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Energy Procedia 12 (2011) 936 – 943

Energy Procedia

ICSGCE 2011: 27–30 September 2011, Chengdu, China

Electricity Generation by the Ocean Thermal Energy

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Abstract

With considering the increasing of global temperature, and also the concern of global climate change, many policy makers worldwide have been accepted the importance of reducing greenhouse gas emissions, in particular from the power industries. Energy resource use is one of the most important and Contentious issues of our time. The ocean provides a vast source of potential energy resources. Of the total solar radiation, oceans are the largest collectors, accumulating 250 billion barrels of oil equivalent, according to an estimate. This vast amount of solar energy absorbed in the oceans can be converted into electricity by a process known as Ocean Thermal Energy Conversion, popularly known as OTEC. OTEC makes use of the difference in temperatures of warm surface water (22–27 °C) and very cold water at a depth of 1 km (4–7 °C). an open-cycle plant based on creating a rising mixture of water and steam bubbles or "foam", which is separated at a height above sea-level, such that the water can be used to drive a turbine rotor. In closed-cycle OTEC, warm seawater heats a working fluid with a low boiling point, such as ammonia, and the ammonia vapor turns a turbine, which drives a generator. This paper discusses about the ocean energy, ocean thermal energy potential, ocean thermal energy conversion by the close, open and hybrid cycles, environmental impact and special conditions of these process.

Selection and/or peer-review under responsibility of University of Electronic Science and Technology of China (UESTC)

Keywords: Renewable energy; ocean energy; ocean thermal energy conversion; open cycle; closed cycle

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1. Introduction

The most plentiful renewable energy source in our planet by far is solar radiation: 170,000 TW fall on Earth. Harvesting this energy is difficult because of its dilute and erratic nature. Large collecting areas and large storage capacities are needed, two requirements satisfied by the tropical oceans. Oceans cover 71% of Earth's surface. In the tropics, they absorb sunlight, and the top layers heat up to some 25C. Warm surface waters from the equatorial belt flow poleward, melting both the arctic and the antarctic ice.

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doi:10.1016/j.egypro.2011.10.123

The resulting cold waters return to the equator at great depth, completing a huge planetary thermosyphon.

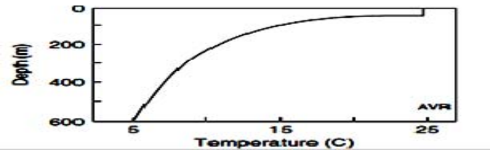


Fig.1. Typical ocean temperature profile in the tropics

Ocean and marine energy refers to various forms of renewable electric energy harnessed from the ocean. There are two primary types of ocean energy: mechanical and thermal. The rotation of the earth and the moon's gravitational pull create mechanical forces.[1] The rotation of the earth creates wind on the ocean surface that forms waves, while the gravitational pull of the moon creates coastal tides and currents. Thermal energy is derived from the sun, which heats the surface of the ocean while the depths remain colder. This temperature difference allows energy to be captured and converted to electric power. With fossil fuel prices increasing and expected to stay high in the future, the search for alternative energy resources is once again on the forefront. In the past few years, a growing interest emerged in ocean energy, and progress is being made to bring ocean energy technologies from development stages to the commercial market. In 1881, a French physicist named Jacques Arsene d'Arsonval discovered the concept of ocean thermal energy conversion (OTEC). His student, Georges Claude, built the first open cycle OTEC plant in Cuba in 1930. With this technology, temperature gradient from the ocean surface to deeper waters converts heat energy to electricity. It functions best when there is a temperature difference of at least 20°C (36°F). Ocean thermal energy conversion, or OTEC, uses ocean temperature differences from the surface to depths lower than 1,000 meters, to extract energy. A temperature difference of only 20°C (36°F) can yield usable energy. Fig. 1 shows the typical ocean temperature profile in the tropics.

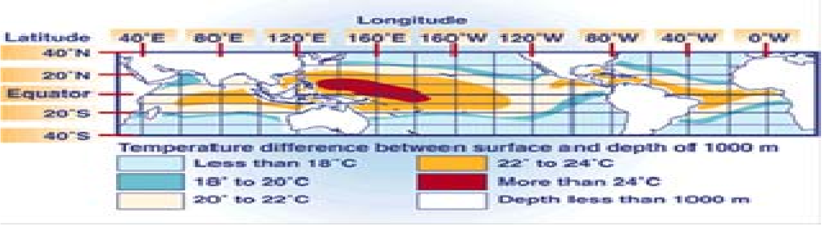


Fig. 2. Ocean Temperature Differences between Surface and 1,000 Meters Deep. [1]

Fig. 2 shows the ocean temperature differences between surface and 1000 meters deep. OTEC works best with temperature differences of at least 20°C (36°F) [1].

