Research on Energy Efficiency Design Index Calculation Method for the Hybrid Ship

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Abstract—The Marine Energy Efficiency Design Index (EEDI) is recognized as an effective tool to measure the level of carbon emissions from ships at home and abroad. It will play an important role in the assessment of carbon emissions from the shipping industry, especially under the current and future development goal of carbon neutrality. Various green technologies to reduce the carbon emissions of ships have been demonstrated and applied. Hybrid power system is one of them. Compared with traditional direct propulsion, it can significantly reduce the energy consumption and carbon emissions of ships in inland waters such as the Yangtze River. Based on the characteristics of the hybrid power system, this paper firstly analyzes the power types of the hybrid power system during ship navigation. Then, according to the principle and elements of EEDI calculation method, it puts forward the key problems that should be solved in ship EEDI calculation of hybrid power system. Then, according to different hybrid operation modes, it also puts forward the calculation method of EEDI of each power mode and the calculation method of acquired EEDI of hybrid ship. Finally, the calculation and analysis of a 7500DWT hybrid bulk carrier show that the EEDI calculation method for hybrid ships proposed in this paper is scientific and reasonable.

1. INTRODUCTION

Climate change is a global problem facing human beings. With the emission of carbon dioxide by various countries, greenhouse gases surge, posing a threat to the life system. In this context, countries around the world to reduce greenhouse gases in the way of global agreement, so that China's carbon dioxide emissions to reach the peak before 2030, and strive to achieve the goal of carbon neutrality before 2060. At the 62nd meeting of the IMO Marine Environmental Protection Committee (MEPC) in July 2011, the Marine Energy Efficiency Design Index (EEDI) was incorporated into MARPOL Annex VI, which was approved and took effect on January 1, 2013. Since then, the shipping industry has become an industry implementing mandatory greenhouse gas emission reduction regulations [1]. In order to reduce greenhouse gas emissions from inland waterway shipping in China, the Ministry of Transport issued the Standard Ship Type Indicator System for Inland Waterway Shipping in 2012 with the No.13 Ministerial Decree [2], requiring that new ships built on July 1, 2012 and later must meet the CO2 emission requirements. China Classification Society published the first EEDI Evaluation Guide for Inland River Vessels in 2012, and proposed the calculation and verification method of EEDI
applicable to inland river vessels. In addition, EEDI limit standard for inland river vessels was put forward in the Rules for Green Inland Waterway Ships, providing technical standard support for reducing CO2 emissions of inland river vessels [3].

China's inland water transportation resources are rich, especially in the last 10 years, inland water transportation has made remarkable achievements, forming a "two horizontal, one vertical, two networks and 18 lines" shipping network. According to the statistics of the Ministry of Transport, at the end of 2018, there were 124,300 inland rivers in China. At the same time, with the transformation of China's shipping ecology priority and green development, stricter standards have been put forward for pollutant emissions from ships. However, because the shipping logistics of the Yangtze River and other major inland rivers is the input type of resources (coal oil and other bulk cargo), the characteristics of full load when up, and light load or no load when down are significant, resulting in a big difference in the power demand of the ships up and down in water. At the same time, the ships basically adopt the power system type of diesel engine driven fixed pitch propeller. Inland waterways are characterized by tortuous waterways, narrow cross-section, frequent riverbed evolution, and obvious seasonal influence on water level. Under the influence of these characteristics, ships sailing in inland waterways cannot operate stably in rated working conditions for a long time, which often results in large engines and small use, leading to increased energy consumption and pollutant discharge. In order to solve the problem of increasing energy consumption and emissions caused by the "large engine and small operation" of inland river ships, the research of hybrid propulsion system has made important progress and started to be demonstrated and popularized in inland river ships. However, the existing EEDI calculation method is mainly aimed at the conventional and traditional propulsion type, which can no longer meet the needs of the new hybrid system ships. Therefore, it is urgent to further study and put forward an applicable EEDI calculation method to fill the needs of the development of hybrid system ships [4][5].

