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Development and Challenges for Power Battery in Electric Ship

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Abstract

With the continuous prosperity and development of the marine industry, the number of ships is increasing while greenhouse gas emissions are rising. In order to meet the relevant international ship emission regulations, the solution of developing electric ships is proposed. As the core device of the electric ship propulsion system, the maturity and applicability of power battery technology play a key role in the development of the electric ship. This article introduces the principles and advantages of the fuel cell, lithium-ion battery as well as supercapacitor battery, respectively, and analyzes the application status and challenges of power batteries in existing electric ships. The development direction and problems to be solved of power battery in current and future ship applications are put forward, which can provide a reference for further research.

Keywords: greenhouse gas, power battery, electric ship, challenges

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1. Introduction

According to data of the IMO Fourth GHG Study as presented in Table I, in 2012, 962 million tonnes were CO_2 emissions, while in 2018 this amount grew to 1,056 million tonnes of CO_2 emissions. The share of shipping emissions in global anthropogenic emissions has increased from 2.76% in 2012 to 2.89% in 2018 (IMO, 2020), which accelerated the process of the greenhouse effect. Additionally, ships are responsible for 90% of global trade, and with the rapid growth of maritime trade, there is an urgent need to reduce CO_2 emissions from this sector (Muhammad et al., 2022). The electric ship that uses the power battery as the sole primary power source or the power battery as an auxiliary power source combined with other energy devices to form a hybrid power source has been recognized as one of the most credible options to alleviate the problem of greenhouse gas emissions [César et al., 2019].

Electric ships have gradually become the focus of the marine industry due to their advantages of low or even zero emissions meeting the increasingly stringent pollutant discharge requirements, high transmission efficiency, and low operating costs (Jeong et al., 2020) (Carlos et al., 2021). Power batteries are the core of electric ships to achieve decarbonization, especially for all-electric ships. At present, the power batteries used in electric ships basically include fuel cells, supercapacitor batteries, lithium-ion batteries, and hybrid power batteries. Moreover, researchers have carried out a lot of research on power batteries to promote the rapid development of electric ships. Owing to the remarkable technological advances in power batteries, as of March 2019, the number of electric ships in the world is more than 150 (DNVGL, 2019).

From the perspective of power batteries, this article is dedicated to discussing the current development and application of power batteries in electric ships, focusing on the advantages and challenges of fuel cells, supercapacitor batteries, and lithium-ion batteries. In the end, the prospect of development direction and challenges of power batteries in electric ships are put forward.

2. Applications and Challenges of Fuel Cell

The fuel cell is a power generation device that directly converts the chemical energy of fuel into electric energy through an electrochemical reaction, which is not restricted by the Carnot cycle. Depending on the electrolyte, fuel cell systems can be divided into different categories. Among them, proton exchange membrane fuel cell (PEMFC) and solid oxide fuel cell (SOFC) with obvious and mature technical advantages, have entered the stage of engineering application and popularization (Van Biert, 2016). Their cell structures are shown in Figure 1.

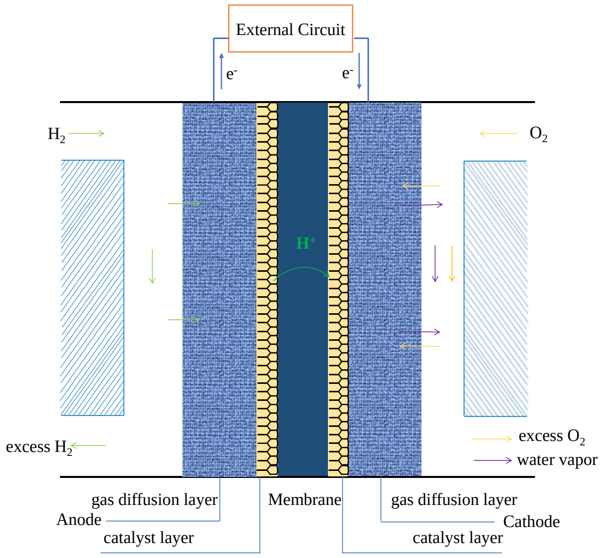
Table 1: Total shipping CO_2 emissions

Year	Global CO_2 (million tonnes)	Total shipping CO_2 (million tonnes)	Percentage
2012	34793	962	2.76%
2013	34959	957	2.74%
2014	35225	964	2.74%
2015	35239	991	2.81%
2016	35380	1026	2.90%
2017	35810	1064	2.97%
2018	36573	1056	2.89%