OTEC produces electricity from the natural thermal gradient of the ocean, using the heat stored in warm surface water to create steam to drive a turbine, while pumping cold, deep water to the surface to recondense the steam. In closed-cycle OTEC, warm seawater heats a working fluid with a low boiling point, such as ammonia, and the ammonia vapor turns a turbine, which drives a generator. The vapor is then Condensed by the cold water and cycled back through the system. In an open-cycle plant, warm seawater from the surface is pumped into a vacuum chamber where it is flash evaporated, and the resulting steam drives the turbine. Cold seawater is then brought to the surface and used to condense the steam into water, which is returned to the environment. Hybrid plants, combining benefits of the two systems, would use closed-cycle generation combined with a second-stage flash evaporator to desalinate water [2]. OTEC plants can either be built onshore or on offshore floating platforms. Floating platforms could be larger and do not require the use of valuable coastal land, but incur the added expense and impact of transporting energy to the shore. Energy can be transported via seafloor cable, a well-developed but costly technology that impacts the environment by disrupting seafloor communities, or stored in the form of chemical energy as hydrogen, ammonia or methanol. Plants hips used to produce hydrogen, ammonia or methanol would‘‘graze’’ the ocean slowly, store products for about a month, then transfer products to a tanker that would take the products to shore [3]. It is possible to derive ancillary benefits from both the warm and cold water cycled through OTEC plants. In an open-cycle plant, the warm water, after being vaporized, can be recondensed while keeping separated from the cold seawater, leaving behind the salt and providing a source of desalinated water fresh enough for municipal or agricultural use. The cold-water effluent can be applied to mariculture (the cultivation of marine organisms such as algae, fish, and shellfish), air conditioning and other applications. At the National Energy Laboratory of Hawaii (NELHA), once the locus of OTEC research and pilot programs, there are no longer any functioning, net energy-producing OTEC plants, but research into uses for deep seawater pumped to the surface using OTEC technology continues. Cold, deep seawater brought up by OTEC pipes is nutrient-rich-parasite and free, and can be pumped into onshore ponds producing algae or other products in a controlled system [3].At NELHA, private companies have already profited from raising lobsters, flounder, and high-protein algae in mariculture ponds fed by the cold water. Additionally, this cold water has been used to grow temperate crops such as strawberries in Hawaii’s tropical climate [4].Air conditioning and industrial cooling may be the most lucrative of all ancillary benefits of OTEC plants .Currently, both of the two main buildings at the NELHA lab are effectively air conditioned by cold seawater pumped through OTEC pipes [5].[6]

2. Open-Cycle OTEC

In an open-cycle plant, warm seawater from the surface is pumped into a vacuum chamber where it is flash evaporated, and the resulting steam drives the turbine. Cold seawater is then brought to the surface and used to condense the steam into water, which is returned to the environment. [7] The open cycle consists of the following steps:

- Flash evaporation of a fraction of the warm seawater by reduction of pressure below the saturation value corresponding to its temperature.
- Expansion of the vapor through a turbine to generate power.
- Heat transfer to the cold seawater thermal sink resulting in condensation of the working fluid.
- Compression of the non-condensable gases (air released from the seawater streams at the low operating pressure) to pressures required to discharge them from the system.

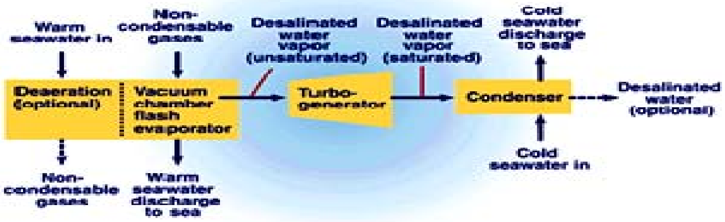


Fig. 3. Open Loop Cycle OTEC. [1]

In the case of a surface condenser the condensate (desalinated water) must be compressed to pressures required to discharge it from the power generating system. The evaporator, turbine, and condenser operate in partial vacuum ranging from 3 percent to 1 percent atmospheric pressure. This poses a number of practical concerns that must be addressed. First, the system must be carefully sealed to prevent in-leakage of atmospheric air that can severely degrade or shut down operation. Second, the specific volume of the low-pressure steam is very large compared to that of the pressurized working fluid used in closed cycle OTEC. This means that components must have large flow areas to ensure that steam velocities do not attain excessively high values. Finally, gases such as oxygen, nitrogen and carbon dioxide that are dissolved in sea water essentially air) come out of solution in a vacuum. These gases are uncondensable and must be exhausted from the system. Fig 3 shows the open- cycle OTEC process.