2. HYBRID SHIP DESIGN

More than 90% of the ships in the inland river use the traditional direct propulsion system, that is, the main engine is connected to the shaft through the gearbox, and the shaft drives the propeller to rotate and push the ship forward or backward. The main advantages are simple structure, less equipment, and the defect is propulsion system fixed optimization design, difficult to adapt to the navigation condition optimization of inland river, especially the Yangtze River, such as the high load in the very short time when the ship is rushing ashore/rushing, the high load in the upstream sailing, and the low load in the launching sailing, so as to achieve the demand of energy saving and emission reduction. Therefore, a hybrid power system is proposed to satisfy the efficient operation of inland river ships under multiple operating conditions.
2.1. Structure Type of Hybrid Power System

Hybrid power system consists of engine, generator set, lithium battery, reversible motor (PTI/PTO), gear box, shafting, power conversion device, clutch, propeller, etc. The engine, generator set and lithium battery provide propulsion power and Daily load power supply, among which engines and generator sets can be diesel engines or LNG engines, and the propellers can be propeller propellers, or pod propellers, or azimuth propellers, or shaftless rim propellers. The engine and the reversible motor can be paralleled through the gear box, and either side can also be disconnected from the gear box. That is, the engine and the motor can provide torque to the transmission system separately, or can be driven together through a torque coupling device (gear box). The motor can also be used as a generator to supply power to daily loads and charge lithium batteries [6]. The basic structure is shown in Figure 1.

Fig. 1 Structure type of hybrid power system

2.2. Analysis of Efficient Operation Mode of Hybrid Power System

The First is the single engine operation mode (direct thrust mode). Under normal sailing conditions or slightly higher operating conditions (depending on the engine power configuration), the propeller can be directly driven by the engine, that is, the engine alone provides torque to the transmission system to allow The engine works in a high efficiency zone.

The second is the motor's stand-alone operation mode (PTH mode). When the ship is under low sailing conditions or normal sailing conditions (depending on the configuration of the generator set), the propeller can be driven by the reversible motor, and the propulsion system is completely For electric propulsion, the surplus power can also be used to charge the lithium battery, and the number of generator sets that can be turned on can be determined according to the sailing conditions of the ship, so that it can work in a high-efficiency area [7].

The third is that the engine and the reversible motor drive the propeller at the same time (BOOST mode). In order to meet the ship's propulsion power requirements when the ship is in high or high sailing conditions, the engine and the reversible motor drive the propeller together. The generator set is the reversible motor and the whole ship. Load power supply, the generator set can start 1, 2 or more according to actual needs[8].

Fourth, the engine drives the propeller and the shaft generator (PTO mode), that is, the engine drives the propeller and drives the shaft motor at the same time. At this time, the shaft motor is used as a generator to supply power to the ship's load and charge the lithium battery.
Fifth, the generator set + lithium battery power mode. In this mode, when the load of the generator set is high, the lithium battery provides extra power for the shaft motor in a short time when the load needs to be accelerated instantaneously.

Sixth, the lithium battery alone power supply mode, which can supply power for the entire ship during the port area, anchorage, and dam crossing, so as to achieve zero emission of waste gas pollutants in the port, anchorage and other areas, and reduce the aggregate emission of waste gas pollutants.

From the above analysis, it can be seen that ships equipped with hybrid power systems can flexibly select the applicable operating mode according to cargo loading, season, water loading or launching during the voyage, so as to always maintain a green and efficient operating state.

3. EEDI CALCULATION METHOD FOR HYBRID SHIPS

3.1. EEDI Calculation Method

The inherent meaning of EEDI refers to the estimation of CO2 emissions based on the propulsion power required by the ship to sail at a certain speed at the maximum load and the fuel consumed by the relevant auxiliary machinery power required by the ship. The greater the EEDI value, the greater the amount of CO2 emitted by the ship per unit distance and the higher the energy consumption. EEDI calculation formula is as follows:

$$\text{Attained EEDI} = f_j \cdot \sum_{i=1}^{n} P_{\text{ME}(i)} \cdot (SFC_{\text{ME}(i)} \cdot C_{\text{ME}(i)} + SFC_{\text{QME}(i)} \cdot C_{\text{QME}(i)})$$  \hspace{1cm} (1)

$$+ \sum_{i=1}^{n} P_{\text{AE}(i)} \cdot (SFC_{\text{AE}(i)} \cdot C_{\text{AE}(i)} + SFC_{\text{QAE}(i)} \cdot C_{\text{QAE}(i)})$$

$$- \sum_{i=1}^{n} f_{\text{eff}(i)} \cdot P_{\text{eff}(i)} \cdot SFC_{\text{ME}(i)} \cdot C_{\text{ME}(i)} - \sum_{i=1}^{n} f_{\text{eff}(i)} \cdot P_{\text{eff}(i)} \cdot SFC_{\text{QME}(i)} \cdot C_{\text{QME}(i)}$$

