OCEAN THERMAL ENERGY CONVERSION (OTEC) – STATE OF THE ART AND PRESENT STATUS

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More than one century ago, French physicist Jacques Arsene d'Arsonval was the first to propose tapping the thermal energy of the ocean for producing useful energy. The relevant process was named Ocean Thermal Energy Conversion − OTEC. Surface and deep water of the ocean, which have different temperatures, can be used as a heat source and a heat sink in a thermal engine ruled by the Carnot principle. The first plant, that demonstrated the process feasibility and permitted assessing the engineering problems and financial risks stemming from its implementation, was constructed in 1930 (see http://www.clubdesargonautes.org/histoirestem/etmclaude.htm, in french). The background of setting up diverse facilities on the basis of OTEC in different countries is provided. It is emphasized that in recent decade many countries abandoned their activities aimed at OTEC development. The USA and Japan can be mentioned as the only exception, as the countries continued research in OTEC, their efforts being aimed at expansion of possible applications for deep ocean water, besides improving the OTEC processes and studying their potential impacts on the environment. At present there is no OTEC power plant of large enough power (several megawatts), which impedes a better estimation of economic opportunities offered by this renewable energy source.

See also another contribution of the Club des Argonautes to this issue of the International Scientific Journal for Alternative Energy and Ecology 2007: ENVIRONMENTAL IMPACTS ASSOCIATED WITH OCEAN THERMAL ENERGY CONVERSION. *Research Proposal*.

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The "Club des Argonautes" is a small group of retired scientists and engineers who happened to work with French public institutions such as IRD, IFREMER, Météo France, CNES, CNRS, and MNHN

Introduction

Ocean Thermal Energy Conversion – OTEC – is the process that uses warm water from the surface and cold water from the depth of the tropical ocean to produce useful energy. For more than one century OTEC has been addressed a possible alternative for traditional sources of energy supply. During the 1930s, OTEC demonstrated its feasibility and an OTEC commercial plant was developed that allowed assessing the technical difficulties and financial risk inherent in the use of the OTEC resource. After World War II, several projects for building OTEC electric plants were studied with the idea of supplying some French overseas territories with electricity. Nevertheless, these projects were abandoned in the mid 1950s, as they did not appear competitive with local hydroelectric resource. Then, OTEC has been "forgotten" for almost 20 years until the 1973 oil crisis.

A continuing rise in oil prices through the late 70s highlighted the defects of oil market, vulnerability of oil supply, and ineluctable limits of the oil resource itself. The crisis reactivated public interest in renewable energy including OTEC, therefore 1975-1985 became a golden period for OTEC. Strong political support encouraged important funding from both public and private sectors. In the USA, under the Carter Administration, this support was expected to lead to a vivid demonstration of commercial-sized OTEC plants by 1990 [1]. However, the drastic drop of oil market price in 1986 killed this ambitious prospect and OTEC activities were shut down in many countries, except in the USA and Japan. These two countries got adapted to the situation and focused their attention on the development of technology helping reduce construction and operation costs of future OTEC plants as well as study other commercial applications of deep cold water.

OTEC process and components

On a large area of the tropical ocean, the temperature difference between the surface water and the water at the depth of 800 to 1000 m is in the range of 20-25 °C. This thermal gradient between the surface water and the deep water results from the wind driven global circulation of the ocean. The surface water and the deep water can be used respectively as a heat source and a heat sink of a thermal engine ruled by the Carnot principle. A very simplified scheme of OTEC system is shown in Fig. 1.

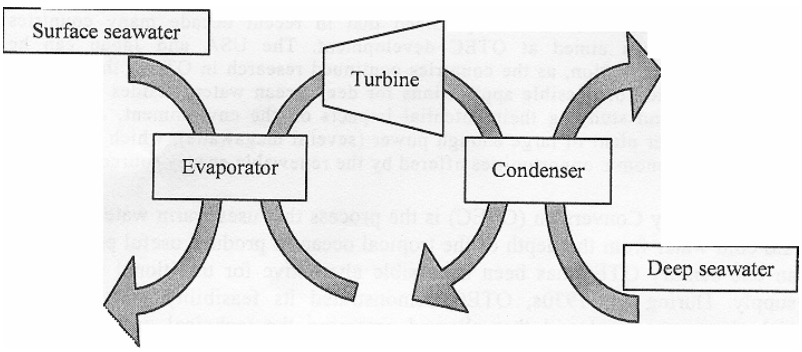

***Fig. 1.** Simplified OTEC diagram*

The main components of the system are:
– supply pumps and pipes;
– evaporator with warm sea water;
– condenser with cold sea water;
– working fluid that is vaporized;
– steam turbine driven by the working fluid that generates mechanical energy.

