Two-Phase Energy Efficiency Optimisation for Ships using Parallel Hybrid Electric Propulsion System

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ABSTRACT

Developing a green, intelligent, and efficient power system is an important way for the shipping industry to respond to increasingly stringent emission regulations, and to achieve improvements in energy conservation and efficiency. In this study, a two-phase energy efficiency optimisation method is proposed for reducing energy consumption. The method comprises a combination of speed optimisation and energy management. On the demand side, the minimum accumulated power consumption required by the propeller is set as the objective function for the speed optimisation model, whereas on the supply side, the lowest cost of energy consumed by the hybrid power system is set as the objective function for the energy management model. An inland parallel hybrid electric powered bulk carrier is selected for a case study of the two-phase energy efficiency optimisation method. The optimisation results are compared with the energy consumption data of a bulk carrier under normal working conditions. The results show that the proposed method can reduce the energy consumption by 2.60% and 9.86% in the westbound and eastbound voyages, respectively. Accordingly, this study can provide methodological support for inland hybrid-powered ships aiming to achieve intelligent energy efficiency management.

Keywords: inland ship, parallel hybrid electric Propulsion, two-phase optimisation, speed optimisation, energy management

1. INTRODUCTION

At present, green and low-carbon technology for ships is a popular topic in the international shipping industry. According to the Fourth International Maritime Organisation (IMO) Greenhouse Gas Study 2020, if effective measures are not taken in time, CO_2 emissions from the shipping industry by 2050 are expected to be 30% higher than in 2008, and 50% higher than in 2018 (IMO, 2020). To promote energy conservation and reductions in shipping emissions, the IMO has proposed mandatory ship energy efficiency rules; these mainly include the Ship Energy Efficiency Design Index (EEDI) for new ships, and the Ship Energy Efficiency Management Plan for ships over 400 gross tonnage (IMO, 2016; Fan A et al., 2015). In 2018, the IMO Maritime Environment Protection Committee (MEPC) adopted a preliminary strategy to halve the total CO_2 emissions from shipping by 2050. Two projects of the EU Seventh Framework Programme (FP7) has have been carried out for on the low carbon shipping. The TEchnologies and scenarios For Low Emissions Shipping (TEFLES) project focused on reducing emissions effectively in EU motorways of the seas, analysing the potential of Emission Reduction Technologies (ERT's) from based on the EEDI and EEOI indexes (EU FP 7 project, 2014). The Targeted Advanced Research for Global Efficiency of Transportation Shipping (TARGETS) project put their attention to resistance improvement optimisation technologies and propulsion improvement technologies to reduce energy consumption, improved auxiliary on-board energy generation and propulsion improvement technologies, and integrated them in a global energy consumption simulation holistic simulation to determine optimal solutions (EU FP 7 project, 2014).

During IMO MEPC 74, the Energy Efficiency Existing Ship Index was proposed for managing the emission reduction problems in existing ships for which the EEDI is not applicable. The determination of IMO to reduce emissions is evident, and has forced ships to become more environmentally friendly. Applying clean energy and developing green ships can not only solve the pollution problems caused by diesel engines, but also meet the requirements regarding energy structure adjustments and environmental protection. A multi-energy hybrid power system is a promising form of green energy, and can increase system redundancy by employing the comprehensive advantages of two or more power sources. By reducing the rated power of the main engine and implementing energy management, it can achieve the efficient use of multiple energy sources (Wang K et al., 2015; Fan A et al., 2016;). Unlike a traditional diesel system, where optimisation can only focus on a fixed load point in the design phase, a hybrid-powered system can not only optimise the configuration based on various operating conditions to improve the EEDI in the design phase, but also can optimise the IMO Efficiency Operational Indicator based on energy efficiency optimisation, energy management, and other means in response to changes in operating conditions (Zhang C et al., 2019; Fan A et al., 2020).

Speed optimisation is a common energy efficiency optimisation method (Perera L P et al., 2016), and is also important for ships in the context of intelligent energy efficiency management (CCS, 2020). At present, a significant amount of research on speed optimisation has been conducted. Corbett et al. (2009), Lindstad et al. (2011) and Chang et al. (2016) showed that if the speed of cargo ships is halved, the reduction in exhaust emissions can reach 70%. Fagerholt K et al. (2015) considered that the type of fuel used can affect the ship speed when a ship sails inside and outside an emissions control area. Aydin N et al. (2017) considered that fuel consumption is an important factor affecting ship emissions and economic benefits, with the sailing speed directly affecting the ship emissions. Xing Y et al. (2019) discussed speed optimisation for container ships, based on considering two carbon emission policies. Some researchers have use machine learning to obtain fuel consumption models. Lin H et al. (2019) used a back propagation neural network to train relevant data for a real-time fuel consumption prediction model, and further used this data for ship speed optimisation. Tarelko W et al. (2020) used artificial neural networks to build ship speed and fuel consumption models.

