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Ocean Thermal Energy Conversion Power Plant

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Abstract

A new era in the technology of Ocean Thermal Energy Conversion (OTEC), which is a system of converting thermal energy in ocean into electricity, has come now. The concept of OTEC was first proposed by French physicist in 1881. Since then, although many scientists have made earnest effort to materialization, OTEC has never commercialized yet. However the National Institute of Ocean Technology
(NIOT) in India succeeded to construct 1MW pilot OTEC plant, so called 'Indian plant', in 2001. As to the matter of thermal engineering, the Indian plant was fully supported by Saga University in Japan. In fact the Indian plant was pushed technical break through of innovative thermal cycle, which is called 'UEHARA CYCLE' invented in 1994, and its associated heat exchanger technology. The Indian plant has created a great sensation in the world, and it will be demonstrated in due course of time in 2002. Now many people are concerning the consequence of the Indian plant's experiments, and at the same time many countries have started to investigate the feasibility of OTEC.

OTEC provides not only power generation but also some solutions to the three greatest global issues we are facing in 21st century, i.e. 'Energy', 'Water' and 'Food' associated with the fundamental problems of environment destruction and population explosion. In collaboration among Saga University, Xenesys Inc., the title holder of execution right of patents registered by Saga University, and Hitachi Zosen Corporation, the partner in marine field, they are promoting several projects concerning the above technologies. As the ocean thermal energy is perfectly clean and renewable, and the potential is very huge, a bright future for the new OTEC technology and the wide application is prospected.

This paper describes an outlook and a trend of the new OTEC technologies spreading rapidly now in the world.

Keywords: *Ocen thermal Energy conversion, Closed Rankine cycle, Uehara Cycle, Heat Exchanger, DOW*

1. Introduction

Energy, water and food are some of the essential requirements for the continuation and evolution of mankind. Presently almost of all the energy depends on fossil fuels and nuclear power.

The world population is 6.1 billion in 2000, and it is still growing explosively. At the same time, energy consumed by human is also increasing explosively, as shown in Fig.1. By considering future economic

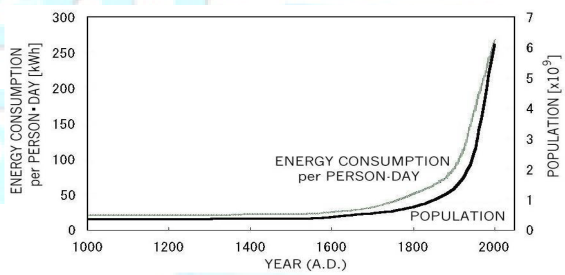

Fig.1. Population and Energy Consumption/Person-Day

growth and environmental problems it is obvious that in the 21st century we cannot rely on the current mainstream resources, i.e. oil, coal, and uranium for the world energy supply. Thus, we must face the urgent and important problem of developing an alternative energy source to fossil and nuclear fuel. For the alternative energy sources we can easily consider, for example, such as wind, solar and geothermal power. However, ocean energy should become also an important potential energy source which must be obtained.

Among the various forms of ocean energy, the ocean thermal energy is plentiful and very stable.

During the last decade, the technology of OTEC has been made great strides. It is worthy of special mention that OTEC technology is easily applicable in many industrial fields for recovery and saving of energy in lower temperature range and small thermal head.

Fig. 2 Indian Plant "SAGAR-SHAKTHI".

The world's first conceptual invention to utilize thermal energy stored between warm surface seawater and cold depth seawater was formed by a French physicist Mr. J. D'Arsonval. It was in 1881. In that same year 1881, the world's first thermal power generator was made. In 1883, Mr. De Laval, a Swede, has manufactured the world's first thermal steam turbine. 1880s remained however an infant era of power generation technology in general.

Another French scientist Mr. G. Claude had inherited the idea of D'Arsonval and had worked on it as his life work but could not make much progress. One of the reasons of his repeated failures can be laid on the fact that he had attempted with an open thermal cycle system.

