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Review

Introduction of State-of the-Art of Deep Ocean Water Applications

Koji OTSUKA[1]

Abstract

Deep ocean water (DOW) is seawater found at depth of several-hundred meters or deeper, and has attracted special interest as one of the renewable resources with great potential, since the large amount of cold and stable DOW is renewed in thermohaline circulation such as great global conveyer. DOW has also been focused as important resource for enhancing marine primary production, because DOW contains much inorganic nutrients, such as nitrogen, phosphorus and silica. In this paper, we describe fundamental features of DOW, and introduce the state-of-the-art of DOW applications, such as ocean thermal energy conversion (OTEC), air conditioning, fisheries application, agricultural application, freshwater production, and so forth.

Key Words: Deep Ocean Water, Renewable Resources, Low Temperature, Moderate Nutrient Concentration, Low Viable Bacterial Count

1. Introduction

World population has increased rapidly following the industrial revolution, reaching 7.8 billion in 2020 as shown in Fig. 1 (FAOSTAT). Meadows *et al.* (2004) reveal serious problems concerning global water, food and energy supply to meet the needs of this growing population. Growth in these resource productions has been accomplished through tremendous use of fresh water, chemical fertilizer and fossil fuels. This, in turn, has resulted in depletion of water resources, expanding areas of infertile land, climate change, and so forth.

It is well known that 70% of the earth surface area is covered by the ocean. The difference of three-dimensional capacity between ocean and land is much bigger than that of the surface area. While the average height of the land is 840 m, the average depth of the ocean is 3,800 m. The ocean is also abundant in water and carbon resources, which are fundamental materials of organisms, and stores 97% of water and 85% of carbon on the earth. Therefore, it is necessary to change the land-based conventional production systems into the ocean utilization systems for sustaining human life with increasing world population.

Deep ocean water (DOW) is seawater found at depth of several-hundred meters or deeper, and has attracted special interest as one of the renewable resources with great potential, since the large amount of cold and stable DOW is renewed in thermohaline circulation such as great global conveyer. DOW has also been focused as important resource for enhancing marine primary pro-

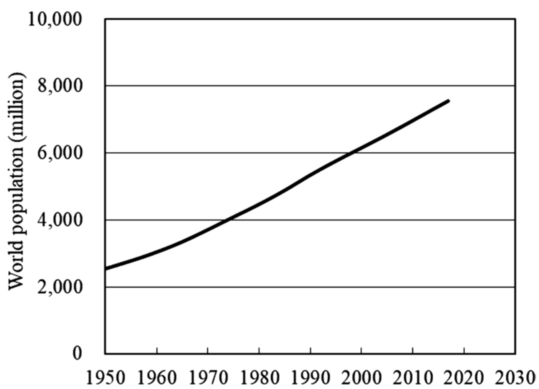

Fig. 1 World population trend (FAOSTAT)

[1] Osaka Prefecture University (1–1 Gakuencho, Nakaku, Sakai, Osaka 599–8531, Japan)

duction, because DOW contains much inorganic nutrients, such as nitrogen, phosphorus and silica. In this paper, we describe fundamental features of DOW, and introduce the state-of-the-art of DOW applications, such as ocean thermal energy conversion, air conditioning, fisheries application, agricultural application, freshwater production, and so forth.

2. Features of Deep Ocean Water

DOW has several remarkable features, such as low temperature, moderate nutrient concentration, and low viable bacterial count, in comparison with surface seawater. As shown in Fig. 2, year-averaged surface water temperature in north Pacific Ocean is around 20℃, while the temperature drastically decreases with increasing water depth at −500 m or deeper, and reaches to 5℃ at the depth of −1,200 m (Fujita and Takahashi, 2006).

This "low temperature" characteristic is caused by global thermohaline circulation. Stommel and Arons (1960) proposed an abyssal circulation model shown in Fig. 3, which is based on a lot of ocean monitoring data and geophysical theory. They estimated budget of transports in various portions of the world ocean using the model. The estimated results suggest that seawater of 40 Mt/s circulates in deep layer and distributes to each ocean in proportion to the volume of each ocean. This means that those amounts of DOW are renewed by a great global conveyer.

