Analysis of energy development of ship power

Jianhao Zhu1*, Peng Zhao1 and Yueqi Pan1

1Key Laboratory of Marine Power Engineering & Technology (Ministry of Transport), Wuhan University of Technology, Wuhan, 430063, China*

*Corresponding author’s e-mail address: jhzhu@whut.edu.cn

Abstract: Because the shipbuilding industry is affected by the Paris Agreement, the traditional ship power and conventional power propulsion methods no longer meet the needs of the future shipbuilding industry. Therefore, people are paying more attention to exploring new energy sources as well as new clean propulsion methods based on new energy. This paper introduces the new power energy sources and clean power propulsion methods of some modern ships. It not only systematically sorts out the advantages, disadvantages and applicable types of ships of these new power sources, but also makes a brief analysis of the development direction of new power ships and the problems that need to be overcome.

1. Background
Since the industrial revolution, the widespread use of coal and petroleum fuel has greatly promoted the process of human industrialization and civilization. Their use as the main fuel on ships also greatly promotes the development of the global shipping industry. At present, marine diesel engines dominate the civilian power plant. In the past two decades, the proportion of marine diesel power units in civil marine power units has exceeded 98.5%, and even up to 100% in some years[1-2]. Although the diesel engine has the advantages of high reliability, fast start-up, long application time, and mature technology, its working efficiency is constantly being surpassed. At the same time, the pollution problem brought by the traditional marine diesel engines also becomes a problem that the world needs to face together. In recent years, as people’s awareness of environmental protection and energy-saving continues to increase, the International Maritime Organization (IMO) becomes more stringent in controlling emissions from marine engines. Therefore, searching for reliable and clean new energy for ship power and exploring the future development trend of intelligence and energy-saving of ships are turning into hot topics of current research[3].

2. New energy (clean) ship power

2.1 Electric propulsion
Ship electric propulsion uses electric motors as the main engine of the ship to drive ship propellers to provide propulsion power for ships. Compared with the traditional method, the structure and operating system of the electric propulsion system are simple with the flexible maneuverability and higher economy. In addition, the motor system itself has low inertia, low energy consumption, and quick response, so it runs more efficiently[4-5]. At the same time, because the electric propulsion system uses electrical speed regulation to replace the traditional mechanical speed regulation, it can effectively achieve the precise control of continuously variable speed[6]. At present, the main uses of electric propulsion systems as marine power sources are pure electric propulsion ships, diesel-electric hybrid...
propulsion ships, and solar-powered propulsion ships.

2.1.1 Pure electric propulsion ships
The energy storage components of pure electric ships mainly include batteries, supercapacitors, and flywheels [7]. Due to the defects that the flywheel battery cannot store energy for a long time and the mass-energy density of the supercapacitor is low, the main energy storage device that can be mainly used at present is only a battery. However, the battery has high requirements for the environment and use. If it is not charged in time, or it is overcharged and discharged, or the temperature is too low or too high, it will affect its performance and life. The environment of the engine room is relatively harsh, and at the same time, the requirements for environmental management and control are high, so this limits the application of the battery to a certain extent [8]. In addition, the battery itself has the disadvantages of low energy density and short cruising range. As a result, new energy ships that use batteries as the main power can only be tested in small inland ships [9].

2.1.2 Diesel-electric hybrid propulsion ships
The marine diesel-electric hybrid power system is a power system that switches the driving mode and combines fuel and electricity according to different working conditions and different needs [10]. This system uses diesel and electric motors with both motive power and a high economy. It is a new hybrid system solution combining traditional mechanical propulsion and electric propulsion. However, because its technology involves engines, motors, control modules, and transmission systems, diesel-electric hybrids are still in a key R & D period and have not yet been applied on a large scale. At present, diesel-electric hybrid power has three working modes: (1) PTO mode of the axle generator: When the ship is operating in an economical sailing condition, it uses the conventional propulsion of the main engine. At this time, the motor is working in the PTO mode, and the diesel engine can use the surplus power of the main engine to supply power to the ship’s power grid. Economical operation of the power system is achieved by using the minimum number of auxiliary power generation. (2) PTI mode of the electric motor: When the ship is starting or maneuvering at a low load or the main engine is malfunctioning, the electric power of the auxiliary machine is transmitted to the motor through the distribution board to realize the electric propulsion condition. PTI mode can not only improve the maneuverability of the ship, but also greatly save fuel consumption. (3) Diesel engine mode: Due to its high thermal efficiency and high-power density, diesel engines are widely used in ship propulsion systems.

