Discussion and Conclusion

The descriptions provided in this review cover only the most general of water masses, their core properties and their geographic distribution. In most regions of the ocean it is possible to resolve the water mass structure into even finer elements describing more precisely the differences in temperature and salinity. In addition other important properties can be used to specify water masses not obvious in the TS curves. Although dissolved oxygen is often used to define water mass boundaries care must be taken as this nonconservative property is influenced by biological activity and the chemical dissolution of dead organic material falling through the water column. Nutrients also suffer from modification within the water column making their interpretation as water mass boundaries more difficult. Characteristic diagrams that plot oxygen against salinity or nutrients can be used to seek extrema that mark the boundaries of various water masses.

The higher vertical resolution property profiles possible with electronic profiling instruments also make it possible to resolve water mass structure that was not even visible with the lower vertical resolution of earlier bottle sampling. Again this complexity is only merited in local water mass descriptions and cannot be used on the global scale description. At this global scale the descriptive data available from the accumulation of historical hydrographic data are adequate to map the large-scale water mass distribution as in this review article.

See also

California and Alaska Currents. Kuroshio and Oyashio Currents. Ocean Circulation. Ocean Subduction. Pacific Ocean Equatorial Currents. Thermohaline Circulation. Wind Driven Circulation.

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WAVE ENERGY

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Introduction

In the last half of the twentieth century, humankind finally realized that fossil fuel resources are finite and that use of those fuels has environmental consequences. These realizations have prompted the search for other energy resources that are both renewable and environmentally 'friendly'. One such resource is the ocean wind wave. This is a form of solar energy in that the sun is partly responsible for the winds that generate water waves.

The exploitation of water waves has been a goal for thousands of years. Until recent times, however, only sporadic efforts were made, and these were generally directed at a specific function. In the 1960s, Yoshio Masuda, the 'renaissance man' of wave energy conversion, came up with a scheme to convert the energy of water waves into electricity by using a floating pneumatic device. Originally, the Masuda system was used to power remote navigation aides, such as buoys. One such buoy system was purchased by the US Coast Guard which, in turn, requested an analysis of the performance of the system. The results of that analysis were reported by McCormick (1974). This was the first of a long list of theoretical and experimental studies of the pneumatic and other wave energy conversion systems. (For summaries of some of the works, see the Further Reading section.) The most recent collective type of publication is that edited by Nicholls (1999), written under the joint sponsorship of the Engineering Committee on Oceanic Resources (ECOR) and the Japan Marine Science and Technology Center (JAMSTEC). In the late 1970s and early 1980s, JAMSTEC co-sponsored a full-scale trial of a floating, offshore pneumatic system called the Kaimei. The 80 m long, 10 m wide Kaimei

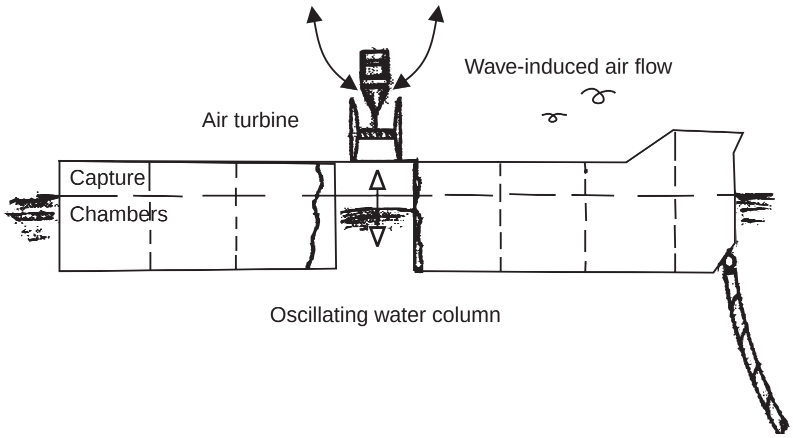

Figure 1 Schematic diagram of the Kaimei wave energy conversion system, consisting of 10 capture chambers and 10 pneumatic-electric generating systems.

(**Figures 1** and **2**) was designed to produce approximately 1.25 MW of electricity while operating in the Sea of Japan. This power was to be produced by 10 pneumatic turbo-generators. Eight of these (produced in Japan) utilized a unidirectional turbine. The other two utilized bi-directional turbines designed by Wells in the UK and McCormick in the USA. Unfortunately, the designed electrical power production was never attained by the system. The Wells turbine was found to be the most effective for wave energy conversion, and is now being used to power fixed pneumatic systems in the Azores, in India, and on the island of Islay off of the coast of Scotland.

