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Opportunities and challenges of ocean thermal energy conversion technology

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1 Introduction

With the rapid development of the world economy, the energy crisis and environmental issues have become two important issues facing humanity. Developing and utilizing renewable and clean energy is an effective way to relieve the pressure of the energy crisis and environmental issues. The energy received daily from the sun is sufficient to supply all the energy needed on the earth for a year (Chapo, 2008) and about 80% of the solar energy reaching the earth is absorbed by the ocean (Malik et al., 2020). Therefore, ocean energy has attracted wide attention due to its abundant resources, clean and stable characteristics. Ocean energy can be divided into ocean thermal energy, salinity energy, tidal energy, current energy and wave energy. The above types of ocean energy have the potential to be used as alternatives to traditional fossil energy.

Ocean thermal energy is the energy contained in the temperature difference between the surface warm seawater and the deep cold seawater. Between 25°N and 25°S, the surface seawater temperature is above 26°C (Nithesh et al., 2016), and the deep seawater temperature at 900 m below the sea surface is maintained at 4°C–6°C (Yang and Yeh, 2014). The reserve of ocean thermal energy is second only to wave energy in all ocean energy. Ocean thermal energy can be utilized in many forms, such as power generation (Rajagopalan and Nihous, 2013), refrigeration (Bian et al., 2019), hydrogen generation (Khanmohammadi et al., 2020) and desalination of seawater (Park et al., 2014). Ocean Thermal Energy Conversion (Abbreviated as OTEC) (Rajagopalan and Nihous, 2013) technology utilizes the temperature difference between the surface warm seawater and the deep cold seawater to generate electricity through heat exchangers and turbines. If all the ocean thermal energy is used for power generation, 87,600 TWh of electricity can be generated every year, which is more than five times the annual global electricity demand (Khan et al., 2017). Due to the enormous potential of ocean thermal energy in power generation, many coastal countries, including the United States (Mitsui et al., 1983), China (Yang and Yeh, 2014), and Japan (Johnson, 1989; Marti et al., 2064) have conducted research on ocean thermal energy conversion technology.

In this paper, the development status of OTEC technology is introduced in detail, and the potential challenges and development prospects of OTEC technology in future applications are discussed, so as to provide reference for the development and utilization of renewable energy.

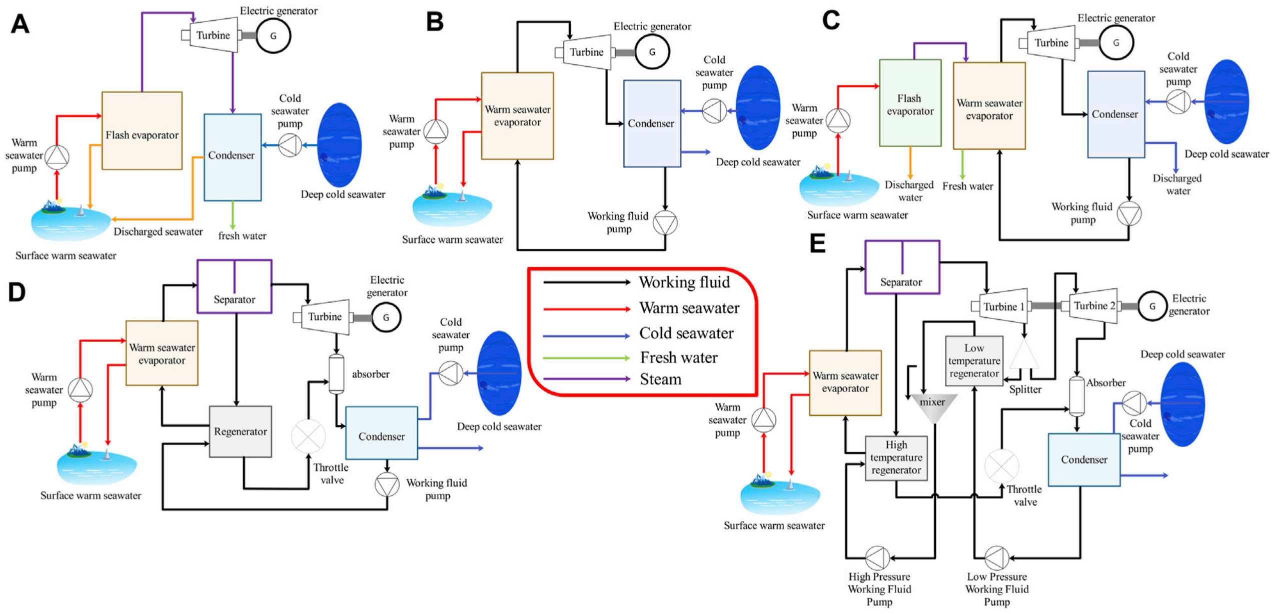

FIGURE 1
Schematic of the **(A)** open cycle, **(B)** closed cycle, **(C)** hybrid cycle, **(D)** Kalina cycle, and **(E)** Uehara cycle.

