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A review of propulsion methods for nuclear-powered ships : Mechanical Propulsion & Electrical Propulsion

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1. Introduction

A nuclear-powered ship derives its propulsion force from nuclear energy and its internal configuration is the same as that of a land-based nuclear power plant. The energy from nuclear fission in a reactor produces steam, which drives a turbine to obtain useful work. Where it differs from a land-based nuclear power plant is that the rotation of the turbine does not generate electricity, but turbine rotates propeller by connecting the turbine directly to a propeller with propulsion shaft. As a result, the propeller pushes against the water and propels the ship forward. This is one of the 'Mechanical Propulsion (MP)' methods. MP are classified into various methods depending on how to create rotational force, such as steam turbine, gas turbine, and reciprocating engines (e.g. diesel engine). The most important feature of MP is that it directly uses the rotational energy of rotating machines as a propulsion energy.

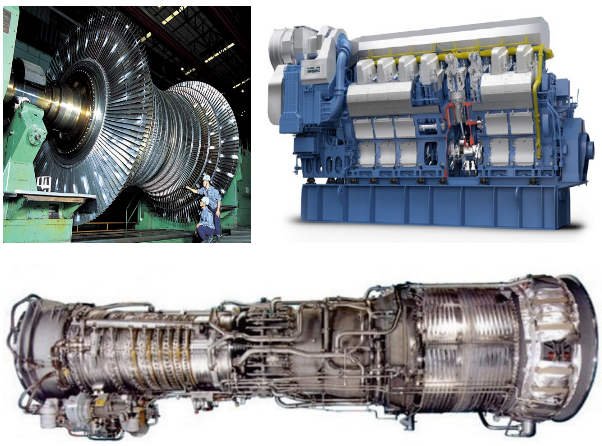

Fig 1. Steam Turbine (up, left) [1],
Diesel Engine (up, right) [2], Gas Turbine (down) [3]

On the other hand, it is also possible to generate electricity like a land-based nuclear plant and utilize electricity for propulsion using a motor. The electricity generated from rotating machine operates a motor connected to a shaft with propeller allowing the propeller to rotate and propel. This is the 'Electric Propulsion (EP)' method.

When building nuclear-powered ships, choosing which propulsion method to apply is considered to be one of the important issues. This paper will analyze and compare the system structure and characteristics of the two propulsion methods, and review the factors to be considered in selecting the propulsion method.

2. Analysis of two propulsion methods

2.1. Configuration

Even if nuclear energy is not used, MP and EP are widely applied in diesel-powered vessels, which are currently the main power sources for ship propulsion. For a basic understanding of the two propulsion methods, the structures of the two will be reviewed based on cases applied to diesel-powered propulsion system.

A simple MP system with diesel engine is shown in Fig. 2. The shaft connects a diesel engine to a gearbox and a shaft from the gearbox connects a propeller. The rotational energy generated by the diesel engine is directly transmitted through the shaft mechanically, causing the propeller to rotate. The speed of the ship can be controlled by changing the engine power or by manipulating the gear ratio of the gears in the gearbox. The MP system has an intuitive and simple configuration, and has high reliability as a propulsion method that has been used for many years.

Fig 2. Simple Mechanical Propulsion System [4]

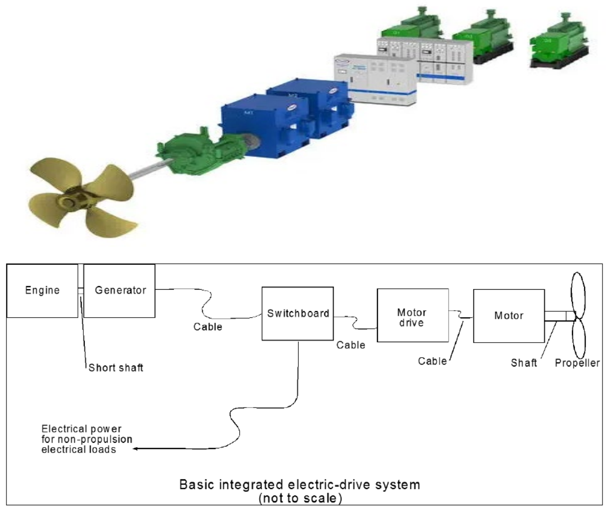

Fig 3. Electric Propulsion (shaft-type) System [5, 6]

The main difference between MP and EP is that the power source is not a diesel engine but diesel generator. Instead of connecting engine and propeller mechanically, it connects via electricity. EP is divided into two types: shaft-type and pod-type propeller. The configuration of the shaft type is shown in Fig 3. A structure of the propeller and the shaft connected to the motor is similar to that of TP system. When electricity is generated from the diesel generator, electricity is supplied to the motor through the main switchboard in the ship.