In spite of the aforementioned complications, the Claude cycle enjoys certain benefits from the selection of water as the working fluid. Water, unlike ammonia, is non-toxic and environmentally benign. Moreover, since the evaporator produces desalinated steam, the condenser can be designed to yield fresh water. In many potential sites in the tropics, potable water is a highly desired commodity that can be marketed to offset the price of OTEC-generated electricity. Flash evaporation is a distinguishing feature of open cycle OTEC. Flash evaporation involves complex heat and mass transfer processes. In the configuration tested by a team lead by the author, warm seawater was pumped into a chamber through spouts designed to maximize the heat-and-mass- transfer surface area by producing a spray of the liquid. The pressure in the chamber (2.6 percent of atmospheric) was less than the saturation pressure of the warm seawater. Exposed to this low-pressure environment, water in the spray began to boil. As in thermal desalination plants, the vapor produced was relatively pure steam. As steam is generated, it carries away with it its heat of vaporization. This energy comes from the liquid phase and results in a lowering of the liquid temperature and the cessation of boiling. Thus, as mentioned above, flash evaporation may be seen as a transfer of thermal energy from the bulk of the warm seawater to the small fraction of mass that is vaporized to become the working fluid. Approximately 0.5 percent of the mass of warm seawater entering the evaporator is converted into steam. A large turbine is required to accommodate the huge volumetric flow rates of low-pressure steam needed to generate any practical amount of electrical power. Although the last stages of turbines used in conventional steam power plants can be adapted to OC- OTEC operating conditions, existing technology limits the power that can be generated by a single turbine module, comprising a pair of rotors, to about 2.5 MW. Unless significant effort is invested to develop new, specialized turbines (which may employ fiber-reinforced plastic blades in rotors having diameters in excess of 100 m), increasing the gross power generating capacity of a Claude cycle plant above 2.5 MW will require multiple modules and incur an associated equipment cost penalty. Condensation of the low-pressure working fluid leaving the turbine occurs by heat transfer to the cold seawater. This heat transfer may occur in a DCC, in which the seawater is sprayed directly over the vapor, or in a surface condenser that does not allow contact between the coolant and the condensate. DCCs are relatively inexpensive and have good heat transfer characteristics due to the lack of a solid thermal boundary between the warm and cool fluids. Although surface condensers for OTEC applications are relatively expensive to fabricate they permit the production of desalinated water. Desalinated water production with a DCC requires the use of fresh water as the coolant. In such an arrangement, the cold seawater sink is used to chill the fresh water coolant supply using a liquid-to-liquid heat exchanger. Effluent from the low-pressure condenser must be returned to the environment. Liquid can be pressurized to ambient conditions at the point of discharge by means of a pump or, if the elevation of the condenser is suitably high, it can be compressed hydrostatically. Non-condensable gases, which include any residual water vapor, dissolved gases that have come out of solution, and air that may have leaked into the system, must be pressurized with a compressor. Although the primary role of the compressor is to discharge exhaust gases, it usually is perceived as the means to reduce pressure in the system below atmospheric. For a system that includes both the OC-OTEC heat engine and its environment, the cycle is closed and parallels the Rankine cycle. Here, the condensate discharge pump and the non-condensable gas compressor assume the role of the Rankine cycle pump.

3. Closed-Cycle OTEC

In closed-cycle OTEC, warm seawater heats a working fluid with a low boiling point, such as ammonia, and the ammonia vapor turns a turbine, which drives a generator.The vapor is then condensed by the cold water and cycled back through the system [7].

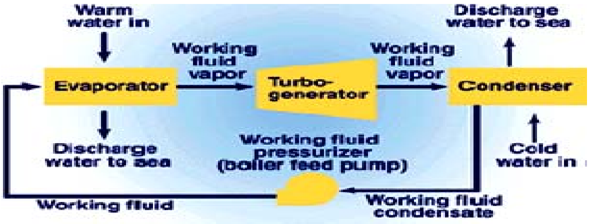


Fig. 4. Closed-Cycle OTEC Flow Diagram[1]