In 1964, J. H. Anderson and his junior conceived of a new closed cycle OTEC plant, which overcome the weak point of Claude's system. This invention of Anderson's attracted considerable attention and created the opportunity for rekindling research concerning OTEC. Later, the first energy crisis in 1973 provided the motivation for Japan and U.S. to perform fundamental research. Since that time, actual OTEC plants had been constructed in rapid succession.

In the meantime, a new movement had come around 1980s and 90s. Before then, however, the Rankine cycle providing with single composition medium as working fluid was the common practice being applied for closed cycle OTEC, an American physicist Dr. Alex. Kalina invented a new heat cycle, so called Kalina cycle, for thermal energy conversion using ammonia/water mixture as working fluid, in 1985. Subsequently, a more advanced cycle was invented by Japanese physicist Dr. H. Uehara, who is one of the authors, in 1994. For coming such advanced cycle technology, possibility of commercial OTEC has become greater.

Looking at the current from another view, the necessity due to developing practical solutions to CO_2 reduction against global warming has been bringing earnest expectation on OTEC. One of typical aspects in this trend is the world first 1MW class OTEC experiment project being proceeded in India. According to the program, the Indian Plant will be demonstrated in 2002. Fig.2 shows snaps of the Indian plant.

2. OTEC Principles

OTEC is one of natural and renewable energy of course. Comparing to the other natural energy resources, the ocean thermal energy has the following characteristics.

1) Clean and renewable (solar source energy) 2) Stable throughout a moment, a day and a year. 3) Huge amount but low-density energy

Some of temperature distribution of ocean seawater measured in vertical direction in tropical and subtropical zones are shown in Fig.3. Sea water temperature in the surface layer is a warm 20~30℃, while that is a cold 2~7℃ in the deep layer about 700m in depth.

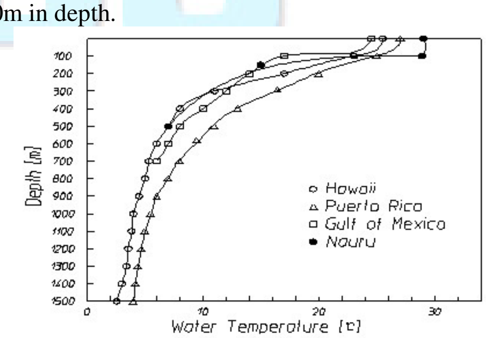

Fig.3. Distribution of Seawater Temperature.

OTEC obtains the thermal energy associated with the temperature difference between the warm seawater in surface layer and the cold seawater at greater depth. When there are any thermal head, the heat should transfer from higher temperature side to lower temperature side naturally. It is the thermal cycle technology to convert thermal energy into power, i.e. kinetic and/or electric energy.

Open cycle, closed Rankine cycle, Kalina cycle and Uehara cycle are considerable for thermal cycle of OTEC at present.

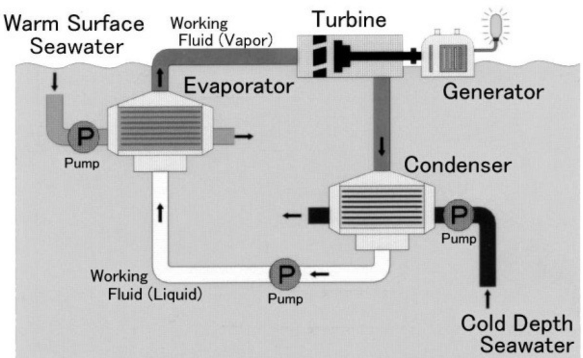

Fig.4. Principle of OTEC (Closed Rankine cycle).