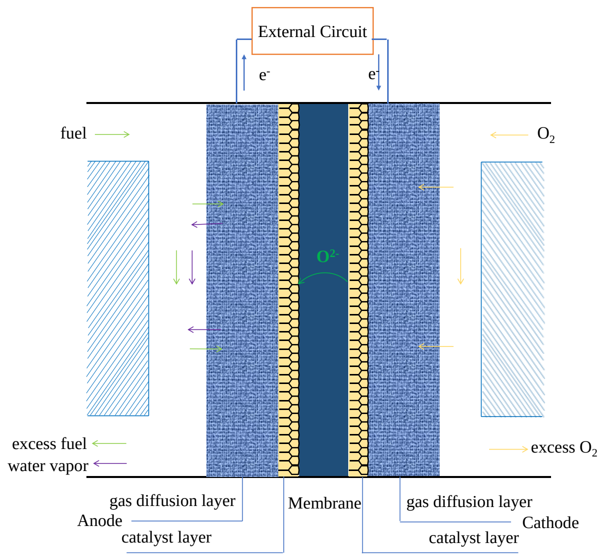
PEMFC generally uses hydrogen as fuel. On the anode side, hydrogen is catalyzed and dissociated into hydrated protons and electrons. The former reaches the cathode through the proton exchange membrane, while the electrons are transferred to the cathode through the external circuit. On the surface of the cathode catalyst, oxygen molecules combine with hydrated protons and electrons to generate water molecules and give off a lot of heat. SOFC can directly use hydrogen, carbon monoxide, methane, methanol, etc. as fuel. On the cathode side, the oxygen absorbed by the cathode surface is converted into O_2- by catalytic action, which is then diffused to the surface of the catalyst layer of the anode through the solid oxygen ion conductor and reacts with the fuel gas to generate water molecules and release a lot of heat. The lost electrons return to the cathode through the external circuit.

The research and application of fuel cell ships in Europe, America, Japan, South Korea, and other countries and regions started earlier. In the field of military industry, initially, Germany initially applied fuel cells as auxiliary power to the submarine field and built the world's first

212A type of “AIP” submarine equipped with oxyhydrogen fuel cells. Later, Germany and Italy jointly improved the fuel cell submarines manufacturing.



(a) PEMFC



(b) SOFC

Figure 1: Structure Diagram of (a) Proton Exchange Membrane Fuel Cell and (b) Solid Oxide Fuel Cell

The United States and Britain plan to carry out research on the application of fuel cell technology on destroyers and small frigates. In the field of civil ships, in 2008, Germany launched the “Alsterwasser” equipped with a 48 kW proton exchange membrane fuel cell, which is the world’s first fuel cell electric propulsion passenger ship. In 2009, Norway built the Viking Lady, an ocean engineering supply ship equipped with a 320 kW fuel cell power system. At the end of 2015, the hydrogen fuel cell jointly developed by Japan’s Toda Construction and Yamaha Engine was put into trial on a fishing boat. In 2017, “Energy Observer”, a fuel cell ship developed by France and using hydrogen, was officially launched. In 2018, Ballard Company of Canada and Siemens Group of Germany also successively proposed the research and application of a marine fuel cell system. China State Shipbuilding Corporation took the lead in the research and development of the first hydrogen-based fuel cell-powered ship in China. At present, the basic design work has been completed, and it has obtained approval in principle from the China Classification Society.