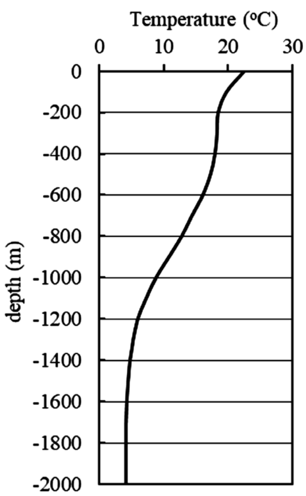

Fig. 2 Water temperature profiles in north Pacific Ocean (Fujita and Takahashi, 2006)

As shown in Fig. 4 (left), while the nutrient concentration in north Pacific Ocean is almost zero at the surface layer, the value drastically increases with increasing the water depth, and saturates at the depth of −700 m (Fujita and Takahashi, 2006). This "moderate nutrient

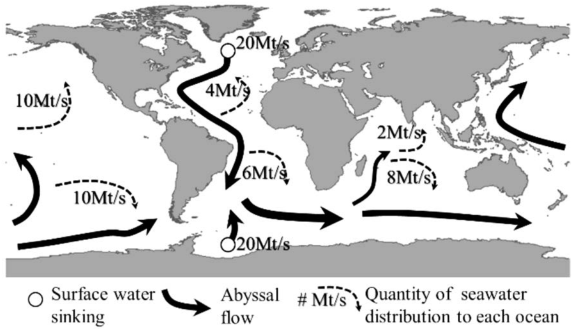

Fig. 3 Abyssal circulation model (Stommel and Arons, 1960)

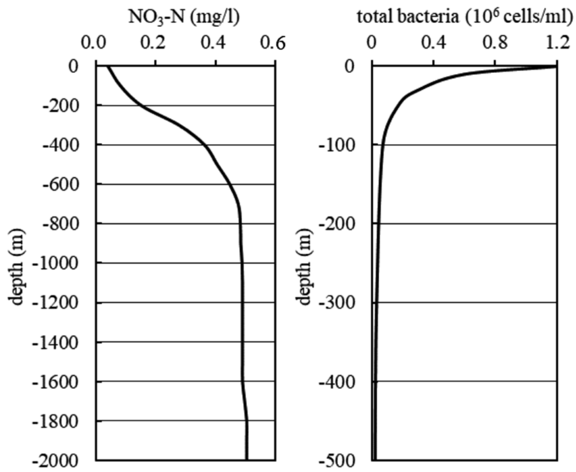

Fig. 4 Nitrate (Fujita and Takahashi, 2006) and total bacteria (Naganuma *et al.*, 1990) profiles in north Pacific Ocean

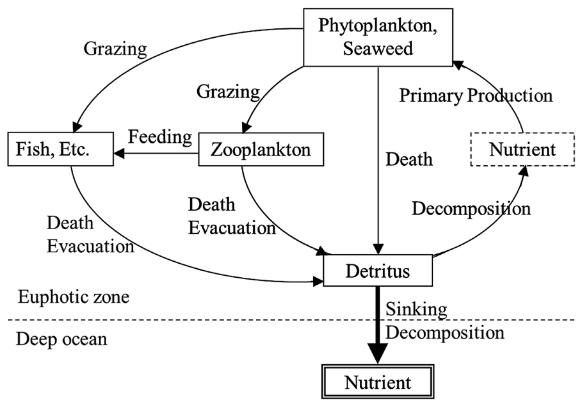

Fig. 5 Soft-tissue biological pump

concentration" characteristic is caused by soft-tissue biological pump shown in Fig. 5. Inorganic nutrients in euphotic zone are rapidly utilized by primary producers, such as phytoplankton in the photosynthesis process. The organisms thus produced finally change into detritus via grazing, feeding, evacuation and natural death. This detritus sinks to the deep ocean with decomposition by bacteria. The nutrients reproduced by the decomposition are stored in the deep ocean, since there is not enough light intensity for photosynthesis. Therefore, DOW contains moderate inorganic nutrients and very little organic matters.

As shown in Fig. 4 (right), the viable bacterial count in the surface layer is large, because of active material circulation and large detritus concentration as shown before. However, the value drastically decreases with increasing water depth, since only decomposition occurs in the deep layers (Naganuma *et al.*, 1990). This "low viable bacterial count" is also caused by the soft-tissue biological pump.

3. Deep Ocean Water Applications

DOW has three significant features, such as low temperature, moderate nutrient concentration, and low viable bacterial count. Utilizing these features, various DOW applications have been developed as shown in Table 1. In this section, we introduce the state-of-the-art of DOW applications, such as ocean thermal energy conversion, air conditioning, fisheries application, agricultural application, freshwater production, and so forth.

