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RESEARCH ARTICLE

Significant Development Potential of the Solid Oxide Fuel Cell for the Technical Progress of the Marine Main Propulsion Plant in the Context of Energy Conservation and Emission Reduction

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Abstract: The International Maritime Organization (IMO) has proposed a series of strict pollutant emission regulations and carbon emission reduction targets, and the shipping industry pays more attention to the research and development of the marine electric propulsion technology whose electric power source is fuel cell. The proton exchange membrane fuel cell (PEMFC) dominates the global research of the marine applications for fuel cell supplying propulsion power at the moment, which has realized successful commercialized application or demonstration application. The development trend of the application of the marine fuel cell supplying propulsion power are from low power to high power, which will create more development opportunities for the solid oxide fuel cell (SOFC) with the advantages of higher power, greater efficiency, long life span and fuel diversity. Although some challenges exist, the solid oxide fuel cell with significant development potential can certainly lead the technical progress of the marine main propulsion plant to achieve energy conservation and emission reduction of the shipping industry.

Keywords: Fuel cell, Electric propulsion, Marine clean energy, Energy conservation, Emission reduction

1. Introduction

More than four-fifths of the global freight transportation is undertook by the shipping industry with the advantages of low cost, high transport capacity and freight diversity[1-3]. But at the same

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time, it also causes over 1.1 billion tons of the carbon dioxide emission that accounts for three percent to four percent of the world's total emissions approximately[4,5]. In the face of such a severe situation, the International Maritime Organization (short for IMO) focus more on the energy conservation and emission reduction of the shipping industry, and proposed that the carbon dioxide emission of the shipping industry is supposed to decrease by 40% by 2030 and 50% by 2050 based on the emission level of 2008, and the shipping industry is planned to realize the carbon neutrality at the end of the 21st century and this long-term goal is expected to be achieved even earlier than the originally scheduled[6,7]. Furthermore, the International Maritime Organization also delimited the latest sulfur emission control area (short for SECA) in 2020 and nitrogen emission control area (short for NECA) in 2021. In addition, the International Maritime Organization declared that the enforcement of the energy efficiency design index (short for EEDI) would be brought forward to April 2022. These measures reflected the determination of the International Maritime Organization to mitigate the adverse environmental effects of the shipping industry and improve the energy efficiency of the shipping industry. In order to achieve the abovementioned goals of energy conservation and emission reduction, an effective way is using high-efficiency and low-emission marine main propulsion plant[8]. With the increasing maturing technique, the marine electric propulsion technology highlights its significant potential increasingly in the energy conservation and emission reduction of the shipping industry and other advantages such as low noise and low vibration[9,10].

2. Status of the Marine Electric Propulsion Technology

The fundamental principle of the marine electric propulsion technology remains the same that the propulsion electric motor is driven by the electrical energy, and thus turns the propeller rotating. At present, there are four mainstream methods of the marine electric propulsion technology according to the source of electrical energy as following.

2.1. Battery

The batteries used in the marine electric propulsion technology include but not limited to the lithium battery, the lead-acid battery, the nickel metal hydride (Ni-MH) battery and the super capacitor as well as the combination of them. This method is also applied to the pure electric car. The ship can be charged by the shore power and achieve zero emissions without fuel consumption[11,12]. But the disadvantages of this method are also notable that the cruising radius is small due to the its insufficient endurance. Thus, this method is only used for the specific ship with suitable technical characteristics such as the tourist ship, houseboat, yacht, patrol boat, law-enforcement boat and passenger ferry whose shipping line is short range. The schematic diagram of this method is shown in Figure 1(a).

2.2. Diesel Generator

In this method, the generator is driven by the medium-speed or high-speed diesel engine, producing electricity to drive the propulsion electric motor and the propeller as Figure 1(b) shows. With this method, the continuously variable speed and good control performance can be achieved. But it is obvious that the electrical energy used in this method still originates from the fuel combustion in the diesel engine, which also contributes to the pollution with low energy efficiency. This method is usually used for the ship with large tonnage or long range shipping line[13].

2.3. Fuel Cell

Fuel cell technology can convert the chemical energy of the gaseous fuel into the electric energy directly without combustion and mechanical motion. The thermal efficiency of the fuel cell is not constrained by the Carnot cycle and is up to 2-3 times higher than that of the diesel engine[14,15]. Among numerous types of the fuel cell, namely alkaline fuel cell (short for AFC), phosphoric acid fuel cell (short for PAFC), molten carbonate fuel cell (short for MCFC), proton exchange membrane fuel cell (short for PEMFC) and solid oxide fuel cell (short for SOFC). The PEMFC and the SOFC are research focuses which have achieved successful commercialized application or demonstration application at the present in many field such as the shipping industry, especially the PEMFC[16,17]. This method shown in Figure 1(c) has the potential to achieve real zero emissions in long range sailing as the main propulsion power plant.