Compared with traditional power ships, diesel-electric hybrid ships have the following advantages. (1) For more complicated navigation channels, including ship entering and leaving ports, and narrow areas, they are usually used due to frequent acceleration and deceleration and high maneuverability requirements, which allows the motor to take advantage of its energy-saving, environmental protection, and good maneuverability; (2) In the low-load maneuvering phase, starting the motor is more cost-effective than starting the diesel engine, while reducing dependence on fossil fuels. It is more energy-saving and environmental protection; (3) When sailing at low speed, the motor can run stably under low-speed conditions that cannot be achieved by a diesel engine. This enables the ship to obtain more stable low-speed performance, which is convenient for docking or approaching other targets; (4) Adopting a combination of conventional and electric propulsion to increase the redundancy of the propulsion device; (5) The degree of intelligence of diesel-electric hybrid ships is high [11-12].

2.1.3 Solar-powered propulsion ships
The application of solar power in ships mainly uses photovoltaic technology to generate electricity. By using the original internal combustion engine as the prime mover for grid-connected power stations, ship propulsion and control, as well as daily electricity use are promoted. There is also a power storage device set. Therefore, the key technologies of solar ships involve the integration of multiple subsystems such as ship design, photovoltaics, energy storage, main propulsion, battery management system (BMS), and power management system (PMS) and their technologies. Although the energy of solar-powered ships has the advantages of cleanness, environmental protection, and inexhaustibility, there are still
many technical problems. For example, the low energy distribution density of solar radiation leads to the application of more large solar panels on large ships; the cost of the battery is high but the conversion efficiency is low, as the efficiency of a crystalline silicon battery is 13-18%. In addition, complicated production process, high cost, low battery energy density of the conventional solar power storage device, and the short life of the charge and discharge cycle also limit the large-scale application of solar-powered ships. At present, solar-powered propulsion ships are particularly suitable for occasions with low propulsion power and long voyage time, which is very suitable for unmanned surface vehicles\textsuperscript{[13-14]}. \par

2.2 Hydrogen fuel cell-powered ships

As a clean, efficient, safe and sustainable new energy source, hydrogen energy is mainly used in the shipping industry in the form of fuel cells. Compared with traditional thermal engines, hydrogen fuel cells can directly convert the chemical energy of fuel into electricity, and the energy conversion efficiency can reach 40% to 80%. The combustion products of traditional thermal engines pollute the atmosphere and endanger human health, while the product of hydrogen fuel cells is water, which does not produce COX, NOX and various particles. In addition, the hydrogen fuel cell has the advantages of simple structure, flexible layout, low noise, low vibration, and no mechanical wear during operation. However, the current hydrogen fuel cells for ships still have deficiencies in terms of technical performance, life span, and environmental adaptability. Taking the life span as an example, at present, the life of fuel cells in the world generally does not exceed 5000 hours. This figure is obviously not enough for long-distance ocean-going vessels. Subject to the development status of hydrogen fuel cells, hydrogen fuel cell-powered ships are still in the experimental research stage. The research on marine hydrogen fuel cell systems is mainly concentrated in Japan and Europe, and some major R & D projects are shown in Table 1\textsuperscript{[15]}. \par

Table 1 Related research and development projects of marine hydrogen fuel cell.

| Ship name/project name | Main Contents | Contract company | Year |
|------------------------|--------------|-----------------|------|
| MF vegan               | Testing a small 12-kilowatt passenger ship | CMR Prototech ARENA Project | 2010 |
| Nemo H2                | Testing a small 60-kilowatt passenger ship in Amsterdam, Germany | Rederij Lovers | From 2012 to now |
| Bristol Boat Trips     | Testing a small 12-kilowatt passenger ship in Brussels | Hydrogenesis | From 2012 to now |
| SF-BREEZE              | Feasibility study of fuel cell system in 120 kW High Speed Passenger and cargo ship | Sandia National Lab. Red and White Fleet | From 2015 to now |
| Raicho N              | Two fixed hydrogen fuel cell power systems with an output power of 3.5kw are installed on the ship for the development and test of the test ship | Toshiba. Tokyo University of Marine Science and Technology | From 2016 to now |
| --                    | Cooperate to develop and optimize the technicality of fuel cell / power cell, and study the control, energy storage and efficiency optimization of fuel cell stack. | ABB, SINTEF Ocean | From 2018 to now |
| --                    | Joint development of marine energy supply system of fuel cell | Siemens, Power Cell Sweden AB | From 2018 to now |