Fig.4 shows a OTEC principle of closed Rankine cycle. A single pure thermal medium is used for the cycle as working fluid. The working fluid is circulated in a closed circuit system. The system consists of a feed pump, an evaporator, a turbine and a condenser. The fluid is heated in the evaporator by warm seawater, and then the fluid evaporates into vapor. The vapor is led to the turbine and works for power generation. The fluid exhausted from the turbine is cooled down and re-liquefied in the condenser by cold depth seawater. By repeating this cycle, power can be generated without any assists of fuel.

Recent research and development to OTEC have been pursued using closed cycle application with ammonia as working fluid.

The closed Rankine cycle OTEC is essentially the same cycle as that employed for ordinary thermal power plants as well as nuclear power generation. There are some decisive differences, however, between ordinary power generation systems and OTEC. One is the difference of thermal head, in other words, temperature difference between evaporation and condensation. Another is the working thermal medium for which water (H_2O) is used in ordinary power generation, while low temperature boiling fluid e.g. ammonia (NH_3) is used in OTEC. And above all, no any fuel like fossil or nuclear fuel but seawater is needed for OTEC.

Looking back the history of thermal cycle technology, every approach was tried with the Rankine cycle, of which theory was established by Rankine in 1851, but invented by Watt in 1769. The Rankine cycle is to use single thermal medium as said before.

In 1985, Dr. Kalina put forward a new cycle employing quite a different concept providing with

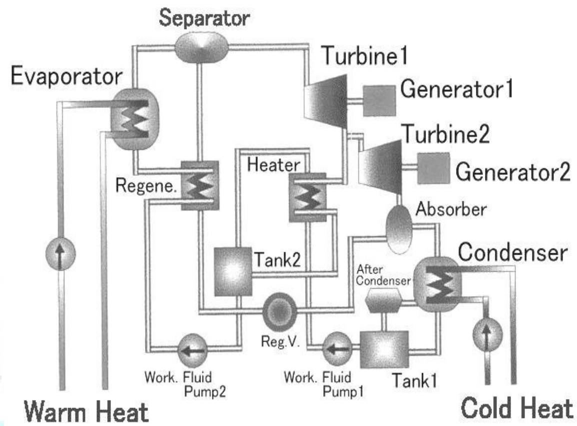

Fig.5. Block Diagram of Uehara Cycle

ammonia/water mixture as heat medium. The new cycle, so called 'Kalina cycle', attained epochmaking improvement of cycle efficiency, which was a large jump up on previous known cycles. For instance, however the efficiency is varied depending upon condition, under the condition of 28℃ warm water and 4℃ cold water, expected thermal cycle efficiency of conventional Rankine cycle to be approx. 3%, while approx. 5% efficiency is to be expected by applying Kalina cycle.

However, there is a demerit caused by mixture medium employed in thermal cycle. That is the increase of load on heat exchangers particularly on condenser.

For the purpose of relieving condenser load, a new thermal cycle using ammonia/water mixture is invented, in 1994. That is so called 'Uehara cycle'. Uehara cycle assures theoretically higher efficiency than Kalina cycle by lessening the load for condenser by means of extraction of vapor from the turbine. It should be possible now to construct an OTEC plant of more compact in size but higher in efficiency than before.

A schematic block diagram of Uehara cycle is shown in Fig.5, and Fig.6 shows the experimental plant of Uehara cycle in Saga University.

3.Evolution of Heat Exchanger

Evaporator and condenser are two vital components for success of the OTEC. It is thus needed to develop highly effective evaporators and condensers in order to improve the total efficiency and hence to improve the economics.
In OTEC a power generating system uses huge provided much higher heat transfer efficiency than ordinary tubular type. Consequently, required flow quantity of both warm and cold water is reduced drastically, and thus required power for both surface and deep seawater pumps is decreased and total system efficiency goes up. Comparison of required seawater quantity between conventional closed Rankine cycle with ordinary tubular type heat exchangers and latest Uehara cycle with advanced plate type ones is shown in Table 2. The final designs and other related criteria worked out by Saga University have been transferred to Xenesys Inc. for their commercial undertaking. Xenesys is expected to announce shortly the delivery availability of evolutionary style heat exchangers for dual phases application of vapor and liquid.