Table 1 Various DOW applications and the features that they utilize

Applications	Low temperature	Moderate nutrient concentration	Low viable bacterial count
Ocean thermal energy conversion	X		
Air Conditioning	X		
Fisheries application	X	X	X
Agricultural application	X		X
Fresh water production			X
Medical and healthcare uses			X
Cosmetics, foods and drinks			X

3.1 Ocean Thermal Energy Conversion

Ocean thermal energy conversion (OTEC) is based on the use of the temperature difference between cold DOW and warm surface water to generate electricity as shown in Fig. 6. There are two basic types of OTEC systems (Avery and Wu, 1994). In the closed-cycle system (CC-OTEC), a low boiling point working fluid (e.g. ammonia)is alternately evaporated by the surface water and condensed by the DOW. A turbine generator is employed to extract a portion of the thermal energy received from the warm surface water. For the open-cycle system (OC-OTEC), surface water is flash-evaporated in vacuum chamber and condensed by the DOW. This process can produce desalinated fresh water as a by-product.

Two prototype CC-OTEC plants have been constructed in Japan and Hawaii one after another. In April 2013, an operation of a 100 kW-scale OTEC pilot plant started at Okinawa Prefectural Deep Sea Water Research Center in Kumejima Island, Japan (Fig. 7). This center was established in 2000, and intakes DOW of 13,000 t/d from the depth of −600 m. In August 2015, another 100 kW-scale OTEC pilot plant opened at Natural Energy Laboratory of Hawaii Authority (NELHA) in Big Island, Hawaii (Fig. 8). This laboratory was established in 1974. They have three sets of pipelines delivering

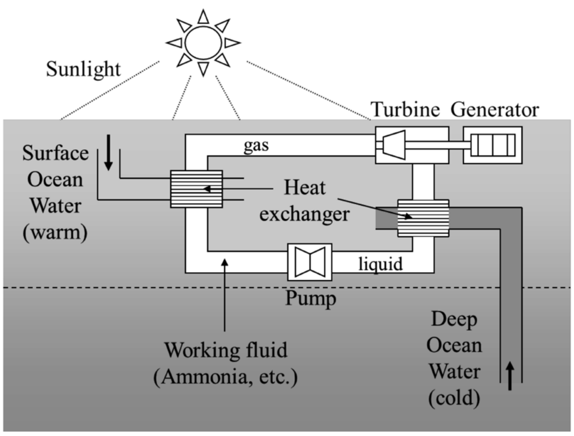

Fig. 6 Concept of ocean thermal energy conversion (OTEC)

Fig. 7 100 kW OTEC pilot plant in Kumejima Island, Okinawa

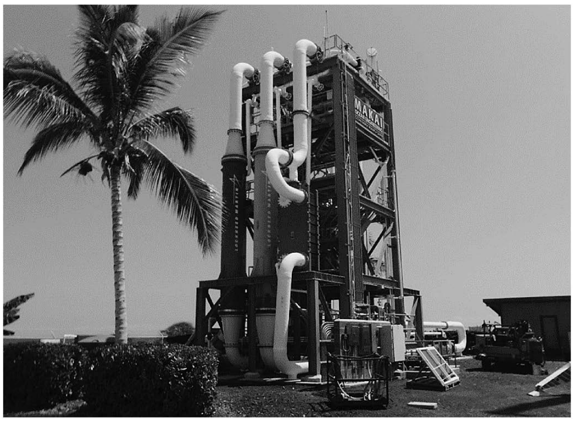

Fig. 8 100 kW OTEC pilot plant in Big Island, Hawaii

Fig. 9 Seaweed-abalone mixed farming in Big Island, Hawaii

Fig. 10 Vegetable cultivations in Kumejima Island, Okinawa

DOW from up to about −900 m depth, and the system is capable of pumping up to 540,000 t/d.

3.2 Air Conditioning

The DOW air conditioning system is very simple, for example, cold water pipelines are directly distributed into buildings, or the heat exchanges between DOW primary closed loop and freshwater secondary closed loop. These systems use only small fractions of the electrical power required for conventional systems and have been demonstrated to be reliable and cost effective (Van Ryzin and Leraand, 2000). Additional benefits cited include the availability of the refrigeration for food storage system, and ice production.

One of the typical examples of the DOW air conditioning can be observed at The InterContinental Bora Bora Resort & Thalasso Spa in French Polynesia. They equiped DOW air conditioning system, and save 90% of the electricity consumed by a conventional cooling system. Wooke Corporation in Toyama prefecture, Japan has a unique multi-step DOW utilization system. They equipped a heat exchange-type DOW air conditioning system to cool their boiled rice factory, and utilize the heated DOW for abalone cultivation.

3.3 Fisheries Applications

Land-based DOW aquacultures have been widely spread in Japan, Taiwan, Korea and Hawaii. Utilization of the moderate nutrient concentration DOW raises the yields of microalgae and seaweed, and the high purity and the ability of water temperature control of DOW greatly increase growth rates of fish, shellfish, lobsters, and so forth. Fig. 9 shows an example of the seaweed-abalone mixed farming in Big Island, Hawaii. At present, a land-based aquaculture of "virus-free oyster" using

DOW is tried in Kumejima Island, Japan.

