatively sheltered gully, the LIMPET plant (originally rated at 500 kW) was facing south westerly towards the teeth of the Atlantic gales. This plant has been in operation since late 2000. The original turbine system has been replaced; the plant is now used as a continuous test bed for the turbine designs to be used in Voith Hydro Wavegen’s commercial projects with over 60 000 turbine running hours logged to date (figures 6–8).

There is little published information on the performance of air-turbine-based PTO systems for OWC collectors, and it is important to note that success of the system will depend on a good turbine design, an effective control strategy and the matching of the turbine to the OWC collector to ensure efficient collector operation. It is interesting to note that the size of a turbine will often be determined by the requirement for collector matching rather than the ability of the machine to absorb the power from the collector. An example of the energy conversion efficiency of the 1.25 m diameter Wavegen turbine shown in figure 8 and measured in irregular seas at LIMPET is shown in figure 9. The pneumatic
power flow was measured as the product of chamber pressure and flow through the turbine, while the electrical power was recorded at the input to the generator frequency converter.

Each point on this chart represents a 5 min average of the pneumatic power flowing through the turbine and electrical power delivered to the frequency converter. The dataset represents over 400 h of operation. The marginal efficiency of conversion in low to moderate seas is 60 percent. A programme of improvements is in process to further improve this performance.

The conversion efficiencies shown in figure 9 represent a very significant improvement on previously published data for Wells turbines, and are the product of cooperative development between Voith Hydro Wavegen and the universities of Stuttgart and Siegen in Germany, together with control systems development at Wavegen. The turbine blades and the associated fixed stators are the product of a self-optimizing design analysis developed by the university teams followed by computational fluid dynamics and laboratory testing [1–3]. The efficacy of this work is borne out by the field measurements.

The efficiency of the turbine will be influenced by the regularity of the incident waves. The incident resource at LIMPET is not measured directly, but the ratio of the peak chamber pressure to the r.m.s. over a 15 min spectrum is typically in
the range of 5–6. Waves in the LIMPET gully are significantly influenced by the shallow water at the LIMPET site (4–6 m dependent on tidal height).

At the same time as the LIMPET development, a 400 kW OWC was built by Electricidade dos Açores on the island of Pico. This plant is now operated intermittently by the Wave Energy Centre and provides important data for ongoing OWC development.

While Voith Hydro Wavegen has focused on proving PTO performance and reliability prior to deployment in ever more challenging locations, other developers in the OWC field have adopted different development strategies. In conjunction with the University of Cranfield, Dresser-Rand has developed a ‘variable radius’ turbine for use and has tested the unit in an alternating flow.

In Ireland, Ocean Energy has developed the backward bent ducted buoy concept originally proposed by Masuda, and the hull has over 20 000 h of live sea trials at the quarter scale. Figures 10 and 11 show the unit at the wave energy test site at Spiddal in Galway in Ireland. There it was subjected to a wide range of wave conditions, including a severe storm when wind speeds reached 25–30 m s$^{-1}$ and a wave height of 8.2 m was recorded. For some of the test period, a Wells turbine system developed in Ireland for Ocean Energy was fitted to the buoy. During the testing, the airflows and power output from the tests scaled up predictably, and the hull behaviour was also consistent and reliable.

An alternative design of floating OWC has been developed by Oceanlinx. Their most recent OWC deployment involved its MK3 floating device. The unit (figure 12) is a one-third scale demonstration version of the 2.5 MW full-scale device. It was installed offshore from the eastern breakwater of Port Kembla Harbour from February to May 2010. The unit was grid connected, and supplied electrical power directly into the grid of local retailer, Integral Energy.

Returning to the nearshore, Voith Hydro Wavegen is partnering utilities in two pivotal projects; pivotal because they both represent significant steps in taking wave power systems from single test units towards full-scale commerciality.

The first of these is at Mutriku in the País Vasco of northern Spain, where the energy authority Ente Vasco Energia (EVE) is developing an OWC breakwater using Voith Hydro Wavegen PTO technology. The project, which has been delayed for 2 years as a consequence of planning delays and civil engineering
Figure 10. Ocean Energy buoy in storm. Reproduced with permission from Ocean Energy. (Online version in colour.)

Figure 11. Ocean Energy buoy with Wells turbine. Reproduced with permission from Ocean Energy. (Online version in colour.)

Figure 12. Mk3 Oceanlinx wave energy generator. Reproduced with permission from Oceanlinx. (Online version in colour.)
problems was commissioned in spring 2011. It is significant in that the 16 units forming the OWC breakwater section (figures 13 and 14) represent the first multiple oscillating water column (MOWC) plant offering the opportunity for studying the interaction of the units and the complexities of multiple control. The research and monitoring activities associated with the plant are supported under the European Union FP6 Nereida project.

Voith Hydro Wavegen is also providing the technology for a project at Siadar on the north west coast of Lewis in Scotland. Here, it is planned to build a shore-connected breakwater comprising 15 OWC cells, each fitted with two Wavegen 132 kW turbo-generation units giving a nominal rating of 4 MW. This plant is ground breaking in that it will be the first breakwater built as a power station rather than as an addition to an already planned breakwater. While there will be considerable community benefits in that the scheme will provide a sheltered slipway, these benefits are secondary to power generation. It is also the first
wave power plant where the plant output will have the potential to have a major influence on the local grid, and as such, power quality issues become very important. For this reason, power storage and associated power quality control software are included in the scheme.

4. The future challenge

With 10 years operational experience and over 60,000 turbine running hours, LIMPET has demonstrated that Voith Hydro Wavegen has a reliable generation system ready for widespread application. The Mutriku and Siadar projects are the first multiple applications of the technology. Other companies are developing new platforms and PTO systems. If the technology is available and effective, then one has to ask the question why there has not been a greater uptake. The answer is quite simple; while OWC technology is effective, it is not yet cost effective (figure 15). There are good reasons why this is so:

— projects are small so that project costs are disproportionately high;
— small volumes mean high equipment costs; and
— weak grids at suitable coastal sites mean high connection charges.

The challenge to the industry is to reach the point where these conditions no longer apply and the industry is truly commercial. The problem has been recognized by interested governments, and in Scotland and Portugal, in particular, there are high-support tariffs for wave-generated electricity. The Siadar project could not be considered without the Scottish government’s support mechanism via multiple renewable obligation certificates and targeted grants. In the rest of the UK, the marine renewable proving fund and the marine renewable deployment fund are helping to promote ocean energy. Industry cannot rely on disproportionate funding support indefinitely and must improve the basic competitiveness of wave energy. This can only be done by reducing costs and improving capture and conversion efficiencies. To this end, Voith Hydro Wavegen expects to reduce the effective cost of wave-generated power by 50 per cent within the next 5 years, and other companies must meet the same challenge.

5. Conclusion

As a concept, the OWC is probably the most studied and the best developed of all systems. In shore-based operation, it has demonstrated the reliability necessary...
for a viable plant, and there is no reason to believe that this reliability cannot be transferred to other platforms. While not specific to OWC systems, the major limitation to the uptake of wave power generators in commercial operation is the cost of power; this is being addressed. The combination of early stage public support and the commitment from industry to improve competitiveness suggest that OWCs will be part of the future mix of generation.

References