The meaning of the main parameters in the formula: $n_{\text{ME}}/n_{\text{AE}}$—Number of main engine/auxiliary equipment, $P_{\text{ME}}/P_{\text{AE}}$—Main engine 75% rated power/auxiliary equipment 50% rated power value, kW. $SFC_{\text{ME}(i)}/SFC_{\text{QME}(i)}$ is the fuel/gas consumption rate corresponding to $P_{\text{ME}}$. $SFC_{\text{AE}(i)}/SFC_{\text{QAE}(i)}$ is the fuel/gas consumption rate corresponding to $P_{\text{AE}}$. $C_F$ is CO2 conversion coefficient of fuel. $n_{\text{eff}}$, $f_{\text{eff}(i)}$, $P_{\text{eff}(i)}$, $P_{\text{AEeff}(i)}$ are related parameters of energy efficiency technology. $V_{ref}$ is the speed of the ship in deep water under full load conditions and the main engine is propelled at 75% of the rated power in calm waters without wind and waves, kn. Capacity is the carrying capacity. $f_j$, $f_i$, $f_c$ are the correction coefficients related to the ship type.

3.2. EEDI Calculation Method for Ships With Hybrid Power System

3.2.1. Principles for determining the EEDI calculation method for ships with hybrid power systems.

The original purpose of EEDI calculation formula is mainly for the conventional traditional direct propulsion type, that is, the main engine drives the propeller to propel the ship sailing through the gearbox and shafting, and the auxiliary engine generates electricity for the whole ship's electrical facilities and equipment. Therefore, it can be seen from the above calculation formula that the EEDI calculation formula mainly contains three parts. The first part is to measure the CO2 emission of the main engine under the design condition; the second part is to measure the CO2 emission of the auxiliary engine under the common condition; and the third part is the amount of CO2 emission reduction brought by the adoption of new energy efficiency technologies such as sailing aid. For hybrid power system, there is no strict distinction between main engine and auxiliary engine in the setting of power
system. Under different power operation modes, all power sources (engine, generator set, lithium battery, etc.) can play the role of the main propulsion and power supply of the ship.

At present, in the IMO’s the MARPOL convention and China classification society’s Rules for the inland waterway green ships contains only the traditional straight push EEDI calculation methods of the ship, there is no EEDI calculation methods of hybrid system of ship, therefore, in the light of the features of the hybrid system structure and function model, to study and put forward the EEDI calculation method under different operating mode, Mainly based on the following principles:

3.2.1.1. Coordination. The determination principle of hybrid power system EEDI calculation method should be consistent with international and domestic standards, so that the EEDI index of ships with hybrid power system can be measured with the same EEDI reference line value as that of ships with traditional conventional propulsion type.

3.2.1.2. Focus on the main contradiction. From the ship specification standard, the main difference between the EEDI calculation method of different power type ships is the power determination method of the main engine power $P_{ME}$ and the auxiliary machine power $P_{AE}$. Therefore, according to the characteristics of the hybrid system structure and function mode, it is mainly necessary to study the calculation method of the main engine power $P_{ME}$ and the auxiliary machine power $P_{AE}$ required to calculate the EEDI in different operating mode.

3.2.1.3. Take into account a variety of energy mix. Because the energy usage of hybrid power system may include oil fuel, LNG, lithium battery and other energy devices, the EEDI calculation problem with the coexistence of multiple energy sources should be considered in the study of the EEDI calculation method.