From the studies mentioned above, it is evident that speed optimisation techniques based on energy efficiency have been widely discussed. However, most of them have focused on traditional single-power ships, and mainly consider the fuel consumption; and there is a certain research gap in regards to the speed optimisation for hybrid-powered ships. Based on analyses of energy flows, it is evident that speed optimisation reduces the required power from the power demand side, whereas energy management mainly optimises the power allocation of the multiple energy sources from the power supply side, and aims to meet the demanded power with the minimum energy consumption. However, the hull-engine-propeller relationship indicates that the supply-distribution-consumption of energy on a ship is an integrated process. In hybrid power systems that supply multiple energy sources, the combined optimisation of the energy efficiency and energy management could achieve the lowest power requirements, along with the optimal operating mode and power allocation. Research studies have been conducted on energy management for hybrid power system. Many methods have been applied, including those based on rules, wavelets, and model predictive control (Tang D et al., 2017; Hou J et al., 2019; Yuan Y et al., 2020), as well as various intelligent algorithms. Tang R et al. (2018) and Panday A et al., (2016) adopted a particle swarm algorithm and genetic algorithm to manage the power of a hybrid power system.

The power flow of a parallel hybrid-powered ship is illustrated in Fig. 1. The energy efficiency optimisation of hybrid-powered ships involves multiple sub-systems and various factors of the ship's operation, including the hybrid power system, propulsion system, transmission system, hull, and navigational/environmental factors. When a hybrid-powered ship sails, the navigational environment factors will change consistently, making the ship's propulsion power change correspondingly; this can affect the speed of the ship, and the energy consumption of the hybrid power system. An optimised speed can be obtained through a speed optimisation model. As a result, corresponding power will be demanded from the hybrid power system to propel the ship to attain the optimised speed. In addition, the output power of each power source can be decided based on an energy management strategy. Optimising from the power demand side and power supply side simultaneously would bring more energy-efficient benefits for a parallel hybrid-powered ship.

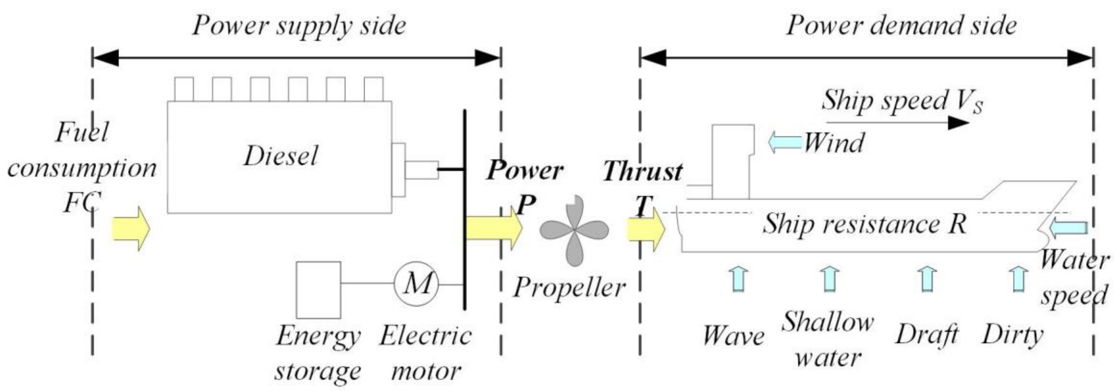

Fig. 1. Power flow of a parallel hybrid-powered ship

The two-phase energy efficiency optimisation method is introduced in Section 2, including the procedures for speed optimisation and energy management. The process of the two-phase energy efficiency optimisation for a parallel hybrid electric powered ship is introduced in Section 3. Section 4 describes the optimisation results, and provides comparisons. The paper is concluded in Section 5.