Most of the published works resulting from research, development, and demonstration efforts are directed at the production of electrical energy. However, Hicks *et al.* (1988) described a wave energy conversion technique that could be used to produce potable water from ocean salt water. This technique had been developed earlier by Pleass and Hicks. Their work resulted in a commercial system called the Del Buoy, and inspired the efforts of others to apply the McCabe wave pump (**Figures 3** and **4**) to the production of potable water. The high-pressure pumps located between the barges pump sea water through a reverse osmosis (RO) desalination system located on the shore. The first deployment of the McCabe wave pump occurred in 1996 in the Shannon River, western Ireland. A second deployment of the system is expected in the spring of the year 2000 at the same location.

Wave Power: Resource and Exploitation

A mathematical expression for the power of water waves is obtained from the linear wave theory. Simply put, the expression is based on the waves having a sinusoidal profile, as sketched in **Figure 5**. The wave power (energy flux) expression is:

$$P = \frac{1}{8}\rho g H^2 b c_G \qquad [1]$$

Figure 2 The Kaimei deployed in the Sea of Japan.

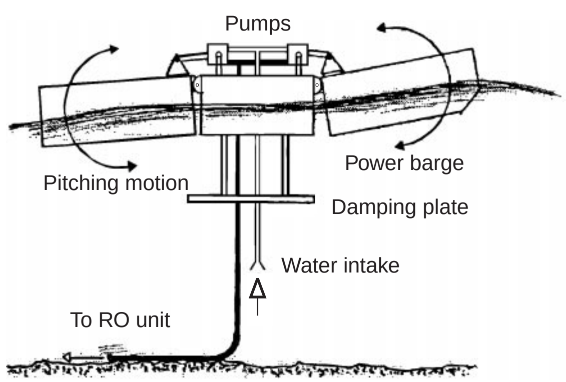

Figure 3 Sketch of the McCabe wave pump.

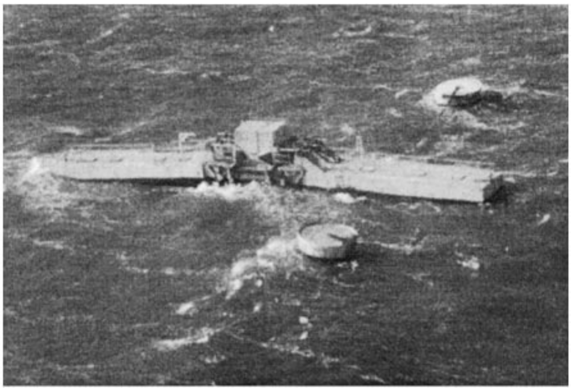

Figure 4 The McCabe wave pump located 500 m off the coast of Kilbaha, County Clare, Ireland.

where ρ is the mass density of salt water (approximately $1030\,\mathrm{kg\,m^{-3}}$), g is the gravitational acceleration ($9.81\,\mathrm{m\,s^{-2}}$), H is the wave height in meters, b is the wave crest width of interest in meters, and the vector c_G is called the group velocity. In deep water, defined as water depth (h) greater than half of the wave length (λ), the group velocity (in $\mathrm{ms^{-1}}$) is approximately:

$$|c_G| \simeq \frac{c}{2} \simeq \frac{gT}{4\pi} \qquad [2]$$

where c is the wave celerity (the actual speed of the wave), and T is the period of the wave in seconds. In shallow water, defined as where $h \leq \lambda/20$, the group velocity is approximated by:

$$|c_G| \simeq c \simeq \sqrt{gh} \qquad [3]$$

Consider an average wave approaching the central Atlantic states of the contiguous United States. The average wave height and period of waves in deep water are approximately 1 m and 7 s, respectively. For this wave, the wave power per crest width is:

$$\frac{|P|}{b} = \frac{1}{32\pi}\rho g^2 H^2 T \simeq 6.90\,(kW/\mathrm{m}) \qquad [4]$$

from eqn [1] combined with the expression in eqn [2].