For now, hydrogen fuel cell-powered ships still do not have the conditions for large-scale applications. With the continuous improvement of ship environmental protection requirements and the improvement of marine hydrogen fuel cell system technology and cost reduction, it is believed that it is only a matter of time before large-scale applications of hydrogen fuel cell-powered ships are realized. For ships, hydrogen fuel cells are ideal for passenger ships such as riverboats, ferries, and cruise ships.
2.3.1 LNG-powered ships

LNG-powered ships are developed based on current marine diesel engines by installing a natural gas supply system and a diesel/natural gas dual fuel electronically controlled injection system. The use of electronic switches allows flexible switching between pure diesel fuel and dual fuel states of oil and gas.

LNG-powered ships have the following advantages over traditionally-powered ships: (1) Economical fuel: The price of LNG in the market is cheaper than the price of fuel, especially the HH price in the United States and the NBP price in Europe. Although domestic LNG prices are basically the same as heavy oil in China, China has gradually become the world's largest importer of LNG. It is foreseeable that fuel prices will decrease further shortly. (2) Abundant raw material reserves: In the situation that other fossil fuels are increasingly depleted, the proven natural gas reserves in the world are still very abundant. If some unconventional energy sources are included, such as shale gas and methane ice, they converted into usage can be used by humans for 250 years. (3) Environmental protection of LNG-powered ships: With the same operating costs and output power, using LNG clean energy can save about 20% of the cost compared with traditional fossil fuels. At the same time, it reduces the amount of nitrogen oxides by 80%, cuts the amount of sulfur oxides in half, and lowers the emissions of small particles by 94% [16].

Since the application of LNG started relatively late, LNG-powered ships also have the following problems: (1) Higher operating costs: The cost of LNG-powered ships is higher than that of ordinary ships of the same tonnage. In addition, retrofitting of LNG ships is more expensive. Besides, the labor cost of LNG ships is about 22% higher than that of traditional diesel ships. (2) Lagged supporting infrastructure: At present, LNG-powered ships suffer from insufficient bunkering stations and unreasonable distribution. The bunkering types of Ship-to-Ship and Truck to Ship is not only costly but is not recognized by the competent authority. What’s more, due to the shortage of maintenance professional teams and the difficulty in purchasing spare parts, ship repair can only rely on manufacturers, who charge high maintenance fees and need a long maintenance period. (3) Imperfect technical specifications: The application of LNG fuel on ships is still in its infancy, and related technical specifications are also constantly being improved. Therefore, it is inevitable that in the construction and transformation of ships, irregularities in ship design and equipment installation will occur, which increases the cost of ship construction and affects the completion time. (4) The technical performance of the system is not high: Although domestic LNG fuel and LNG/diesel dual fuel marine natural gas engines have been developed and produced in China, and great progress has been made in supporting ship design and manufacturing, storage tanks, and control systems. However, due to immature technology, system failures often occur during the operation of LNG engines, safety alarm systems, and central control systems (ECU) [17].

As a clean and low-carbon energy source, LNG has the advantages of protecting the ocean and being highly economical. It can not only meet the requirements of cleanliness, environmental protection and energy-saving in this era, but also meet the requirements of the International Ocean Convention on future ship construction and development. Therefore, LNG fuel applications usher in new opportunities for development. LNG fuel is suitable for container ships, oil/chemical tankers, and bulk cargo carriers.

2.3.2 Methanol-fuel powered ships

The methanol-to-hydrocarbon ratio of the methanol fuel is 1/4, which can be completely burned by self-supplying oxygen, resulting in reduced emissions. Since the density and calorific value of methanol are lower than that of fuel, the volume of methanol fuel will be 2.5 times the volume of fuel that produces the same energy. Because methanol can be converted into methoxymethane, it is also a fuel that can be used by the main engine.