2. METHODOLOGY

In this study, a two-phase energy efficiency optimisation method based on a combination of speed optimisation and energy management is proposed for deciding the optimal ship speed and power allocation, and a genetic algorithm is used to obtain the global optimal results. The proposed method is composed of five elements as shown in Fig. 2, *i.e.* provision of basic information, data characteristics analysis, hull-engine-propeller analysis, speed optimisation and energy management, and energy efficiency evaluation. The basic information provides the relevant parameters; the analysis of data (*e.g.* ship speed, main engine power, and fuel consumption) aims to find the characteristics of the environmental and ship operational parameters; the hull-engine-propeller analysis draws the dynamic relationship between the power and speed; the speed optimisation and energy management determine the optimal speed and power allocation; and the energy efficiency evaluation aims to analyse the energy-saving benefits.

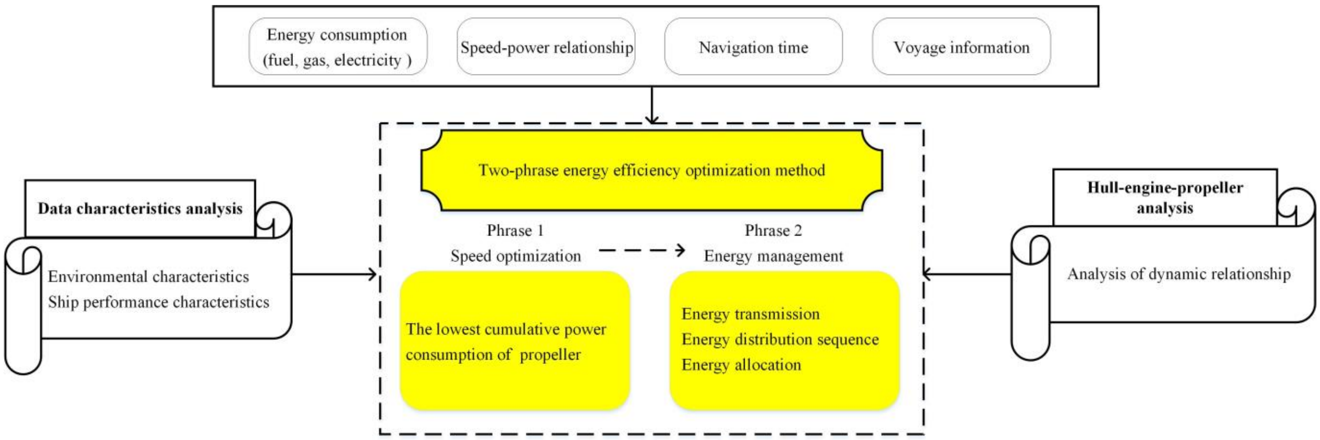

Fig. 2. Overview of the proposed two-phase energy efficiency optimisation method

2.1. Hull-engine-propeller analysis

When the ship sails, the power output by the hybrid power system is ultimately converted by the propeller into the thrust that drives the ship to sail. The thrust overcomes the ship resistance R, and propels the ship forward. Assuming that the ship sails at a constant speed V_s over the water, the relationship between the thrust of propeller T, effective thrust T_E, and resistance R can be expressed by Equation (1).

$$R = T_{\mathrm{E}} = (1-t)\ T \tag{1}$$

The effective power of the propeller P_E can be expressed by Equation (2).

$$P_{\mathrm{E}} = T_{\mathrm{E}} V_{\mathrm{s}} = R V_{\mathrm{s}} \tag{2}$$

Considering the mechanical efficiency, the power delivered by the power system P_B can be described as:

$$P_B = \frac{P_E}{\eta_S \eta_G \eta_R} \tag{3}$$

Where η_s is the shaft transmission efficiency; η_G is the gearbox efficiency; η_R is the relative rotation efficiency.

The thrust of propeller T can be calculated using Equation (4).

$$T = K_T \rho n^2 D^4 \tag{4}$$

In the above, K_T is the thrust coefficient; ρ is the water density; n is the propeller revolution speed; and D is the diameter of the propeller.

The open water efficiency of the propeller η_o can be calculated using Equation (5).

$$\eta_o = \frac{K_T}{K_Q} \cdot \frac{J}{2\pi} \tag{5}$$

Here, K_Q is the torque coefficient; and J is the advance coefficient of the propeller.

The advance coefficient of the propeller J can be calculated using Equation (6).

$$J = \frac{(1-w) \cdot V_S}{nD} \tag{6}$$

In Equation (5), w is the wake fraction.