3.2.2. EEDI calculation method of hybrid power system ship. a) Main engine power $P_{ME}$ calculation method

- Direct push mode

Because the direct push mode of the hybrid power system is that the engine directly pushes the propeller through the gearbox and shafting, which is the same as the EEDI calculation method in MARPOL Convention and Rules for Inland waterway Green Ship, the power redundancy of 15% of engine power and the power decline reserve of 10% caused by equipment aging over time are mainly considered. Determine the power of the main engine is 75% of the rated power of the engine;

- PTH mode

Based on the coordination of the above main principles, in the PTH mode, the powertrain design mainly considers the propulsion motor power 15% redundancy reserve; At the same time, the propeller is driven by a propulsion motor in this mode, and its energy comes from the generator set. Therefore, the nominal power of the main engine needs to be determined from the back to the front, that is, according to the power of the propulsion motor and the power generation efficiency and energy transfer efficiency between the prime movers and the propulsion motor:

$$P_{ME(i)} = 0.85 \times \frac{MPP_{Motor(i)}}{\eta(i)}$$ (2)

Where: $MPP_{Motor(i)}$ is the rated output power of the propulsion motor (motor); $\eta(i)$ is the product of the electrical efficiency of the generator, transformer, converter, and motor

- BOOST mode

According to the operation characteristics of Boost mode mentioned above, ship propulsion power is the integration of engine and propulsion motor, so under this mode, the calculation method of nominal main engine power should include two parts:

$$P_{ME} = \sum P_{ME(i)} + 0.85 \times \frac{MPP_{Motor(i)}}{\eta(i)}$$ (3)
• PTO mode

In this mode, the nominal power $P_{ME}$ of the main engine should be calculated by deducting the power generated by the engine which is used for PTO power generation. The calculation method of $P_{ME(i)}$ is as follows:

$$P_{ME(i)} = 0.75 \times (MCR_{ME(i)} - P_{PTO(i)})$$

Where: PTO is 75% of the rated power output of the shaft generator.

• Generator + lithium battery mode

If the electric energy of the lithium battery comes from charging the battery by the generator set at ordinary times, since in this mode, the lithium battery only temporarily provides additional electric power for the shaft motor in the case of instantaneous acceleration, it can not be included in the EEDI calculation formula. In this case, the EEDI calculation method of the PTH mode can be adopted.

• Lithium battery alone power mode

Because in this mode, the ship is in the berthing state, and the power supply for the ship is only sometimes in the port area, anchorage, dam crossing and other sluice period, so this part should be included in the auxiliary engine power.

3.2.2.1. Determination of the power of the auxiliary machine. The auxiliary machine power is mainly considering the electric equipment load in normal navigation. Due to the multiple power mode of the hybrid system, it is difficult to use the normal navigation of the ship to use the tradition of normal navigation of the ship to determine the power generation power of the net generator set. Therefore, the auxiliary power should be determined by the power load table.

3.2.2.2 Attained EEDI calculation method of hybrid system. In each mode determined by the above 3.2 (2), the main and auxiliary machine power is entered into the EEDI calculation formula of 3.1, and the Attained EEDI value in each mode is obtained, and the Attained EEDI calculation method of the hybrid system ship is:

$$\text{Attained EEDI} = f_1 \times \text{Attained EEDI}_{\text{Direct push}} + f_2 \times \text{Attained EEDI}_{\text{Boost}} + f_3 \times \text{Attained EEDI}_{\text{PTH}} + f_4 \times \text{Attained EEDI}_{\text{Generator + battery}}$$

Where: $f_1$, $f_2$, $f_3$, $f_4$, $f_5$ is the sailing distance of the hybrid ship in each mode, $f_1 + f_2 + f_3 + f_4 + f_5 = 1$, documentation files in each mode should be submitted to the hybrid system ship at the same time.

4. Calculation Examples

4.1. Basic Information of Hybrid Ship

4.1.1. Ship power system configuration. The target ship is a 7,500DWT bulk carrier with hybrid power system. The power system configuration scheme is "diesel main engine + shaft motor + gas generator set + lithium battery", as shown in Table 1:

| Equipment       | Rated power | NO. | Note                          |
|-----------------|-------------|-----|-------------------------------|
| Main engine     | 648kW       | 2   | Diesel engine                 |
| Generating set  | 220kW       | 3   | Gas generator set             |
|                 |             |     | (Prime mover~265kW)           |
| Shaft motor     | 320kW       | 2   | Reversible motor (Can and do PTO, PTI) |
| The lithium battery | 150kWh |     |                               |
4.1.2. Main modes in ship navigation. During the voyage along the Yangtze River, the main operation modes of the ship are: PTH mode, PTO mode and BOOST mode.