The configuration of the pod-type propeller is shown in Fig 4. The pod-type propeller uses equipment in which a motor and a propeller are combined into one. Therefore, one of the characteristics is that a long shaft connecting the motor to propeller is not used. By using the motor, not only the propeller rotates, but the vertical pod of the equipment can also rotate, so the direction of the propeller can be rotated 360 degrees. A normal ship moves only in a straight direction with the thrust of the propeller and moves left and right by manipulating a separate structure called a rudder. However, this propulsion type can change the direction of the ship by rotating direction of the propeller without a rudder.

Fig 4. Pod- type propeller propulsion system [7]

2.2. Comparison of two propulsion methods

EP is known to have advantages over MP in several ways. First, the noise and vibration resulting from the movement of the mechanical devices is reduced because the number of mechanical devices is much smaller. Next, it allows for more flexibility in the general arrangement of the ship. MP structurally requires a rotatory machine, propeller, and shaft of the power source to be connected, which requires substantially large continuous space. However, EP has great autonomy in space design because generators and a motor can be placed separately by establishing an electric transmission system. There are also fuel efficiency and environmental benefits. As the power source changes to electricity, the generator will take care of all electricity demand, such as propulsion and hotel loads. if the generator can be properly operated at an optimal load factor that can have good power generation efficiency, fuel efficiency can be increased and a lower fuel consumption rate can be obtained. If fuel consumption is lowered, pollutant emissions to the atmosphere can also be reduced. In particular, the pod-type propeller has an additional advantage that it has excellent control performance that can move quickly in all directions compared to the all shaft-type propulsion method including MP

Although EP has many advantages, one of the most powerful disadvantages is that the construction and maintenance cost of the ship is higher than that of MP [8, 9].

The difference in the characteristics of these two propulsion methods is more clearly revealed in that the main propulsion method is specified according to the type of ship. Upper diagram of Fig 5. is a chart showing the propulsion method applied to cruise ships currently operating in the world. It can be seen that most cruise ships commissioned after year 2000 are applying EP. Since cruise ships are intended to sail with many passengers, it is necessary to minimize noise and vibration from mechanical devices in the ship. Additionally, having a generator that can cover the capacity required for large propulsion power allows the cruise ship to respond flexibly to varying hotel loads and is efficient for the ship's overall energy management. For example, the largest cruise ship by gross tonnage to date, the Oasis-class cruise ship, has a propulsion power of approximately 60 MW.

Icebreakers are also similar to cruise ships. When icebreaking, sail at a rather low speed of about 3 to 4 knots, not the speed in the open sea. In the case of a turbine, a ‘turbo lag’ phenomenon in which torque is not transmitted well at low RPM occurs, whereas a motor delivers the designed torque well even at low RPM. Frequent speed changes are required during icebreaking. Compared to a turbine, motor driven by electrical energy has little delay in obtaining the desired RPM and speed. Since it is reasonable to use a motor to achieve the ultimate goal of an icebreaker, they seem to have adopted EMP decades ago. Also, when navigating in iced seas, icebreakers must be able to change direction quickly to avoid getting stuck around glaciers. In this regard, A pod-type propeller that improves the maneuverability of a ship is also widely applied to icebreakers. Propulsion method trend of icebreakers is shown in downside of Fig 6.