According to Equations (1)–(6), the power delivered by the power system P_B can be calculated using Equation (7), as follows:

$$P_B = \frac{2\pi\rho D^2 (1-w)^3 K_Q}{J^3 \eta_S \eta_G \eta_R} V_S{}^3 \tag{7}$$

2.2. Speed optimisation

Speed optimisation is a widely used energy efficiency practice. The objectives of speed optimisation usually include minimum fuel consumption, minimum emissions, or both of them. In the optimisation process, it is necessary to consider the influence of the environment (especially the water flow speed) and scheduled sailing time. A waterway partition-based method is often used to simplify the optimisation problem.

2.2.1 Objective function of speed optimisation

For the propulsion system of a single power ship, there is only one energy flow path, and the minimum fuel consumption is generally taken as the optimisation goal. However, for hybrid-powered ships, there are two or more energy flow paths. Especially for parallel hybrid electric power systems, optimisation involves a problem of electromechanical coupling. Thus, the traditional method, which fits a relationship between fuel consumption and speed and optimises the speed under an objective function for minimum fuel consumption, is not applicable for hybrid-powered ships. Therefore, considering the energy transfer characteristics of the parallel hybrid electric power system, the minimum accumulated power consumption required by the propeller is selected as the optimisation goal. The accumulated power consumption can be calculated using Equation (8), as follows:

$$W=\sum_{i=1}^{k}\left(P_{E,i}\cdot T_i\right) \tag{8}$$

In the above, k is the number of legs in the voyage; T_i indicates the time spent in i th leg, and can be calculated using Equation (9).

$$T_i=\frac{d_i}{V_{gi}}=\frac{d_i}{V_{s,i}\pm V_{w,i}} \tag{9}$$

Here, d is the waterway distance (km); V_g is the ship speed over ground (km/h); V_s is the ship speed over water; and V_w is the water flow speed. In an inland river, $V_g=V_s\pm V_w$.

Based on Equation (9), the mathematical model for the accumulated power consumption is shown in Equation (10).

$$W=\sum_{i=1}^{k}\left(\frac{P_{E,i}(\mathrm{V_s})\cdot d_i}{V_{\mathrm{s},i}\pm V_{\mathrm{w},i}}\right) \tag{10}$$

To minimise the total power consumption of the entire voyage, the speeds in different legs should be optimised. Based on Equation (10), the ship speed optimisation model including constraints can be established, as shown in Equation (11).

$$
\begin{aligned}
&\min W=\sum_{i=1}^{k}\left(\frac{P_{E,i}(V_{\mathrm{s}})\cdot d_i}{V_{\mathrm{s},i}\pm V_{\mathrm{w},i}}\right)\\
&\text{s.t.}\begin{cases}\sum_{i=1}^{m}T_i=\dfrac{d_i}{V_{gi}}=\dfrac{d_i}{V_{s,i}\pm V_{w,i}}\leq T\\ V_{\mathrm{g}}\in[V_{\mathrm{g}1},V_{gu}]\end{cases}
\end{aligned}
\tag{11}
$$

The constraints includes a limit of the total voyage time $\sum_{k=1}^{m}t_k\leq T$ and the ship speed limit in a specific leg $V_{\mathrm{g}}\in[V_{\mathrm{g}1},V_{gu}]$.

2.3. Energy management

2.3.1. Energy transmission analysis

Owing to losses of conversion efficiency and various friction sources during the transmission process, P_E should be less than the total power. As there are multiple energy flow paths in the parallel hybrid power system, it is necessary to analyse and calculate the transmission efficiency of each path, which can be divided into the mechanical transmission efficiency and electrical transmission efficiency.

The mechanical transmission efficiency η_{MET} can be calculated using Equation (12).

$$
\eta_{MET}=\eta_S\eta_G\eta_{ME} \tag{12}
$$

In the above, η_S is the shaft transmission efficiency; η_G is the gearbox efficiency; and η_{ME} is the efficiency of the main engine.

For different hybrid powered ships, the energy options for the electric propulsion energy are diverse, such as batteries, fuel cells, super capacitors, and propulsion generators. According to different working conditions, there will be many combinations for hybrid powered ships to select. Therefore, when discussing the energy transmission efficiency of the electricity η_{ELET}, for conciseness, each situation circumstance is not discussed herein.