| Working condition | Segment | Distance (km) | Navigation mode |
|-------------------|---------|---------------|-----------------|
| Upward along the river | Luohuang Port - Liuhe River | 2357.2 | PTH |
| Downward along the river | Liuhe River - Taizhou | 199.3 | BOOST |
| | Taizhou - Fengjie (Changshou) | 1676 | PTH |
| | Fengjie - Chongqing (Changshou) - Luohuang Port | 355.8 | PTO |
| | Chongqing - Luohuang Port | 126 | BOOST |

### TABLE 2 POWER TYPE DISTRIBUTION DURING SHIP NAVIGATION

| Navigation mode | Distance | Proportion |
|-----------------|----------|------------|
| PTH             | 4033.3   | 0.855      |
| PTO             | 355.8    | 0.075      |
| BOOST           | 325.3    | 0.070      |
| Total           | 4714.4   | 1          |

4.1.3. The ship's route and the type of power used in different sections. The ship mainly travels back and forth between Luohuang Port and Liuhe River. Due to the effect of the Yangtze River current, the ship adopts different power types in the process of entering water and launching water. The main distribution is shown in Table 2 and Table 3.

4.2. The Calculation of Attained EEDI for the Ship

According to the above calculation formula, the EEDI value of the ship is shown in Table 4. The actual ship calculation shows the effectiveness of the EEDI calculation method proposed in this paper, which can fully reflect the carbon emission level of the ship with this type of power.

| No. | Item                            | Symbol | Unit | BOOST | PTH | PTO |
|-----|---------------------------------|--------|------|-------|-----|-----|
| 1   | Rated power of main engine      | P<sub>ME</sub> | kW   | 648   | —   | 648 |
| 2   | Number of main engine           | n<sub>ME</sub> |       | 2     | —   | 2   |
| 3   | 75% of the rated power of the main engine | P<sub>ME(1)</sub> | kW   | 486   | —   | 486 |
|   | Description                                                                 | Symbol | Unit | Value       |   |
|---|----------------------------------------------------------------------------|--|-----|------------|---|
| 4 | Fuel consumption rate of the main engine at 75% rated power                | SFC\text{YM}(1) | g/kW·h | 221         | 221 |
| 5 | CO2 conversion coefficient of the fuel used in the main engine            | C\text{FY}(1)    |        | 3.151       | 3.151 |
| 6 | Rated output power of shaft motor                                         | MPP\text{MOTOR}(1) | kW    | 320.0       | 320.0 |
| 7 | Electrical efficiency of generators, transformers, converters and motors  | \eta(1)          |        | 0.913       | 0.913 |
| 8 | The shaft motor calculates the power output                               | P\text{PTI}(1)   | kW    | 297.9       | 297.9 |
| 9 | Weighted mean of SFC\text{AE}/C\text{AE}                                 | SFC\text{AE}/C\text{AE} |           | 618.8       | 618.8 |
| 10| P\text{ME} value when calculating \(V_{\text{REF}}\)                     | P\text{ME}       | kW    | 1567.8      | 1567.8 |
| 11| Main promotion device power correction coefficient                         | \text{fj}        |       | 1           | 1   |
| 12| Rated power per generator set (prime mover)                               | P\text{AE}       | kW    | 265.0       | 265.0 |
| 13| Number of generators                                                      | n\text{AE}       |       | 3           | 3   |
| 14| 90% calibration power value of the ith in net auxiliary engine required by the ship during normal navigation | P\text{AE}(1)    | kW    | 238.5       | 238.5 |
| 15| The fuel consumption rate of the ith in net auxiliary engine required for the normal operation of the ship | SFC\text{QAE}(1) |        | 225         | 225 |
| 16| The CO2 conversion coefficient of the fuel used by the ith in net auxiliary engine for the normal navigation of the ship | C\text{FAE}(1)  |        | 2.75        | 2.75 |
5. THE CONCLUSION
In view of the current development goal of carbon neutrality, the shipping industry needs an effective means to measure the level of carbon emissions. EEDI can be used as an effective tool to evaluate the carbon emissions of ships. In order to reduce the carbon emissions of ships and meet the power needs of ships sailing in the Yangtze River, a new type of hybrid power system ships came into being. However, the current EEDI calculation method cannot cover hybrid power ships, so this paper based on the principle of hybrid power and the principle of EEDI calculation method. The EEDI calculation method of hybrid electric ship under different power operation modes is proposed, and the final EEDI calculation method considering the proportion of each power mode is put forward. Finally, the validity, rationality and scientificity of this method are illustrated by the actual ship calculation.

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