Combined with the actual ship application of fuel cell technology, fuel cell technology has the main advantages of high-power generation efficiency, green environmental protection, near-zero pollution, diversified fuel, wide application range, and low vibration and noise (Jialun, 2021). However, the application prospects of fuel cell technology in ships still face the following major challenges:

At present, PEMFC can only use pure hydrogen as fuel, and the fuel cost is relatively high. Although the cryogenic liquid hydrogen storage system and the compressed hydrogen storage scheme can improve the volumetric energy density of hydrogen, they bring about a significant cost increase, occupy more space resources, and have greater safety risks. In comparison, SOFC can directly use conventional liquid fossil fuels, but it should be noted that the problem of electrode carbon deposition needs to be overcome in the use of conventional liquid fossil fuels.

In addition, fuel cells are currently mainly used as auxiliary or backup power sources for conventional power devices. This is because the power generation of the single fuel cell unit is low, and a large number of battery units need to be connected in series and parallel to meet the output voltage and power requirements. Therefore, the stability and safety of fuel cell operation and the consistency of each cell unit need further research.

3. Applications and Challenges of Lithium-Ion Battery

The lithium-ion battery is a kind of rechargeable high-energy battery, in which lithium intercalation compounds are generally used as the cathode, and artificial graphite carbon series materials are usually used as the anode. According to different cathode materials, lithium-ion batteries are classified into many types. At present, the widely used lithium-ion batteries mainly include lithium iron phosphate, lithium manganate, ternary lithium, and lithium titanate batteries. Among them, the technology of lithium iron phosphate batteries is quite mature and has been recognized by the China Classification Society. It has been widely used in land transportation, solar energy, wind power generation, energy storage, electric tools, and other fields (Quanhu, 2020). Its structure is presented in Figure 2.

During the charging process, part of the lithium ions in the lithium iron phosphate are extracted and transferred to the anode through the electrolyte. At the same time, electrons reach the anode from the external circuit to ensure the charge balance of the cathode and anode. During the discharge process, the lithium ions released from the anode are embedded into the cathode through the electrolyte, while the electrons reach the cathode from the external circuit. The charge-discharge reactions can be written as follows (x means the number of ions and electrons):

$$LiFePO_4 - xLi^+ - xe^- \xrightarrow{charge} xFePO_4 + (1-x)LiFePO_4 \quad (1)$$

$$FePO_4 + xLi^+ + xe^- \xrightarrow{discharge} xLiFePO_4 + (1-x)FePO_4 \quad (2)$$

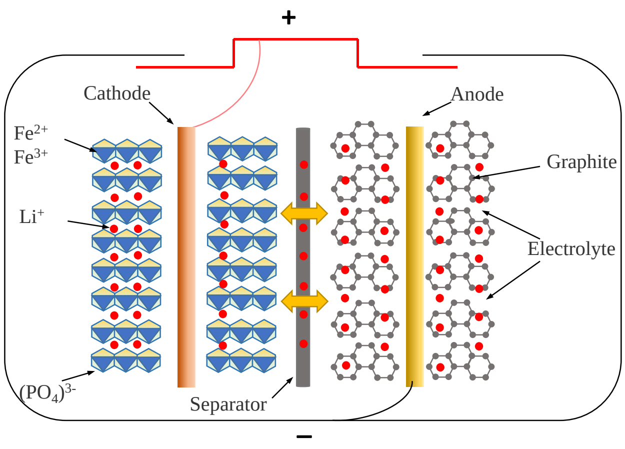


Figure 2: Structure Diagram of Lithium Iron Phosphate Battery

With the decreasing cost of lithium-ion batteries and the continuous maturity of technology, the market recognition of ships powered by lithium-ion batteries is increasing. In 2015, Norway built the world's first large-scale lithium-ion battery-powered all-electric vehicle ferry "Ampere" (Paul, 2020). In April 2019, the world's largest hybrid ro-ro ship "Color Hybrid" invested by Norway's Color Line was launched. The ship is equipped with a 4.7 MWh lithium-ion battery pack, which can sail 12 nm on battery power alone. In 2020, China's first large-scale all-electric passenger ship "Jun Lv" made its maiden voyage, which was equipped with a power system of lithium-ion battery and pod propulsion. In March 2022, a pure battery-powered ship "Chang Jing San Xia 1" with the world's largest battery capacity was delivered in China. The ship adopted the world's top standard lithium iron phosphate battery system, equipped with a 7.5 MWh marine power battery. In addition, lithium-ion batteries are widely used in "Deutschland" (luxury cruise ship in Germany), "Bhagwan D" (scientific research ship in Australia), "Edda Freya" (engineering support ship in Norway), "El-Max" (fishing boat in Norway) and "San Lorenzo" (coastal rescue ship in Italy).