The percentage of this power that can be captured depends on both the width of the capturing system and the frequency (or period) characteristics of the system. Each wave power system has one fundamental frequency (f_n). If the inverse of that frequency ($1/f_n = T_n$) is the same as the average wave period, then the system is in resonance with the average wave, and the maximum amount of wave power will be extracted by the wave power system. This, then, is the design goal, i.e. to design the system to resonate with the design wave. When resonance is achieved, then another phenomenon occurs which is of benefit to the system: i.e. resonant focusing, where diffraction draws energy toward the system. For a single degree of freedom wave power system, such as the heaving buoy sketched in **Figure 6**, the wave power absorbed by the system comes from a crest width equal to the width of the system (B) plus an additional width equal to the wavelength divided by 2π.

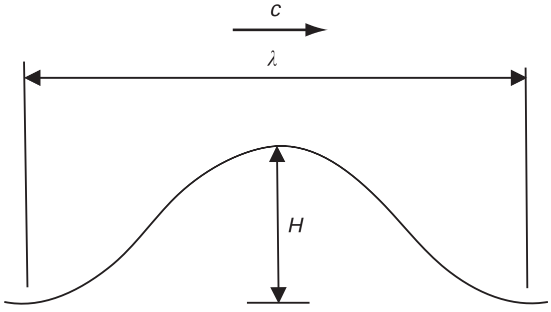

Figure 5 Wave notation.

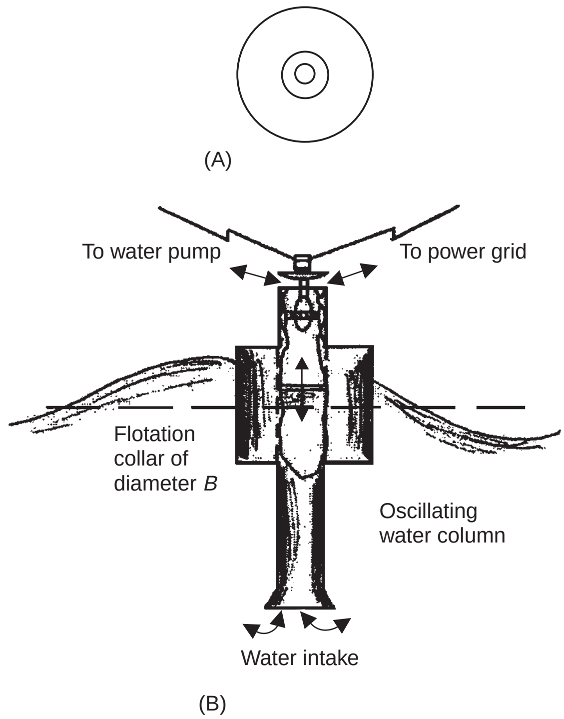

Figure 6 Floating oscillating water column wave energy converter, designed to produce electrical power for either potable water production or electricity. (A) Plan view; (B) elevation.

Hence, in deep water, the total power available to the single degree of freedom system operating in the average wave is:

$$|P| = \frac{1}{32\pi}\rho g^2 H^2 T\left(B + \frac{\lambda}{\pi}\right) \qquad [5]$$

where the wavelength in deep water is approximately:

$$\lambda \simeq \frac{gT^2}{2\pi} \qquad [6]$$

Thus, for the aforementioned average wave, the deep-water wavelength is about 76.5 m.

Consider an ideal 1 m diameter heaving system operating in the 1 m, 7 s average wave. For this wave, the wave power captured by the system is $6.90(1 + 76.5/2\pi)$ kW, or approximately 91 kW. If bus-bar conversion efficiency is 50%, then about 45.5 kW will be supplied to the power grid for consumption. In the contiguous United States, each citizen requires about 1 kW, on average, at any time. Hence, this system would supply 87.5 citizens.

To use the same system coupled with a RO desalinator to supply potable water, the value of the osmotic pressure of the desalinator's membranes is required. This value is 23 atmospheres or approximately 23 bars. From fluid mechanics, the power is equal to the volume rate of flow in the system multiplied by the back pressure. Hence, the 1 m diameter system would supply approximately 5 (US) gallons of salt water per second to the RO unit. Half of this flow would become product (potable) water, while the other half would be brine waste. This ideal system would supply 2.5 gallons per second (about 225 000 gallons per day) of potable water. Each US citizen residing in the contiguous United States uses about 60 gallons per day, on average. So, the wave-powered desalination system would satisfy the daily potable water needs of approximately 3700 citizens.

The numbers presented in the last two paragraphs illustrate the potential of wave energy conversion. The electrical and water producing systems described are ideal. In actuality, the waves in the sea are random in nature. The system, then, must be tuned to some design wave, such as that having an average wave period.