2.4. Hybrid Power Source

This method is the combination of the above-mentioned methods[18]. The prime example is the combination of the battery and the diesel generator, in which the battery can be charged continuously by the diesel generator as Figure 1(d) shows. This method can balance zero emissions and long range sailing. To be specific, the battery can be used in the emission control area to achieve zero emissions and the diesel generator can provide propulsion power directly in non-emission control area[19,20]. The other typical combination is the battery and the fuel cell with the advantage of convenient power regulation[21-23]. The fuel cell may not satisfy the change of the power demand of the propulsion motor individually. What is more, the power fluctuations can damage the fuel cell and shorten its cycle life. Thus, the fuel cell can be combined with other energy storage device like the battery to increase the power density of the marine electric propulsion plant and fulfill the demand of the propulsion power at any time[24]. That is to say, when the power of the fuel cell is surplus, the battery is used to absorb and storage the power. When the power of the fuel cell is insufficient ,the battery is used to release and compensate the power. The schematic diagram of this method is shown in Figure 1(e).

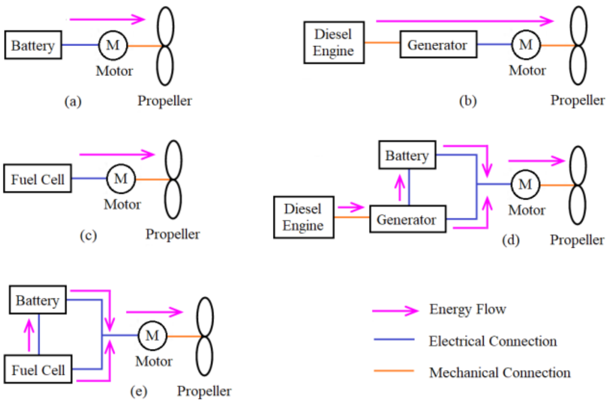

Figure 1. Typical methods of marine electric propulsion according to the source of electrical energy. (a) Battery; (b) Diesel generator; (c) Fuel cell; (d) The combination of the battery and the diesel generator; (e) The combination of the battery and the fuel cell.

3. Analysis of the Significant Development Potential of the Solid Oxide Fuel Cell for Maritime Application

At present, the marine applications for fuel cell supplying propulsion power focuses more on the PEMFC which can only be used in the small boat in the coastal water or inland waters due to its low power. From the viewpoint of the technology, the technological progress of the marine electric propulsion in the next stage are from low power to high power, making it can be used in the small boat in the coastal water or inland waters to the great ship in the ocean. In comprehensive consideration of environmental protection and emission regulations, the combination of the powerful fuel cell and the battery is the best chioce of the marine electric propulsion plant. Throughout the present situation, the PEMFC is the most sought after of all types of the fuel cell by virtues of good dynamic response, low temperature operation characteristic and high power density. But when the needed power is higher than 300kW that exceeds the optimum output power of the PEMFC, the SOFC is a better choice with the theoretical electrical efficiency over 70% and potential of reaching 100MW[25]. What is more, as the third generation type of the fuel cell, the combination of the SOFC and the SOEC (solid oxide electrolysis cell) is envisaged the possibility of setting up large marine power station in the near future.

Based on the perspective of commercial application, an important advantage lies in the fact that the SOFC can use various types of the gaseous fuel, such as hydrogen, hydrocarbons, alcohols and ammonia gas, which adapts to the the actual situation of fuel supplement in different region[26]. In October 27, 2022, the International Energy Agency (for short IEA) issued the "World Energy Outlook 2022" that emphasized the ammonia will meet the needs of nearly 50% of the fuel demand of the shipping industry by the mid-century with the advantages of high power density, low cost, mature technology, adequate infrastructure and convenient storage and transportation[27]. It can provide new development opportunity to the SOFC (namely direct ammonia solid oxide fuel cell) used in the shipping industry. Besides, the cycle life of the SOFC can achieve 100000h, which is well over those of the other types of the fuel cell and the life span of the ship. What is more, the SOFC operates at high temperature (600℃-1000℃), and thus the thermal energy from exhaust gas of the SOFC can also be used in the ship, such as heating the domestic water, heavy fuel oil and lubricating oil. Therefore, the SOFC can provide both thermal energy and electrical energy for the ship, making the overall efficiency of the SOFC reach approaximately 90%[28-30].

To sum up, the SOFC gains the technical and commercial competitive advantages from all aspects for supplying propulsion power to the ship, which highlights its significant development potential to achieve energy conservation and emission reduction of the shipping industry. The comparison of parameters of the PEMFC and the SOFC are shown in Table 1. Figure 2 shows the design of the marine electric propulsion system using only the fuel cell and the combination of the energy storage device like the battery or the super capacitor and the fuel cell.