Among many cathode materials of lithium-ion batteries, the electric heating peak value of lithium iron phosphate can reach 350～500 °C, while that of lithium manganate and lithium cobaltate is only about 200 °C. Because of the use of precious metal elements such as cobalt, the cost of ternary lithium batteries is several times higher than that of lithium iron phosphate batteries, and nickel, cobalt, and aluminum elements are extremely prone to structural collapse at high temperatures. Overall, lithium iron phosphate battery has the advantages of high cost performance, high safety, long cycle life, and fast charging and discharging. However, the large-scale application of lithium-ion batteries in ships still faces the following major challenges:

The ternary lithium battery has the highest energy density, but for safety reasons, more funds need to be invested in the battery management system, which limits the application of ternary lithium batteries in ships to some extent. Same as fuel cells, a single lithium iron phosphate battery has low capacity and voltage. In practical application, it is necessary to expand and package a single battery unit. Therefore, the corresponding safety and stability problems need to be solved through a battery management system. Besides, the anode and cathode materials of lithium-ion batteries need to move towards the research and development of new materials, and the problems of low specific energy and specific power of current electrode materials can be settled by reducing particle size, modifying, coating, and doping active materials.

4. Applications and Challenges of Supercapacitor Battery

A supercapacitor battery refers to a technical battery that combines a supercapacitor with a battery. The supercapacitor is an energy storage device between capacitor and battery. It not only has the characteristics of fast charging and discharging of the capacitor but also has the energy storage characteristics of the battery. Taking the electric double layer supercapacitor battery as an example, the battery structure is exhibited in Figure 3.

When an electric field is applied to the two electrodes, the anions and cations in the solution migrate to the cathode and anode, respectively, forming an electric double layer on the surface of the electrode; After the electric field is removed, the positive and negative charges on the electrodes attract the ions with opposite charges in the solution to stabilize the electric double layer, resulting in a relatively stable potential difference between the cathode and anode (Shihao, 2022).

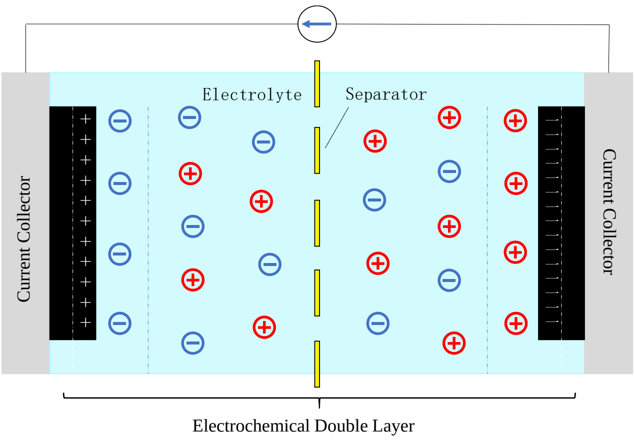


Figure 3: Structure Diagram of Double Layer Supercapacitor Battery

At present, the application of supercapacitor batteries in electric ships is not extensive, and supercapacitor battery technology is generally used in combination with the lithium-ion battery. In January 2017, the 500 t electric-propulsion cargo ship "Zhe Hu Zhou Cargo 1625" delivered by China is powered by a "lithium-ion battery & supercapacitor battery" power module. In January 2019, the fully battery-powered ship "He Tun" delivered by China was driven by a 2400 kWh "lithium-ion battery & supercapacitor battery" power module, with a cruising range of about 80 km. Furthermore, in August 2021, the world's first pure supercapacitor battery-powered passenger ferry "Xin Sheng Tai" successfully completed the trial voyage in Hunan, China. The ship is equipped with two sets of supercapacitor batteries with no less than 200,000 charging and discharging cycles, and the total energy storage of the whole ship is 625 kWh.