In Rausu fishing port in Hokkaido in Japan, they use frozen DOW to keep the freshness of fish. They also use DOW to wash all floors inside the fishing port, and gain HACCP certification.

3.4 Agricultural Applications

Soil temperature control for agriculture was first performed at NELHA in Big Island, Hawaii (Daniel, 1992). Thin cold-water pipes are stretched around cultivated lands to cool the soil. Dewdrops made on the thin cold-water pipes give moistures. Some vegetables and fruits, which are usually cultivated in cold district, can be harvested in such a tropical island. This technology is applied to vegetable cultivation facilities in Kumejima Island, Japan (Fig. 10).

3.5 Freshwater Productions

There are two types of desalination processes as shown in Fig. 11. One is an evaporation method, such as heating and vacuum evaporations. The OC-OTEC includes vacuum evaporation process. Another is a membrane process, including reverse osmosis (RO) and electrodialysis (ED). Surface water desalination using the membrane process requires troublesome pre- and post-treatments, such as suspended material filtration and sludge drain. These treatments can be omitted in the membrane desalination using DOW containing very little suspended materials. Many bottled drinking waters are produced in Japan, Taiwan, Korea and Hawaii. Fig. 12 shows the RO desalination units in Big Island, Hawaii.

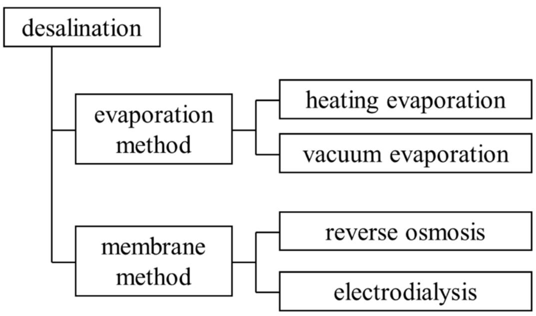

Fig. 11 Seawater desalination technologies

3.2 Other Applications

Medical and health care uses were focused as one of the DOW applications in Japan since 1990's. A research on treatment of allergic dermatitis have been carried out in some places in Japan. DOW applications for healthcare goods and cosmetics have been also focused in Japan since 1990's. At present, many healthcare goods and cosmetics are also produced in Korea and Taiwan (Fig. 13).

The first thalassotherapy facility using DOW opened in 1998 in Toyama Prefecture, Japan. After that, some similar facilities have been constructed in Japan.

The other DOW applications are in productions of beverages and eatables. A lot of merchandises are sold in Japanese, Taiwanese and Korean markets. They have very popular, because they are tasty and good for health.

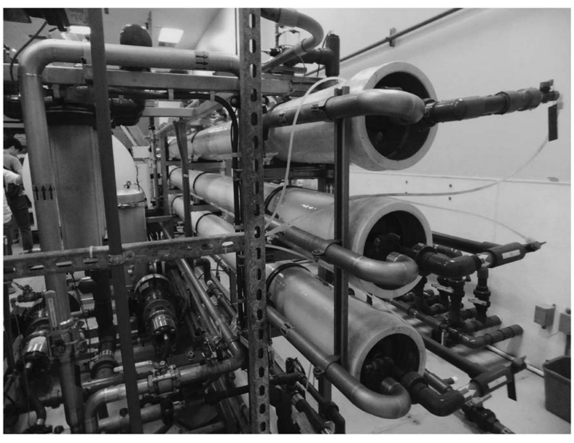

Fig. 12 Reverse osmosis desalination units in Big Island, Hawaii

Fig. 13 DOW cosmetics shop in Hualien, Taiwan

4. Conclusions

DOW has three significant features, such as low temperature, moderate nutrient concentration, and low viable bacterial count. These features can be utilized for various applications, and also for multi-purpose or multi-stage productions. As shown before, 100 kW-scale OTEC pilot plant is operated in Kuejima island. They are planning to install new big pipeline capable to 180,000 t/d, and upscale the OTEC 10 times larger than the present. They have a plan to establish a system of cascade use of the heated up DOW for many applications, such as air conditioning, fishery and agricultural applications, freshwater and cosmetics productions, and so forth. This concept is called Kumejima model, and will become a role model for many island counties.

After regime change of US government, global trends of countermeasures against climate change have been rapidly accelerated. Pandemic of COVID-19 has strongly enhanced our health conscious. OTEC has great energy potential, and is one of the most stable renewable energies. DOW can be applied to many kinds of medical and health care utilizations. These facts suggest that technologies of DOW applications are more and more important as indispensable technologies to achieve sustainable development goals (SDGs).

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