Table 1: Comparison of Required Seawater

	Conventional Rankine	*Advanced Uehara*
Warm surface seawater	*200 m ^{3}/s*	*110 m ^{3}/s*
Cold Depth seawater	*200 m ^{3}/s*	*120 m ^{3}/s*

4. Multiple Industrial Complex with OTEC

In Japan, the research and development for 'Multiple OTEC System', which utilizes the potential of Deep Ocean Water (DOW), have been performed in progress. The image of 'Multi-OTEC' is shown in Fig.7 and considerable systems associated with OTEC are described as follows.

1) Desalination

The Saga University has developed a spray-flush type desalination system. By this system around 1% of raw seawater quantity is to be distilled to pure fresh water. To combine the OTEC and this desalination system, the capability of desalination is quite huge; i.e. the obtainable distilled water capacity is approx. 10,000 m^3/day with 1MW OTEC, approx. 1,000,000 m^3/day with 100MW OTEC.
It is remarkable that the fresh water obtained can be utilized as resource of hydrogen as described later. Fig.8 shows the demonstration plant of spray-flush desalination made by Saga University.

2) Mineral Water Production

DOW is rich in mineral. It is possible to produce 'Mineral water' as by-product of the OTEC. Providing with ion-exchanger and mineralizer, a part of desalinated water comes more valuable industrial product. Mineral water is one of most anticipated byproduct of OTEC in order to promote a sustainable local industry, particularly for island countries.

3) Lithium Extraction

Lithium is the one of important industrial metal as the material of battery. Extracting chloride-lithium dissolved in seawater is one of considerable method of industrial lithium production. For such lithium extraction from seawater, purity of DOW provides longer cleaning interval of seawater contact surface material polluted with impurity of seawater, because DOW is much purer than seawater in surface layer. This is a big advantage of feasibility from the economical point of view.

4) Air Conditioning

Tropical condition suits for OTEC as a matter of course. In the tropical area there is a need for cooling air conditioning for office, hotel, etc. For that purpose OTEC is useful. The temperature of depth cold water after utilization for OTEC is still low; e.g. the temperature is to be around 10°C. It is cold enough to use as chilling source of air cool conditioning. Such air conditioning system requires much less energy than that is needed by ordinary electrical refrigeration method. It means that OTEC makes demand of electricity decrease ecologically.

5) Aquaculture

The characteristics of DOW are cold, pure and nutrient. These characteristics can be used effectively to aquaculture by getting rapid growth and less disease.
In these years, another approach has made for fishery fertilization by using nutrient DOW in Japan. Dr.

Ouchi and his colleagues are developing an architectural sea area fertilizer unit incorporated with OTEC as an energy source of density current generator system.

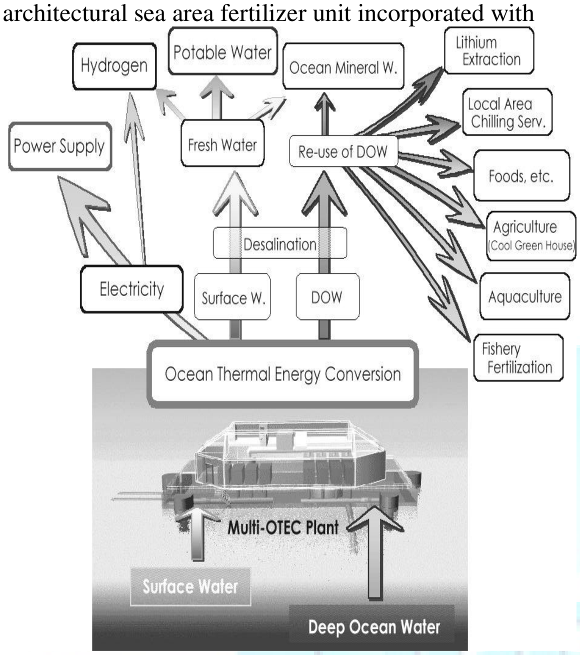

Fig.6. Image of Multiple-OTEC Station.