The details of the process and technology of the components for OTEC systems depend essentially on the choice for the working fluid. There are basically two types of OTEC processes: closed-cycle and open-cycle.

ln the closed-cycle process the heat from the warm surface seawater is transferred through the evaporator to a working fluid, such as ammonia, with an appropriate vapour pressure at the temperature of the available warm to turn it into vapour. The expanding vapour drives a turbo alternator, which produces electricity. The cold seawater, passing through a condenser that contains the vaporized working fluid, turns the vapour back into a liquid, which is then recycled through the system in a "closed cycle".

Open-cycle OTEC uses the warm surface water itself as a coolant. In the near vacuum evaporator the water vaporizes at surface water temperatures. The expanding vapour drives a law-pressure turbine attached to a generator, which produces electricity. The vapour (which is indeed fresh water vapour) is condensed back into liquid water by mixing with cold deep ocean water. If a surface condenser is designed to keep the vapour from direct contact with the seawater, the condensed water can then be used for drinking or irrigation. A "direct contact" condenser that mixes the vapour and the cold seawater is more thermodynamically efficient, but the effluent is salty and not recycled. The process is repeated with a continuous supply of the surface seawater to the evaporator. The cycle of the coolant is "open".

Variations of OTEC open cycle include mist lift and foam lift processes, which use a hydraulic turbine instead of a very low vapour pressure steam turbine applied in Claude's open cycle, have been proposed and tested on a small scale in laboratory conditions. More investigation is required to establish their industrial potential that will not be further discussed in the present article. Also hybrid systems using parts of both open-cycle and closed-cycle systems are used to optimise the production of electricity and fresh water and better answer the users demand.

OTEC history

Jacques Arsene d'Arsonval, a French physicist, was the first to propose tapping the thermal energy of the ocean (1881) and Georges Claude, a former student of d'Arsonval, was the first to build an experimental open-cycle OTEC electric plant to demonstrate the feasibility of the process at sea. The plant was built onshore in Matanzas Bay, Cuba, in 1930. The system using a low-pressure turbine produced 22 kW of electricity. Later, in 1935, Claude constructed a 2.2 MW open-cycle floating plant aboard a 10000-ton cargo vessel "La Tunisie" to be moored off the coast of Brazil. Claude planned to sell industrial ice to Rio de Janeiro and give evidence of the economic potential of OTEC. Unfortunately, during the installation the cold-water pipe was destroyed by the effect of the waves and Claude became bankrupt (La Tunisie, 1991) (see: http://www.clubdesargonautes.org/otec/vol/ vol2-1-10.htm).

After W-W-II, French researchers designed a 3 MW electric open-cycle plants for two French Overseas Territories. However, the projects were not completed because the cost of OTEC energy was not competitive with inexpensive hydroelectric power available on both sites.

In 1974, the Natural Energy Laboratory of Hawaii (NELHA, formerly NELH) was established at Keahole Point on the Kona coast of the big Island of Hawaii. It has become the world's foremost laboratory and test facility for OTEC technologies. ln 1979, the first 50 kW electric closed-cycle OTEC demonstration plant went up at NELHA. Known as "Mini-OTEC", the plant was mounted on a converted U.S. Navy barge moored 2 kilometres off Keahole Point. The plant used a 0.7 m-diameter, 670 m-long cold-water pipe to produce 15 kW of net electric power.

In 1980, the U.S. Department of Energy built OTEC-1, a test laboratory for closed-cycle OTEC ammoniac heat exchangers installed onboard a converted U.S. Navy tanker. The results of the test identified the methods for designing commercial scale heat exchangers for OTEC, and a new design for a suspended cold-water pipe was validated at that test site. The OTEC-l experiment has demonstrated that OTEC systems can operate from slowly moving ships with little effect on the marine environment.

In 1981, Japan built a shore-based 100-kW(el.) closed-cycle plant in the Republic of Nauru in the Pacific Ocean. This plant employed cold-water pipe laid on the sea bed at the depth of 580 m. The working fluid was Freon-22 and a titanium shell-and-tube heat exchanger was used. The plant produced 31.5 kW (el.) of net power during continuous operating tests from October to December 1981.