The electrical transmission efficiency η_{ELE} can be calculated using Equation (13).

$$\eta_{ELE} = f(\eta_B, \eta_{FC}, \eta_{SC,} \eta_g, \eta_{gT}) \tag{13}$$

Here, η_B is the efficiency of the battery; η_{FC} is the efficiency of the fuel cell; η_{SC} is the efficiency of the supercapacitor; η_g is the efficiency of the generator sets; and η_{gT} is the transmission efficiency of the generator sets.

2.2.2. Objective function of energy management

The energy management model, with the goal of lowest cost of energy consumption for a single voyage, is established based on Equation (14), as follows:

$$MinC = \sum_{a=1}^{n}\sum_{b=1}^{m}\sum_{k=1}^{l}(P_{ME,a} \cdot FC_a(P_{ME,a}) + P_{ELE,b} \cdot EC_b(P_{ELE,b})) \cdot T_k \tag{14}$$

In the above, $FC_a(P_{ME,a})$ is the specific fuel consumption of the a^{th} main engine under the corresponding power; $EC_b(P_{ELE,b})$ is the energy consumption of the b^{th} electrical device under the corresponding power; and T_k is the sailing time for each leg.

In addition, to ensure the safe and stable operation of the generators, the power output needs to be restricted, as shown in Equations (15) and (16) as follows:

$$P_{MEMin,a} \le P_{ME,a} \le P_{MEMax,a} \tag{15}$$

$$P_{ELEMin,b} \le P_{ELE,b} \le P_{ELEMax,b} \tag{16}$$

Considering the power balance and the transmission efficiency, the power output should also satisfy Equation (17).

$$\eta_{MET} P_{ME,a} + \eta_{ELET} P_{ELE,b} \geq P_T + P_S \tag{17}$$

Here, P_T is the demand power for propulsion; P_s is the demand power for auxiliary use.

2.2.3. Power allocation

Conventionally, the result from the energy management generally does not allocate a specific power to a specific source, as most studies tend to assume that the mechanical performances of the same power source are consistent. In fact, the mechanical performance of each power source will change slowly and inconsistently. Therefore, it is necessary to determine the power allocation order by evaluating the mechanical performance of each power source. The process of power allocation is shown in Fig. 3.

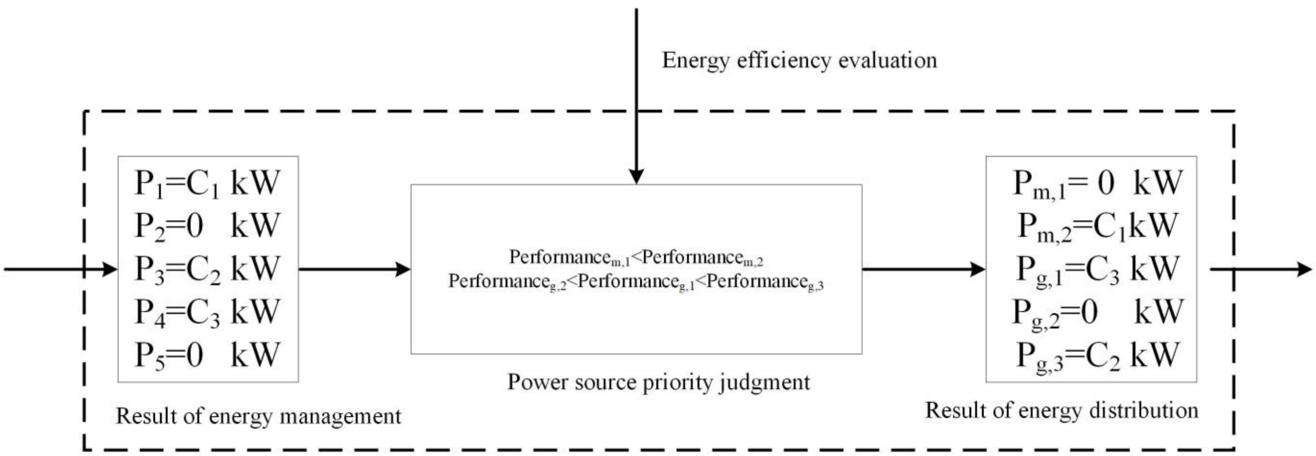

Fig. 3. Process of power allocation

2.4. Genetic algorithm

In this study, a genetic algorithm is used to solve the two-phase optimisation problem. It is a method for searching for an optimal solution by simulating a natural evolution process. The advantages of this algorithm are that its principle and operation are relatively simple, the robustness is strong, and it is not easily constrained by constraints. It also has a certain implicit parallelism, and strong global optimisation ability. Therefore, it has been widely used in solving complex optimisation problems (Revuelta E C et al., 2019). The process of the genetic algorithm is shown in Fig. 4.