6) Food, Cosmetics, Medical Science, etc.

Due to surpassing characteristics DOW draws attention in the various fields of industry and science. In Japan DOW is utilized for food processing of 'Sake', 'Tofu', etc. and some cosmetics made of DOW have got public favour.

Effects of DOW attract medical scientist's attention. It has been said that DOW is efficacious against atopic allergy dermatitis. Thalassotharapie, which is a kind of medical treatment for relaxation, is also one of DOW utilization.

OTEC can provide such broad utilization.

6) Hydrogen Production

To look a little further future, it should be considered "Offshore Hydrogen Production Platform" by OTEC. This concept provides completely clean hydrogen production by using only natural renewable energy. Considering the tendencies of fuel-cell and microgas-turbine, the tide of shifting the basic industrial fuel from fossil to hydrogen would possibly come sooner than expected in common. As a consequence of such thinking, it may be not so far dream that hundreds MW class OTEC for hydrogen generating station to be built as a kind of fundamental energy supplier.

5.Economical Feasibility of OTEC

It goes without saying that economy is one the key elements for verification of OTEC power plant. Advanced studies made thus far on thermal cycle and heat exchanger have brought promising results of far improved efficiency of OTEC system as a whole. Although the efficiency of system itself varies depending upon temperature conditions, Uehara cycle can attain a 30~50% higher efficiency as compared to Rankine cycle. Thanks to the highly effective plate heat exchanges newly developed by Saga University, the power consumption of pumps for cold and warm seawater can be lowered to 30~40% of the conventional case. Considering all new achievements, we can easily predict the latest OTEC technology produce twice as much net power from the same heat source as the conventional OTEC.

In addition to such great improvement of the capability, the reduction of cold depth water quantity with advanced condenser provides smaller sized configuration of piping for DOW riser piping, and thus the economical performance is much improved.

Various accounting models have been applied to determine the cost for the OTEC system. As example of trial calculation, the cost of electricity generated by the OTEC is estimated by NIOT (India), who is now proceeding experiment with 'Indian plant', as shown in Table 2.

According to several accounting models, it has been determined that for a large plant of 50~100MW, the unit cost would be competitive with a coal-fired power station, while for a small plant of 1~5MW the unit cost would be about the same or less than that of a diesel power station.

Table 2: Estimation of Unit Cost of Electricity from OTEC Power in India (1999)

Power Output Gross (MW)	1	25	50	100
Power Output Net (MW)	0.617	15.39	30.88	64.23
Heat exchanger cost (Mill.US $)	1.70	44.40	88.22	152.58
Cost of cold w. pipe (Mill.US $)	0.69	1.74	2.67	4.65
Cost of barge (Mill.US $)	0.69	2.33	4.65	9.30
Mooring cost (Mill.US $)	2.09	3.49	4.65	5.81
Turbine + Inst. Cost (Mill.US $)	1.16	17.44	34.48	69.76
Total cost (Mill.US $)	6.42	69.42	134.67	242.10
Cost of electricity (US$/kWh)	0.189	0.082	0.079	0.068

Table 3: Expected Output of B y-products

Gross Power Output (MW)	***1***	***10***
Net Power Output (MW)	*0.7*	*7.5*
Net Electricity (MWh/year)	*4,900*	*52,500*
Up-welled DOW (t/h)	*4,700*	*43,300*
*Fresh Water (t/h) (*1)*	*1,100*	*10,000*
*Hydrogen (Nm^3/h) (*1)*	*2,000*	*22,000*
Chloride Lithium (kg/day)	*30*	*260*
*Mineral Water (bottle/day)(*2)*	*16,000*	*150,000*

However OTEC is valuable not only in power generating, but in additional activities. The expected quantities of main by-products of OTEC are shown in Table 3. In case of applying $20m^3$/day mineral water production facility with OTEC, for example, total amount of mineral water output is estimated approx. 600 million JP¥ per year based on unit price of 100 JP¥ per litter and 85% operation rate.