The golden age for modern OTEC peaked in 1980 when the US Administration enacted laws [1] to promote commercial development of OTEC (US ACT,1980) and called for demonstration of 100 MW(el) OTEC power plant by 1985 and 500 MW installed by 1990. Unfortunately the construction program was not funded and then abandoned.

During the same period, France launched a study run by IFREMER for a 5 MW(el.) OTEC plant to be created in French Polynesia. The project was abandoned in 1986.

ln 1986 a severe drop in the oil price led to a worldwide reduction in political support and funding of OTEC development. Only the USA and Japan continued significant activities. Their efforts were more or less re-oriented with the objectives to:

– Improve knowledge of OTEC systems and possible environmental impact.

– Two examples of activity illustrating this objective are the construction and test of a 210 kW open-cycle OTEC with 50 kW Net Power Producing Experiment (NPPE) performed by the Pacific International Center for High Technology Research (PICHTR) at NELHA Keahole Point in 1993-1998, and the Japanese world's first experiment on artificial up-welling on the "Hoyo" ("Hoyo" means "productive ocean" in Japan) floating platform in 1989-1990.

– Develop technologies to cut OTEC capital and operation costs.

The activity included the development of aluminium alloys and constructIon of plate exchangers for OTEC close cycle. These were much cheaper than those previously used with titanium tubing. The activity also involved a research of material for the construction of cold water piping several meters in diameter and a research to adapt aerospace light materials to the construction of low-pressure turbine blades for large OTEC open-cycle plants. Development activities for such specific components are most often under the responsability of private companies and detailed results might not be fully available to public.

– Study a broader field of Deep Ocean Water Applications (DOWA), other than OTEC itself.

The deep ocean water is not only cold, but it is also richer in nutrients, "cleaner", and has fewer pathogens than surface water. These characteristics of Deep Ocean Water (DOW) are also stable with time and DOW is recognised as a favourable medium for growing marine organisms. By opening its facilities, including the supply of deep ocean water (NELHA, 2002), to public and private research teams the NELHA greatly contributed to increasing the vision of DOWA and has become an "incubator" for a wide range of new commercial DOW A for aquaculture of fish and sea food, (or cultivation of marine organisms of industrial interest, etc. Also, being available in the tropical region, DOW can be used as a cooling fluid for traditional thermal plants to improve their efficiency. Another simple and promising application is the usage of DOW as a "chilling" fluid for air-conditioning systems in big buildings and hotels. Visiting the NELHA web site to learn more about NELHA "tenants" and DOWA products is an exciting experience. ln Japan, similar smaller facilities exist in several Prefectures, Kochi being the first to be operated. All the above-mentioned make a convincing demonstration of new DOWA commercial success and substantial incomes.

– Identify best target sites and search for possible OTEC funding.

There are two main types of plant sites: the sites "on shore" or "close to shore" which are under the jurisdiction of nations within the limits of Exclusive Economic Zone (EEZ) and the sites located in "high seas" where the resource is accessible to any user. Beginning with the search of Georges Claude and his choice in favour of Cuba in the 1920s, the search for the best favourable sites to install OTEC plants has been – and still is – a "routine" activity for OTEC promoters. There exist long lists of favourable sites for which technical risks and costs have been evaluated and benefits for the local population clearly identified.

OTEC – the state of the art

The history of OTEC as briefly reviewed above recalls past technical successes in building and operating small experimental OTEC plants, but does not give evidence for any reliable assessment of a long-term future for commercial OTEC. Nevertheless, the analysis of the past activities addresses the following assertions and reservations.

The Ocean Thermal Energy resource is abundant and its usage to supply useful energy neither creates, nor adds new heat or chemical substances to the environment. OTEC just introduces a perturbation in the natural process of the Ocean Circulation. On the whole, OTEC is environmentally friendly, but limits and consequences of an intense exploitation of the resource are still to be studied.

OTEC requires rather "low" technologies readily available to build OTEC electric plants with a net production capacity up to several tens of MW – either "open" or "close" cycle, "on" or "close" to shore. They represent the "first generation" of OTEC commercial plants built and operated to supply small isolated communities with base load electricity and other products, e.g. desalinated water, cooling fluid, aquaculture, etc. When carefully planned and executed, the environmental impact caused by the construction of a plant will be similar to that of standard civil works with very limited local consequences. In order to prevent adverse effects on the local environment during plant operation, the plant design can be adapted to the site characteristics. Since Claude's "La Tunisie" attempt and failure in 1935, a high capital cost and lack of experience in long-term operation for OTEC have dissuaded private investors to go commercial before a pilot OTEC plant of reasonable size – at least 1 MW – has been built and operated during a reasonable period of time – at least 1 year – with the support of public funds.