Table 1. Parameters of the PEMFC and the SOFC

Type	*Operating Temperature*	*Fuel*	*Efficiency*	*Lifetime*	*Price*
PEM FC	*20 - 200℃*	*Pure Hydrogen*	*40 - 50%*	*5000 - 10000h*	*50 - 2000$/kW*
SOFC	*500 - 1000℃*	*Hydrogen Hydrocarbons Alcohols Ammonia gas*	*50 - 80%*	*10000 - 100000h*	*1500$/kW*

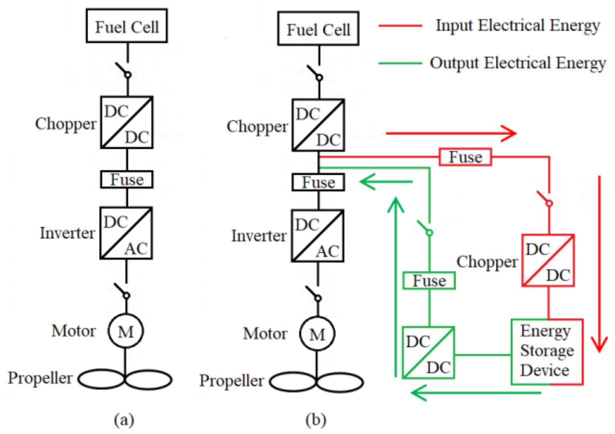

Figure 2. The design of the marine electric propulsion system using the fuel cell.

(a) The marine electric propulsion system using only the fuel cell; (b) The marine electric propulsion system using the combination of the energy storage device and the fuel cell.

As shown in Table 2, there have been some successful applications of the SOFC in the shipping industry for supplying the auxiliary power or the propulsion power. However, the transformation and upgrading from the traditional marine main propulsion plant to the new marine main propulsion plant cannot be achieved overnight. Thus, the application of the SOFC from the auxiliary power to the main propulsion power in the shipping industry is a inevitable choice, and a series of research projects of the SOFC as the auxiliary power have laid a solid foundation for supplying the propulsion power of the ship in the near future.

Table 2. Some successful applications of the SOFC in the shipping industry[31]

The ship	*Application*	*Power*	*Fuel*	*Country*
The cruise "MSC World Europa" 	*Auxiliary power*	*150 kW*	*Natural gas*	*America*
The cargo ship "MS Forester" 	*Auxiliary power*	*50 kW*	*Low-sulphur diesel*	*Germany*
The roll-on/roll-off ship "Undine" 	*Auxiliary power*	*20 kW*	*Methanol*	*Germany*
The support vessel "Viking Energy" 	*Main propulsion power*	*2 MW*	*Ammonia*	*Germany*

4. Challenges and Suggestions

Several challenges are now pretty much the agenda for applying the SOFC as the main electric propulsion plant in the ship on a large scale, such as lacking infrastructure for the storage and supplyment of the fuel, high cost in the initial operational stage, undeveloped high-density hydrogen storage technology, lacking matching standards of shipbuilding, safety management, maritime control and seamen training[31]. Thus, the concrete suggestions are as follows. The SOFC used in the ship and other fields is supposed to achieve common development and the infrastructure should be shared in common, which can achieve the cost reduction. The World Maritime Organization (for short IMO) should accelerate the legislative process, providing guidance and support to the abovementioned aspects related to the new types of the marine electric propulsion plant, especially the fuel cell. China leads the world in this respect and has promulgated a series of laws and regulations, which can provide explicit instruction to the marine application of the fuel cell[32,33].

5. Conclusion

This review summarized the status of the marine electric propulsion technology and emphasized the importance of the fuel cell in it. Among all types of the fuel cell, the SOFC has advantages of higher power, greater efficiency, long life span and fuel diversity. Thus, this review put forward a point of view that with the increasingly stringent environmental protection and carbon reduction requirements, applying the SOFC as the marine main electric propulsion plant in the shipping industry has a very brilliant prospect and can be expected so soon with the cooperative effort of the whole world.

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Author Contributions

Investigation, Xiao-Yu Wang and Jian-Zhong Zhu; resources, Xiao-Yu Wang and Jian-Zhong Zhu; writing—original draft preparation, Xiao-Yu Wang and Jian-Zhong Zhu; writing—review and editing, Xiao-Yu Wang, Jian-Zhong Zhu and Min-Fang Han; visualization, Xiao-Yu Wang, Jian-Zhong Zhu and Min-Fang Han; supervision, Jian-Zhong Zhu and Min-Fang Han; project administration, Min-Fang Han; funding acquisition, Min-Fang Han

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Conflicts of Interest

The authors claim that the publication of this review has no conflict of interest.

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