2 Development status of OTEC technology

The OTEC system can be divided into three basic types: open cycle, closed cycle (Sherwood, 1995) and hybrid cycle (Heydt, 1993). The open cycle was first proposed by Georges Claude, who established an open cycle power generation device with an output power of 22 kW in 1929 (Claude, 1930). The thermal efficiency of open cycle was only about 0.7% (Takazawa et al., 1996) This system consisted of flash evaporator, turbine, electric generator, condenser and seawater pump, but due to site selection and construction technology defects, the system failed to achieve net power output. Figure 1A shows the schematic of the open cycle system. The surface warm seawater is pumped into the flash evaporator by a warm seawater pump, where the warm seawater is vaporized. After vaporization, the steam enters the turbine to drive the generator for power generation, and then enters the condenser and is condensed into fresh water by deep cold seawater. The structure of the open cycle is simple, and seawater is used as the working fluid, whcih has the advantages of environmental protection, pollution-free, and can produce fresh water while generating electricity. However, its disadvantages are also obvious: the flash evaporator volume is huge and the sea water pump has high power consumption.

The closed cycle was first proposed by D'Arsonval in 1881 (D'arsonval, 1881), this system consisted of evaporator, turbine, condenser, electric generator, working fluid pump and seawater pumps. The thermal efficiency of closed cycle was about 2.1% (Flynn and Cicchetti George, 1997). Figure 1B shows the schematic of the closed cycle system. The surface warm seawater is sent into the evaporator by the warm seawater pump to exchange heat with the working fluid, and the working fluid is vaporized in the evaporator. The vaporized working fluid enters the turbine and drives the electric generator to generate electricity. And then the working fluid enters the condenser and exchanges heat with the cold seawater. Finally, the condensed working fluid is pumped into the evaporator to complete a full cycle. Compared to the open cycle, the closed cycle has a smaller equipment size and lower construction costs.

The hybrid cycle was first proposed by Vega et al., in 1989 (Vega, 2002). Figure 1C shows the schematic of the hybrid cycle system. The thermal efficiency of hybrid cycle was 1.6% (Panchal and Bell, 1987). The warm seawater is pumped into the flash evaporator by the warm seawater pump, and then flash to generate steam. Steam enters the evaporator and exchanges heat with the working fluid. The working fluid is evaporated in the evaporator, while the steam is condensed into fresh water. The evaporated working fluid enters the turbine and drives the generator to generate electricity, and then the working fluid enters the condenser for heat exchange with cold seawater. The condensed working fluid is pumped into the evaporator to exchange heat with steam, and the cycle continues (Heydt, 1993). The advantages of the hybrid cycle are high system efficiency and the ability to generate fresh water while generating electricity. However, the hybrid cycle has the disadvantages of too complex structure and low economy.

Early ocean thermal energy conversion systems were all Rankine cycles with simple structure, and the closed cycle is the most widely used system (Chen et al., 2010). However, the thermal efficiency of Rankine cycle was only about 3% (Kleute et al., 2009), because the temperature difference between surface warm seawater and deep cold seawater was only 15–25°C (Jung et al., 2016; Ikegami et al., 2018). Therefore, the researchers began to conduct further research and exploration on more efficient ocean thermal energy conversion technology. Karina cycle was proposed by Karina in 1981 and the ammonia-water mixture was used as the working fluid (ZhangHeZhang, 2012). Compared with the Rankine cycle, the Karina cycle has an additional subsystem for fractionation. Figure 1D shows the schematic of the Karina cycle system. The basic ammonia solution becomes a two-phase mixed working fluid after absorbing heat in evaporator. After entering the separator, the two-phase mixed working fluid is divided into ammonia-poor solution and ammonia-rich vapor. Ammonia-rich vapor drives the turbine to generate electricity. The low concentration ammonia-poor solution enters the regenerator to preheat the mixed working fluid delivered by the working fluid pump, and then enters the absorber after depressurization through the throttle valve. Subsequently, the ammonia-poor solution and ammonia-rich vapor are mixed in the absorber to become a two-phase mixed working fluid again. Then the two-phase mixed working fluid enters the condenser and condenses into the basic ammonia solution. The basic ammonia solution is then pumped by the working fluid pump into the regenerator to preheat, and finally enters the evaporator to complete a Karina cycle. Karina cycle uses the ammonia-water mixture as the working fluid, it can achieves a better temperature match between the cycle and the heat and cold sources. Therefore, the output power of the turbine is improved, and the thermal efficiency of the cycle can be up to 4.5% (Kalina, 1984).