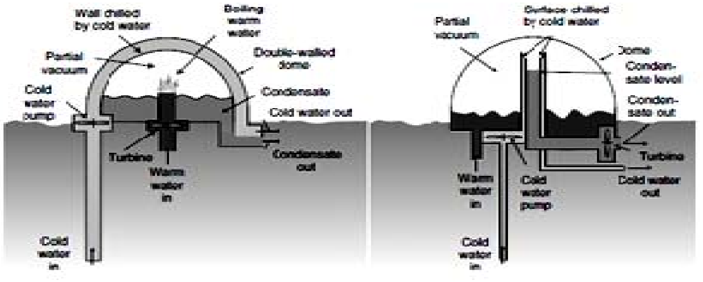
The closed-cycle OTEC power plant was the first OTEC cycle proposed by D’Arsonval in 1881. This cycle uses a working fluid with a low-boiling point, usually propane or ammonia, in a closed flow path (Takahashi and Trenka, 1996). The working fluid is pumped into the evaporator where it is vaporized and in turn moves a turbine. Closed-cycle plants operate on a Rankine cycle. The first stage of this cycle is referred to as isentropic expansion, which occurs in the steam turbine. Isobaric heat rejection in the condenser follows. This stage the water vapor becomes a liquid and therefore the entropy is decreased. The next stage is the isentropic compression in the pump (Takahashi and Trenka, 1996). During this step, the temperature increases due to the higher pressure. The boiler then supplies isobaric heat causing the working fluid to vaporize. In an OTEC system the warm sea water would be pumped into the evaporator where the liquid ammonia would be pressurized. This pressure causes the ammonia to boil or become vapor. This works due to the ideal gas law that states that the temperature is directly proportional to the pressure; therefore if the pressure increases in a system, the temperature does too. The vapor ammonia then expands by traveling through a turbine. This turns the turbine making electricity. The ammonia vapor pressure at the outlet of the turbine is 7°C higher than the cold seawater temperature. The cold seawater is therefore brought up from the depths where heat exchange occurs and ammonia vapor is changed back into a liquid. The liquid ammonia is then pressurized by a pump started the cycle once more. Rankine cycles, in theory, are able to produce non-zero net power due to the fact that less energy is required to increase the pressure of a liquid then is able to be recovered when the same fluid expands as a vapor. It is for this reason that phase changes are essential when producing energy this way. The advantages of using a closed-cycle system are that it is more compact then an open-cycle system and can be designed to produce the same amount of power. The closed-cycle can also be designed using already existing turbo machinery and heat exchanger designs. [8] The operation of a closed-cycle OTEC plant, using anhydrous ammonia as the working fluid, is modeled with the saturated Rankine cycle. Fig. 4 shows a simplified flow diagram of the CC-OTEC cycle. The analysis of the cycle is straightforward.

4. Hybrid Design OTEC

The Hybrid-cycle is one that has yet to be tested but uses principles from both the closed and open cycle OTEC systems to obtain maximum efficiency. The Hybrid cycle uses both seawater and another working fluid, usually designed using ammonia. [9] The fresh water is initially flashed into steam, similar to the closed-cycle; this occurs in a vacuum vessel. In the same vessel the ammonia is evaporated through heat exchange with the warm water. The ammonia is then physically mixed with the warm seawater in a two-phase, two-substance mixture. The evaporated ammonia is then separated from the steam/water and re-condensed and re-introduced into the closed loop cycle. The phase change of the water/ammonia vapor turns a turbine producing energy [10]. Two regular process for the hybrid- OTEC are:

- Those using hydraulic turbines
- Those using vapor turbines.

The first uses the temperature difference between the surface and bottom waters to create a hydraulic head that drives a conventional water turbine. The advantages of this proposal include the absence of heat exchangers. Consider a hemispherical canister as depicted in the Figure 5a. A long pipe admits cold water, while a short one admits warm water. The canister is evacuated so that, in the ideal case, only low-pressure water vapor occupies the volume above the liquid surface. In practice, gases dissolved in the ocean would also share this volume and must be removed. This configuration was proposed by Beck (1978). At a temperature of 15° C, the pressure inside the canister is about 15 kPa (0.017 atmospheres). At this pressure, warm water at 25°C will boil, and the resulting vapor will condense on the parts of the dome refrigerated by the cold water. The condensate runs off into the ocean, establishing a continuous flow of warm water into the canister.



(a) (b)

Fig. 5. Hydraulic OTECs.

The incoming warm water drives a turbine from which useful power can be extracted. The equivalent hydraulic head is small, and turbines of large dimensions would be required. To increase the hydraulic head, Zener and Fetkovich (1975) proposed the arrangement of Figure 5b. The warm surface water admitted to the partially evacuated dome starts boiling. The resulting vapor condenses on a funnel-like surface that seals one of the two concentric cylinders in the center of the dome. This cylinder receives cold water pumped from the ocean depths, which chills the steam-condensing surface. The collected condensed water subsequently flows into the central pipe, creating a head that drives the turbine. The efficiency of the device is substantially enhanced by the foaming that aids in raising the liquid.