Analysis of the results gained from operating OTEC plants of the "first generation" is necessary before building big floating OTEC electric plants of 100 MW or more. The main technical issues for these OTEC plants of the "second generation" are related to the cold water pipes, transfer of electricity to land, and a big low-pressure turbine in case of an open-cycle OTEC. lndustrial study of construction design and materials for floating OTEC plants of 20 to 400 MW have been conducted [2] yielding a primary conclusion that there is a solution to build closed-cycle OTEC plants with metallic heat exchangers and cold-water pipes made of light concrete when located at a reasonable (10 miles) distance from land (Avery 1994). Uncertainties exist as to long-term effects of intensive exploitation on the environment on a regional and global scale. Also intensive exploitation should not be authorized before an international legislation is established to set the rights and duties of OTEC industry.

For a long term, conceptual designs and cost evaluation exist for big OTEC plants of the "third generation" whose goal is to produce synthetic fuels and supply liquid fuels for direct use in transportation, or for electric power production via fuel cells. Meeting all imported motor vehicle fuel demand in the US with OTEC fuels would require "only" three decades to develop (Avery 2002).

Conclusion – OTEC status at the dawn of the third millennium

Despite the fact that OTEC technology is available and offers many advantages compared to others, including such resources as solar PV, wind, biomass, etc., no OTEC plant of decent size (one to few MW seems appropriate) has been operated for a long period of time to permit a better evaluation of OTEC economy. Usual arguments to explain this situation are high capital investment costs and potential marine hazards. These factors dissuade promoters from stepping forward in OTEC development. When considering what is really at stake with OTEC, this explanation seems politically correct, but highly disputable.

Opening the OTEC tap would open access to an energy resource that could probably cover as much as the annual world demand for primary energy as predicted for 2020 (the total power that could be continuously tapped by using the OTEC resource is of the order of magnitude of 10000 GW, equivalent to the power of thermal plants burning 15 G t.o.e. a year), but exploring this opportunity is not a priority for rich and powerful countries which directly or indirectly control the present global energy market. Indeed, in the present state of the world, OTEC can be viewed as best adapted to developing nations. Many are located in the South (close to or within the tropical zone) where the OTEC resource resides, and OTEC technology is better adapted to their present industrial capacity than oil and nuclear technologies. Opening the OTEC tap could be a promise to soften their dependence, decrease the vulnerability of their supply, reduce the burden of their energy bill, and give them new development for opportunities to face their predicted increase in population.

OTEC detractors claim the OTEC costs are not competitive with traditional supplies. However, this categorical general statement might be erroneous in isolated zones where traditional fuel prices are very high and nuclear energy inappropriate. OTEC by-production, e.g. fresh water, aquaculture, cooling, etc. is also a promising approach to economic viability. Moreover, the market price of traditional energy does not reflect its real cost due to ignoring many social, environmental, and political expenses, known as "externalities". A fair evaluation of externalities is a prerequisite to comparing, production costs of energy from different sources (The ExternE Project [3]).

One step for OTEC progress is the construction of a pilot plant of adequate size to build up the confidence of private investors. The main obstacle to that step is the high capital investment required. It is financially out-of-reach for those poor nations that would need it the most. After 1985 it appeared that only an international co-operative effort could gather the expertise and the necessary funding. The IOA International OTEC/DOWA Association was established in 1990 to promote such co-operation (the IOA was established in 1990 at the initiative and with the support of Taiwanese Authorities). Its attempt failed and the IOA was disbanded in 2003.

Looking back, in the OTEC history there was no evidence of any real will on the part of developed nations to invest and proceed within an international project. So, the excitement was great within the World OTEC community when Saga University of Japan and NIOT(National Institute of Ocean Technology) of lndia announced in 1997 that they agreed to a joint development of OTEC in India: a country with a large access to an abundant OTEC resource (The Indian 1 MW OTEC Plant [4]) that faces a dramatic increase in population and future demand in clean) energy. This 1MW floating plant has been built and installed at sea. The success of this pilote operation plant could be an important milestone in the development of OTEC industry. Unfortunately to our knowledge the results obtained by the Indian-Japanese venture have not been release to public yet.

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