Economics of Wave Power Conversion

The economics of ocean wave energy conversion vary, depending on both the product (electricity or potable water) and the location. To illustrate this, consider the following two cases. First, on Lord Howe Island in the South Pacific, the cost of electrical energy is about 45 (US) cents per kilo-Watt hour (kWh). Electricity produced by wave energy conversion would cost about 15 cents/kWh. Hence, for such an application, wave energy conversion would be extremely cost-effective. On the other hand, in San Diego, California, the energy cost is about 13 cents/kWh, making wave energy conversion cost-ineffective. For the production of potable water, the McCabe wave pump, coupled with a RO system, will produce potable water at approximately US $1.10 per cubic meter (265 US gallons). On some remote islands, the cost of potable water is approximately $4.00 per gallon. On the coast of Saudi Arabia, on the Arabian Sea, the cost of potable water is $3.10 per cubic meter. Therefore, these locations, wave-powered desalination systems are very cost-effective.

Concluding remarks

The reader is encouraged to consult the Further Reading section for more information on wave energy conversion. There are many activities presently underway in this area of technology. These can be found on the Internet by searching the world wide web for wave energy conversion.

See also

Coastal Trapped Waves. Internal Tides. Internal Waves. Seiches. Storm Surges. Surface, Gravity and Capillary Waves. Tides. Tsunamis. Wave Generation by Wind. Waves on Beaches.

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WAVE GENERATION BY WIND

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Introduction

It is apparent to the most casual observer that waves grow on water surfaces under the action of wind. Except in occasional conditions of very low wind speed, the sea surface is generally covered by 'wind waves', those produced locally by the wind, as well as swell waves which have come from distant storms. The wind waves span a range of frequencies and wavelengths, with dominant periods typically between 1s and 10 s, and they travel mainly in or fairly close to the wind direction. Waves become higher, with longer wavelength and greater periodicity, as the wind increases, and also with greater fetch, the downwind distance from shore; the further from the upwind shore, the larger and longer the waves.

Although the title suggests the idea of waves being formed by the action of wind blowing over the surface of a calm and smooth sea surface, the sea is rarely calm and the meaning of the title is generally taken to include the wind-related processes which lead to the growth of existing waves on the water surface as well as those which lead to their formation in calm weather. Since growth will involve a balance of processes leading to the transfer of energy into and from waves, the subject involves reference to both the way in which wind causes waves to become bigger and to accompanying processes which lead to their loss of energy or 'dissipation.' Ignoring processes affecting waves but which are related only indirectly to wind, such as surface wave interaction with fronts or internal waves, there are three main factors which lead to changes in the the energy of the waves in a given narrow frequency band. These are:

1. growth through the action of wind which is related to the transfer of momentum from the air into the sea and consequently with wind stress (*see* **Heat and Momentum Fluxes at the Sea Surface**);
2. interactions, i.e., waves of a particular frequency may lose or gain energy as a result of nonlinear resonant interactions with other waves, and their propagation may be affected by interaction with currents (*see* **Surface, Gravity and Capillary Waves;**
3. dissipation, i.e., wave dissipation occurs as a result of wave breaking either in deep water or as waves approach shallow water or shore. Dissipation will also occur through their interaction with turbulence or through viscous action, the latter particularly if they are of small wavelength (e.g., capillary waves, *see* **Surface, Gravity and Capillary Waves**. Energy may also be lost when the water surface is covered by a surface film (*see* **Surface Films**).

This article focuses attention on the first point, wind forcing. A little will be said of the observations that have been made to improve understanding and test the theoretical predictions. These are essential ingredients in the advance of knowledge. Because of the complexity of the sea surface and the fact that the wind is not steady, but turbulent in its nature, the theory of wave generation has developed slowly since its beginnings over 130 years ago. Even now, the available theory offers a less than complete or satisfactory explanation of the changing state of the sea surface, in spite of the evident requirement to predict waves. They are an essential ingredient in the interaction of the atmosphere and the ocean (e.g., in the transfer of momentum from the wind to the water (*see* **Breaking Waves and Near-surface Turbulence**, and in the formation of bubbles, foam and aerosols, thereby affecting gas flux (*see* **Bubbles, Whitecaps and Foam** and **Air–Sea Gas Exchange**), and are consequently involved in those exchanges which control climate change. Wave forecasting is used to find the best routes for ships to avoid severe waves, and to predict when it is safe to tow and