5. Environmental Impact

Though fairly benign in environmental impact compared to traditional power plants, OTEC poses some potential environmental threats, especially if implemented on a large scale. Data from existing electric generating stations on the coast provide insight into possible impacts of OTEC plants. These stations impact the surrounding marine environment mainly through heating the water, the release of toxic chemicals, impingement of organisms on intake screens, and entrainment of small organisms by intake pipes, all of which are concerns for OTEC.[6] Large discharges of mixed warm and cold water would be released near the surface, creating a plume of sinking cool water. The continual use of warm surface water and cold deep water may, over long periods of time, lead to slight warming at depth and cooling at the surface [3].Thermal effects may be significant, as local temperature changes of only 3–41C are known to cause high mortality among corals and fishes. Aside from mortality, other effects such as reduced hatching success of eggs and developmental inhibition of larvae, which lower reproductive success, may result from thermal changes [11].Increased nutrient loading resulting from the discharge of upwelled water could also negatively impact naturally low-nutrient ecosystems typical of tropical seas. Toxic chemicals, such as ammonia and chlorine, may enter the environment from an OTEC plant and kill local marine organisms.[6] Ammonia in closed-cycle systems would be designed not to contact the environment, and a dangerous release would be expected to result only from serious malfunction such as a major breakdown, collision with a ship, a greater than 100-yr storm, terrorism, or major human error [3].The impact of chlorine will likely be minimal, as it would be used at a concentration of approximately 0.02 ppm daily average, while the EPA standard for marine water requires levels lower than 0.1 ppm [3]. Impingement of large organisms and entrainment of small organisms has been esponsible for the greatest mortality of marine organisms at coastal power plants thus far [11].The magnitude of this problem depends on the location and size of the plant; however, if marine life is attracted to OTEC plants by the higher nutrient concentrations in the upwelled cold water, large numbers of organisms, including larvae or juveniles, could be killed by impingement or entrainment. For floating plants, victims of impingement would be mainly small fish, jellyfish, and pelagic invertebrates, while for land-based plants crustaceans would be the most affected [3]. Finally, a small amount of CO2 is released to the atmosphere by OTEC power generation. Bringing deep water to the surface where pressure is lower allows some of the sequestered CO2 in this deep water to outgas, especially as the water is warmed, reducing the solubility of CO2.However, this carbon emission is very minute compared to the emissions of fossil fuel plants. OTEC could significantly improve quality of life in SIDS, where the current cost of power is at a premium and the benefits of desalinated water, mariculture and air conditioning would have a major impact. Further research into environmental impacts is necessary, but if the technology is shown to be benign, the development of OTEC for SIDS should be a priority. Plants in developed tropical sites that face high power prices should also be encouraged, if appropriate sites at which environmental damage will be negligible can be found. Because the governments of the SIDS that would benefit most from OTEC cannot afford such a high capital investment, governments of developed states should contribute to the research effort and investment for OTEC in developing countries.[6] Appropriate measures should be taken to control environmental impacts including:

- Refraining from siting OTEC plants in sensitive areas including prime fishing grounds, spawning areas, and sensitive reef habitats.
- Making use of discharge for ancillary benefits, which prevents discharges from altering local water temperature significantly.
- Carefully regulating the use of toxins such as ammonia and chlorine, and avoiding coating the plants with toxic hull coatings used on ships in harbors which are known to pollute the waters.
- Relying mainly on relatively small plants. While there may be economic benefits to scaling up, large-scale plants are more likely to damage a local community through discharge or impingement/entrainment. Also, benefits from economies of scale are likely to dwindle at the 50MW scale [12].Similarly, if several small OTEC plants are used these plants must be suitably spaced to prevent altering local ecology too significantly at any one site [3].

6. Conclusion

The technologies for OTEC, wave, non-barrage tidal, and offshore wind energy are still fairly new. Further research is needed on the environmental effects as well as economic feasibility of renewable ocean energy projects. However, research has shown that these technologies hold promise, and further research and development could help address one of the most serious threats to the environment and society, global climate change, by reducing dependence of fossil fuels. Ocean thermal energy conversion is a potential source of renewable energy that creates no emissions. The main advantages of OTEC are that the method is fuel free, has a low environmental impact. The disadvantages include high capital cost, potential for hostile ocean environment during construction and use and an overall lack of familiarity with OTEC technology. There have been several analyses of the feasibility of full-scale implementation of OTEC. While some of these investigations are contradictory to each other, research with actual mini OTEC plants is proving that OTEC systems will one day become a feasible, efficient and renewable source of energy.

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