The Uehara cycle was proposed by Haruo Uehara in 1994 and is also a power cycle system using ammonia-water mixture as the working fluid (Uehara, 1995). Figure 1E shows the schematic of the Uehara cycle system. The basic ammonia solution becomes two-phase mixed working fluid after absorbing heat in evaporator, and then the two-phase mixed working fluid enters the separator and is divided into ammonia-poor solution and ammonia-rich vapor. The ammonia-poor solution enters the high temperature regenerator to preheat the working fluid pumped by the high pressure working fluid pump, and then enters the throttle valve for depressurization. In addition, ammonia-rich vapor drives the first turbine to generate electricity, and then a part of the ammonia-rich vapor is extracted into the low-temperature regenerator to heat the working fluid pumped by the low-pressure working fluid pump, and the remaining ammonia-rich vapor enters the secondary turbine to continue generate electricity. The ammonia-rich vapor from the secondary turbine and the ammonia-poor solution after depressurization are mixed into a two-phase mixed working fluid in the absorber. The two-phase mixed working fluid enters the condenser to release heat and is transported into the low temperature regenerator by the low pressure working fluid pump. The working fluid from the low-temperature regenerator and the ammonia-rich vapor from the first turbine are mixed into basic ammonia solution in the mixer. The basic ammonia solution is pumped into the high temperature regenerator by the high pressure working fluid pump to preheat, and finally enters the evaporator to complete a full cycle. Compared to the Kalina cycle, the Uehara cycle is equipped an extraction regenerative cycle, the temperature of the working fluid entering the evaporator is increased, and the heat absorption of the system is reduced. Therefore, the thermal efficiency of the Uehara cycle is higher than that of the Rankine cycle and the Kalina cycle, and its value can reach 4.97% (Uehara et al., 1998). However, the disadvantage of the Uehara cycle is also obvious, the complexity of the Uehara cycle is much higher than that of the Rankine cycle and the Karina cycle.

3 Opportunities and challenges

With the economic development and population growth, the energy demand of human will continue to increase, which brings opportunities and challenges to the application and development of OTEC technology. Therefore, considering the research status and practical application requirements of OTEC technology, the following aspects need to be further studied in the future:

Low energy conversion efficiency is the biggest problem in the development of OTEC technology. This is because the energy conversion efficiency of the OTEC technology is limited by the small temperature difference between cold seawater and warm seawater (YamadaHoshiIkegami, 2006). The temperature difference between the surface warm seawater and deep cold seawater is only about 20°C even in the tropics (Yang and Yeh, 2014; Nithesh et al., 2016). For example, the thermal efficiency of the Uehara cycle can only reach 4.97%. Therefore, more attention should be paid to improving the thermal efficiency of OTEC technology. Ocean thermal energy can be effectively combined with other forms of low-grade heat sources, such as solar energy (Yamada et al., 2009) and industrial waste heat (Kim et al., 2009), to improve the thermal efficiency of the system. Solar energy and industrial heat can be used to heat the surface warm seawater, which increases the temperature difference between warm seawater and cold seawater, thus improving the system efficiency.

2) At present, OTEC technology has the problem of poor economy. There are many utilization ways of ocean thermal energy, such as power generation, refrigeration, hydrogen production, aquaculture of aquatic products and crops, seawater desalination. Therefore, the ocean thermal energy can be comprehensively utilized. According to the principle of cascade utilization, the surface warm seawater and deep cold seawater can be fully utilized for power generation, refrigeration, seawater desalination and deep water aquaculture, which will greatly improve the economic benefits and play a positive role in reducing carbon emissions.

Author contributions

EH contributed to conception of the study. WC wrote the first draft of the manuscript. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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