The two-stroke diesel cycle main engine or the four-stroke to cycle main engine with methanol as fuel are common. The main technical problems currently facing methanol diesel engines and the key research directions in the future include the following: (1) Fuel: At present, the mixed combustion of
methanol and diesel is more practical than burning pure methanol. However, because methanol and diesel oil are not compatible with each other, which leads to the affected blending of methanol and diesel oil, solubilizer technology is particularly important. (2) The application of methanol fuel in swirl chamber diesel engines still needs further research, including the working process, air flow movement, fuel mixing, and combustion mechanism of swirl chamber diesel engines. (3) Emissions from the combustion of methanol: The exhaust contains unconventional emissions, including unburned alcohol, formaldehyde and formic acid. These substances pose a certain threat to humans and the environment, and are likely to cause secondary pollution. Therefore, intensive research is still needed on the emission treatment of methanol after combustion. (4) Fuel injection characteristics of methanol diesel engines: The fuel injection characteristics of methanol diesel engines have an important effect on engine performance. The effects of fuel injection pressure, fuel injection time, and fuel injection amount on the engine’s power, economy, and emissions need to be studied. (5) Methanol will corrode: Methanol has a low carbon content, which is highly corrosive to metals and has swelling effects on plastics and rubber. This can adversely affect components, including valves and valve seats, spark plug electrodes, plastic rubber parts, fuel injection pump parts, and high-pressure fuel pipes. Therefore, choosing the right materials to achieve a robust design and ensure the performance of the entire machine is a salient part of the development process of methanol diesel engines [18-19].

2.4 Wind-powered ships
Due to the impact of environmental degradation and increasing oil prices, the once-forgotten wind-powered ships have once again appeared in the public eye. However, the current wind-powered ships are also unable to use sails to provide most of the power required by the ship itself, and they cannot compare the economic efficiency and transportation capacity with other power-driven ships. There are currently several types of wind-powered ships, including fixed wings, cylinders and skysails.

3. Types of energy-saving and environmental protection technologies and energy-saving performance of new energy (fuels)
In addition to the rich reserves of new energy (fuels), good combustion effects, and no pollution from combustion products, the life cycle of new energy on ships and the performance of energy-saving have also become the criteria for judging new energy (fuels). Details can be found in Table 2.

| Energy saving mode                        | Modifiable (yes / no) | Energy saving level | Life cycle cost (low / medium / high) |
|------------------------------------------|----------------------|---------------------|---------------------------------------|
| Mechanics power                          |                      |                     |                                       |
| Prime mover (generator)                  | Not all              | 5%                  | 20%                                   | Varied |
| Diesel electric hybrid                    | no                   | 5%                  | 10%                                   | Low / medium |
| Hydrogen fuel cell-powered               | Not all              | Unknown             |                                       | High |
| Pure battery power                       | Not all              | 100%                |                                       | Medium / high |
| Fuel cell                                | Not all              | Unknown             |                                       | High |
| Renewable energy                         |                      |                     |                                       |       |
| Solar energy                              | Yes                  | 0%                  | 1%                                    | Medium / high |
| Wind energy                               | Yes                  | 5%                  | 35%                                   | Low / medium |

4. The market application status of new energy (fuels) ships
As new energy (clean) fuels are currently in the early stages of industrial development, most of the applications are mainly concentrated in several typical ship types and trial operation stages. Specifically, the development of LNG fuel is relatively mature, and the types of applications cover almost all types of civilian ships and some industrial ships. Methanol fuel belongs to the initial stage of development, and the application type is limited. Solar energy is currently only suitable for low-power ships due to the current low energy conversion efficiency and the need to lay decks over a large area. The diesel-electric propulsion ship is relatively mature and can be used in a wide range of ships. Details can be found in Table 3 [20].
Table 3. New energy applied to different ships.

| New energy (clean) fuel | Application of ship |
|-------------------------|---------------------|
| Low flash point fuel    | Passenger ferry, Oil / chemical vessel, Platform supply vessel, Container ship, Liner, General cargo ship, Bulk cargo ship and so on |
| LNG                     | Oil / chemical vessel |
| Methanol                | Business ships with complex working conditions and Ocean working ship |
| Diesel electric hybrid  | Liner, Motor carrier ship, Yacht, Patrol boats and Unmanned submarine |
| Hydrogen fuel cell      | Liner |
| Wind energy             | Ocean bulk carrier ship, Oil tanker, roll-on-roll-off ship |
| Solar energy            | A ship with a large open deck, such as a bulk carrier |

5. Future development trends of new energy

Judging from the technical development trend of new energy (clean) ship types, the future development of ship power will change from the current monopoly position of heavy oil to a mode in which multiple energy sources such as diesel, LNG, methanol, and fuel cells coexist. Environmental protective and energy-saving ship design, full life cycle economy, and technical feasibility will become popular products in the future market.