6.New Aspects of OTEC Development

One of the major causes for global warming is said to be attributable to heavy dependence upon fossil fuel for electricity. Nevertheless, a number of countries have been relying on diesel generators for their electricity, since they have had no alternative to take up. But now, the story is getting different turn. Some of island countries in the south Pacific region, whose life is being threatened by rising sea level, have started to look into the OTEC more seriously than ever. For instance, a technical collaboration agreement was signed in April 2001 by and among the Republic of Palau, Saga University and Xenesys Inc. The President of the Republic of Palau expressed at a news conference his determination to replace their diesel power stations with OTEC power plants at an earliest possible date.

Positive movement is recognized in Japan, too. Japan is well known as world-leading country in shipbuilding industry. In order to realize the OTEC, technologies developed and accumulated in shipbuilding industry are very helpful. Hitachi Zosen Corporation, one of the world-most advanced shipbuilding companies in Japan, has started to develop conceptual design for several OTEC applications with the latest technologies in alliance with Saga University and Xenesys Inc.

For the sake of commercialization of OTEC, research and development program should be followed up by demonstration and dissemination activities. For the progress of commercialization, practical strategies are considered as follows.

Step 1: Construction of a 1MW class OTEC for demonstration. The project should be conducted governmentally sponsored body to provide practical usefulness. Image illustration of this class OTEC is shown in Fig.12.

Step 2: Construction of a prototype OTEC plant with 5~10MW for dissemination. The plant should be built somewhere in island countries in the Pacific Ocean probably sponsored by government to government official development assistance. The OTEC is very beneficial for the island nations, since it is to provide not only clean energy but also local industries by multiple usage of DOW resource. Image illustration of the OTEC in this step is shown in Fig.13.

Step 3: Promotion of commercial scale OTEC with 50~100MW. The plant should be built as basic energy source. At this step, the designing of standardized offshore type OTEC power station will be worked out for verifying the economic competitiveness in this range. Image illustration of the OTEC in this step is shown in Fig.14.

Needless to say, assessment of environmental conditions by introducing an OTEC power plant is also a part of the majors concerns in executing each of the above steps.

According to preliminary prediction, in regard to enterprise, it would be expected that total 1,000MW of Multi-OTEC station would be built in Japan annually in near future. At that time, it means that a new industry having 1.5 trillion JP¥ annual production amount and 10 thousand employment will arrive in Japan.

7. Forecasting Future

Although the density of energy is comparatively poor, the ocean provides us a huge amount of thermal energy. Today, the new OTEC technology made possible to extract the energy practically from the ocean realistically. A suitable area for OTEC spreads over very wide range of the world from the tropics to semi-tropics. An advantage of the OTEC technology should be emphasized on not only its tremendous potential for power generation but also the convenient feature that can disperse the power plant with proper cost of the electricity generation. The cost will become competitive with that of the conventional fossil fuel burning power plant as well as nuclear in the near future.

The desalination technology as by-product of the OTEC can produce a large amount of fresh water from seawater for which the island nations and the other desert countries longing eagerly.

Besides, the DOW exhausted from the OTEC plant would contribute to world food security with fishery fertilization.

It is the OTEC, which has a potential to become powerful solution to three greatest global issues of Energy, Water and Food without vital harmful influence on irreplaceable earth environment.
In conclusion, the new OTEC and the derivative technologies would offer the best promise to bring humankind prosperity beyond measure in the 21st century.

Fig.7. Image of 1MW Class OTEC.