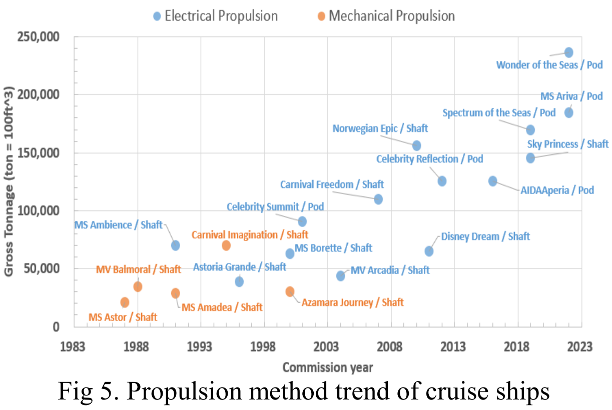

Fig 5. Propulsion method trend of cruise ships

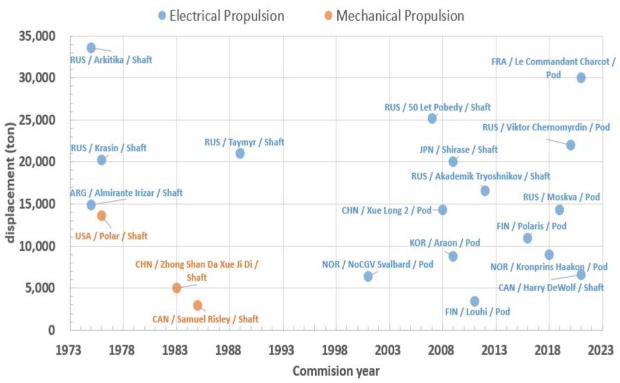

Fig 6. Propulsion method trend of icebreakers

In the case of container ships, it is the exact opposite. Almost all ultra large container ships (ULCS) in service with a capacity greater than 20,000 TEU are using MP. One of the reasons may be that at the time of construction, there were no motor capable of handling the high output required to propel a container ship. Among the propulsion motor applied to actual ships around the world to date, the one with the largest output is the motor loaded on the US Navy's Zumwalt-class destroyer (Displacement: 15,900 ton, max speed: over 30 kts) commissioned in 2016. The motor is known to have an output of 34.6 MW. Compared to a diesel engine that can produce up to about 80 MW, this is a fairly small output. However, with the development of technology, a motor for ship propulsion capable of generating greater output are being developed. According to major ship propulsion equipment companies, such as GEPC and ABB, it is possible to make motors of up to 80 MW in nowadays [10, 11]


Fig 5. Propulsion motors of GEPC (up) [10] and ABB (down) [11]

Although there are motors with high output and EMP has several advantages, it is also a problem that it is expensive. Even considering the characteristics of a container ship, the advantages obtained by using EMP are not so obvious. Compared to its large size, the number of crew members aboard the ship is quite small. Therefore, there are not many hotel loads like cruise ships, and noise and vibration are not as much of a concern. This is because in a large ship, the crew's main living quarters and the engine room are far apart, so this is not a big problem. Container ships sail steadily at planned cruising speeds to their next destination, so there is no need to change speed as often as icebreakers do. From the perspective of container ships, there will be no reason to apply EMP while paying high costs.

2.3. Propulsion methods of actual nuclear powered-ships

The actual use of nuclear-powered ships is limited to the military sector until now with a few, exception of a small number of nuclear-powered icebreakers. The navies of traditional maritime powers, including the United States, have nuclear-powered aircraft carriers and submarines. Meanwhile, it can be confirmed that each country has a different propulsion method that is mainly adopted for its nuclear-powered ships. United States, Russia, and the United Kingdom, which have been building many nuclear-powered warships for decades, are applying MP. In contrast, France is applying EP.

The recent propulsion method seems to be gradually changing to EDP. The new Columbia-class and Dreadnought-class ballistic missile submarines (SSBN) currently being built in the US and the UK are using with TDP. As the performance of armaments and sensors mounted on large scale nuclear-powered ships gradually advances, the demand for power of the equipment is increasing. In addition, it is necessary to flexibly respond to various power changes according to the operation of modular power equipment and unmanned systems. For these reasons, it seems that a large-capacity generator is mounted and an electricity-based propulsion system is applied. This cannot be accomplished by separating the source of a large amount of propulsion from the source of the ship's power demand in a within a confined space of the ship. It appears that the advantage of EP will also apply to nuclear-powered ships.

3. Conclusions

The basic configurations of the MP and the EP systems were reviewed, and the characteristics and strengths and weaknesses of the two propulsion methods were analyzed based on the examples of actually built ships. It is shown that the propulsion methods applied differently depending on the type of a ship.

EP has advantages over MP in many ways, and according to the recent development of motor technology, it seems that motors are capable of generating large thrust and also available in the shipbuilding market. However, since the ship building price and maintenance cost are quite high with EP, it should be confirmed whether the benefit from EP is large even after paying extra cost based on the use and navigational characteristics of the ship.

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