Compared with the development of foreign new energy ship types, there are still some restrictions on domestic issues. For example, the current construction of the LNG bunkering facilities lacks a planning basis, construction site selection is difficult, and the engineering approval basis and requirements are incomplete. In addition, technical problems such as low energy storage efficiency of solar cells and many disadvantages of pure electric energy storage elements still need to be researched. Consequently, the development of new energy ships requires continuous R & D on the one hand, and continuous improvement of policies on the other, which two combined will promote the shipping industry to continue to move towards green and advanced.

References

[1] Li, B. (2008) Marine diesel engine. (The second edition) Dalian Maritime University Press Dalian, Dalian.
[2] Wu, Y.Z., Wu, J.F. (2018) Application and development direction of ship clean energy. China. Water. Trasp., 4:57.
[3] Du, P.S. (2016) Research on the development trend of marine power system. Mod. Manuf. Technol. Equip., 4:74-75.
[4] Wu, S.T. (2018) Application prospect of battery electric ship. Mech.& Electric. Technol., 5:117.
[5] Zhang, M.M., Kang W. (2011) Design of a hybrid electric ship energy management system. China. Water. Transp., 12:67.
[6] Wang, G. (2013) Study on the influence of ship operation condition on the characteristics of electric propulsion system. Wuhan University of Technology, Wuhan.
[7] Han, Y. (2012) Research on the application of new energy in ships. Harbin Engineering University, Harbin.
[8] Wang, Y.W., Hu, K.R., Yan, X.P. et al. (2018) Summary of key technical problems of hybrid energy storage system for new energy ships. Shipbuild.China., 1: 227-229.
[9] Zhu, W.P. (2018) Economic benefit evaluation of 500 tonnage new energy pure electric ship in inland river. Open. J. Transp. Technol., 3:72-74.
[10] Liu, Z.C., Tan, K., Yu, H.Y. et al. (2019) A review of the development of marine diesel electric hybrid system in China and its typical application case. Diesel. Engine., 4:46-47.
[11] Liu, Y.Z., Hu, Y., Xu, Z.F. (2019) Study on the maneuverability of diesel electric hybrid ship. Chin. Intern. Combust. Engine.Eng., 1:51.
[12] Nie, Y.S., Liu, Z.Y., Liu, Y.X. et al. (2006) Principle and application of marine shaft belt motor and its PTO / PTI working mode. J. Navig. Technol., 4: 42-43.
[13] Yu, Q.H. (2018) Research and development of solar powered ships. J. Ship. Electric. Technol., 2:33-34.
[14] Wei, S.Y., Sun, W.H., Chen, Z.J., et al. (2016) Efficiency analysis of solar cell. New. Chem. Mater., 61(16):1748-1753.
[15] Ma, Y.K., Zhang, Q.J., Zhao, J.J. (2019) How far is the way for "hydrogen" loading in the shipbuilding industry. Marine. Equip. Mater. & mark. 3:14-15.
[16] Yu, B.F. (2014) Analysis on the development of LNG powered ships. Technol. Innov. appl., 33:63.
[17] Luo, M.H., Mo, B.Z., Huang, Q.W. (2019) Development prospect of LNG fuel powered ships. Chin. J. ship. Surv., 1:59-61.
[18] Zhan, M.N., Jing, J.C., Lou, C.J. (2018) New alternative energy sources for ships in the future. Shipp. period., 29(A1): 158-159.
[19] Wu, S.T. (2019) Prospect of methanol diesel engine applied in marine power plant. J. Intern. Combust. Engine. 4:13-15.
[20] Qin, Q., Wang, Y.Z. (2018) Global new energy (clean) ships and related intelligent technology development. Shipp. period. 29(A1):29-34.