Compared with fuel cells and lithium-ion batteries, supercapacitor batteries have higher power density, which is dozens of times that of ordinary batteries, and have good dynamic performance and ultra-high long service life (Chen, 2016). In addition, the supercapacitor battery is a new type of green battery with a fast charging speed and wide operating temperature range (-40 ～ +60 ℃). However, supercapacitor battery still faces the following main challenges in practical application:

In comparison with the lithium-ion battery, the cost of the supercapacitor battery is higher. The combination of lithium-ion battery and supercapacitor battery is capable to reduce the cost while making the hybrid energy storage system have good dynamic and steady-state characteristics. Energy density is the "fatal wound" of supercapacitor batteries, which is far inferior to lithium iron phosphate batteries. There is still a long way to go to elevate the specific capacity of electrodes by studying new electrode materials or composite electrodes.

In addition to the above popular power batteries, the technical characteristics of other batteries are summarized in Table 2. In conclusion, different types of batteries possess different technical characteristics and are suitable for different scenarios. For instance, lead-acid batteries are widely used due to their low cost, but their energy density is low (B. Ina, 2022). On the contrary, the sodium-sulfur battery has a high energy density, but it needs a high working temperature (300-350 ℃). The low cycle life and efficiency of nickel batteries and nickel-metal hydride batteries limit their wide application.

After a comprehensive comparison, the lithium-ion battery has the most development potential. In order to balance the pros and cons of various types of batteries, the hybrid battery package used as a power battery module provides a new solution for the development of electric ships. As mentioned above, the combination of supercapacitors and lithium-ion batteries has been applied in practice and shows better performance than using a single power battery.

Table 2: Characteristics of Various Battery Types

Type	Energy density (Wh/kg)	Power density (W/kg)	Cycle life	Efficiency
Lithium-ion battery	75-200	200-315	1000-10000+	85-90%
Supercapacitor	2.5-15	500-5000	100000+	90-95%
Lead acid battery	30-50	75-300	500-1000	70-90%
Nickel-cadmium battery	50-75	150-300	2000-2500	60-65%
Nickel-metal hydride battery	60-100	200-1500	750	65-90%
Sodium-sulfur battery	150-240	150-230	2500	80-90%

5. The Prospect and Challenges of Power Battery

Aiming to minimize emissions and further move towards net-zero emissions, the climate change conference (COP26), the *Paris Agreement*, and the international marine organization (IMO) had made an effort to draw up regulations and plans for both developed and developing countries. At the present stage, in order to reduce the environmental pressure caused by ship emission pollution, some existing ships can be retrofitted by implementing power battery technology according to the technical characteristics and applicable scenarios of different power batteries. In the future, all-electric ships with zero-emission will lead the development direction of electric ships, which requires the continuous improvement and development of power battery technology. In addition to constantly improving the research and development of fuel cells, lithium-ion batteries, and supercapacitor batteries, it is also necessary to continuously promote the research and commercialization of other new power batteries with characteristics of safety, economy, and high capacity, such as lithium-sulfur battery and sodium-sulfur battery. Moreover, the battery management system and energy management system related to power batteries play a vital role in the propulsion system of electric ships. The design of management systems and the layout of power batteries for different types of ships deserve further exploration and optimization. On the other hand, the charging problem of power batteries, such as charging mode and charging station installation, is also an inevitable challenge that limits its universal application in ships.

6. Conclusions

This article first introduces the types of power batteries that are currently in practical use, expounds on the working principles, advantages, and disadvantages of the fuel cell, lithium-ion battery, and supercapacitor battery, and points out the challenges faced by different power batteries in the application of electric ships. Secondly, this article brings up a scheme to retrofit existing ships through the implementation of power battery technology at the current stage and to achieve the goal of zero-emission electric ships by developing new power batteries in the future. Thirdly, this article summarizes the technical characteristics of various power batteries aiming to promote the use of hybrid batteries as power modules for electric ships. Finally, this article briefly describes the two challenges of energy management and charging mode that power batteries face in practical applications.

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