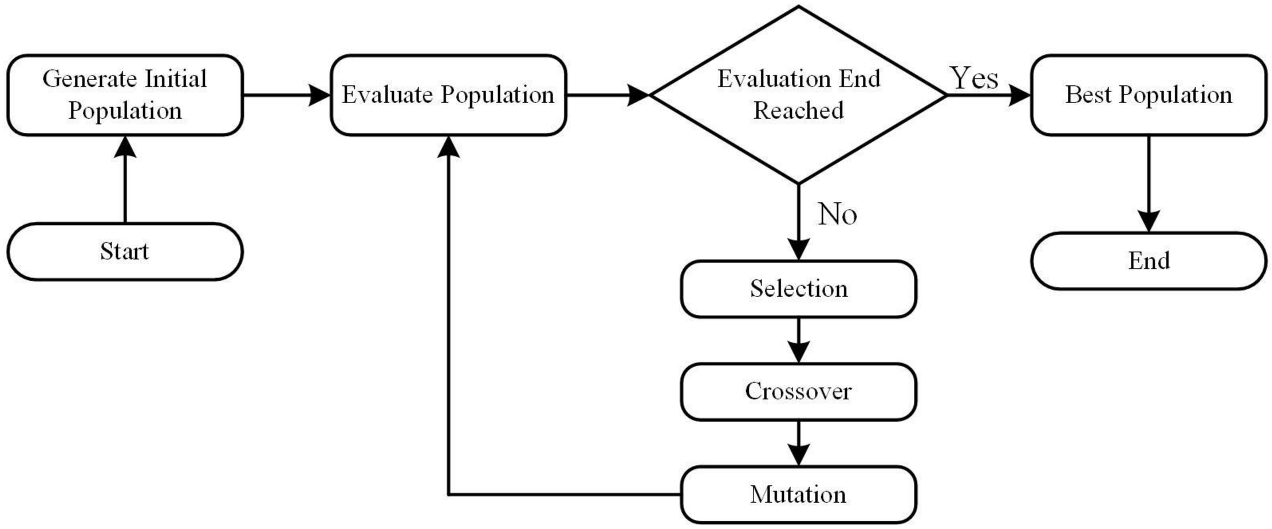

Fig. 4. Structure and process of the genetic algorithm

There are three genetic operators, *i.e.* selection, crossover, and mutation. All these operators have been described below.

2.4.1 Selection

The selection operator determines which individuals will be selected from the population to reproduce new individuals in the next population. The main principle is that the better an individual is, the higher its chance of being a parent. The elitism concept is used to select the best individual to the next generation directly without performing the operations such as crossover and mutation. In this study, 8% of the population is selected as the elite chromosomes and then is passed to the next generation.

2.4.2 Crossover

The crossover operation is performed on the remaining population to obtain the offsprings for the next generation. The single-point crossover operation is used to produce the new individuals on the two-parent chromosomes from the remaining population.

2.4.3 Mutation

Mutation operation is performed on the new offspring chromosome to mutate the one or more genes in the original chromosome to obtain the new chromosome. Thus, the mutation operation on the chromosome preserve the diversity within the population and the premature convergence. In this study, the mutation operation is performed on the chromosome by selecting two genes randomly and exchanging their values.

The genetic algorithm solver of the MATLAB simulator is employed to minimise the objective functions, which also are the fitness function. The settings for the program are as follows:

Table 1

Parameter selection

Parameters	Value taken
Population size	900
Generation number	300
Dimension of problem space	7 for speed optimisation and 3 for energy management
Crossover probability	0.8
Mutation probability	0.001

3. CASE STUDY

In this study, an inland parallel hybrid-powered bulk carrier was selected for implementing the proposed two-phase energy efficiency optimisation method.

3.1. Target bulk carrier

The main parameters of the target ship are shown in Table 2. The power system form of the target ship and its component information is shown in Fig. 5.

Table 2

Main Parameters of the Target Ship

Parameter	Value
Ship length	130 m

Moulded breadth	16.2 m
Depth	7.2 m
Design draft	5.2 m
Maximum draft	6.2 m
Deadweight tonnage (DWT)	9, 600 t (Maximum draft)
Block coefficient	0.8
Propeller diameter	2.8 m

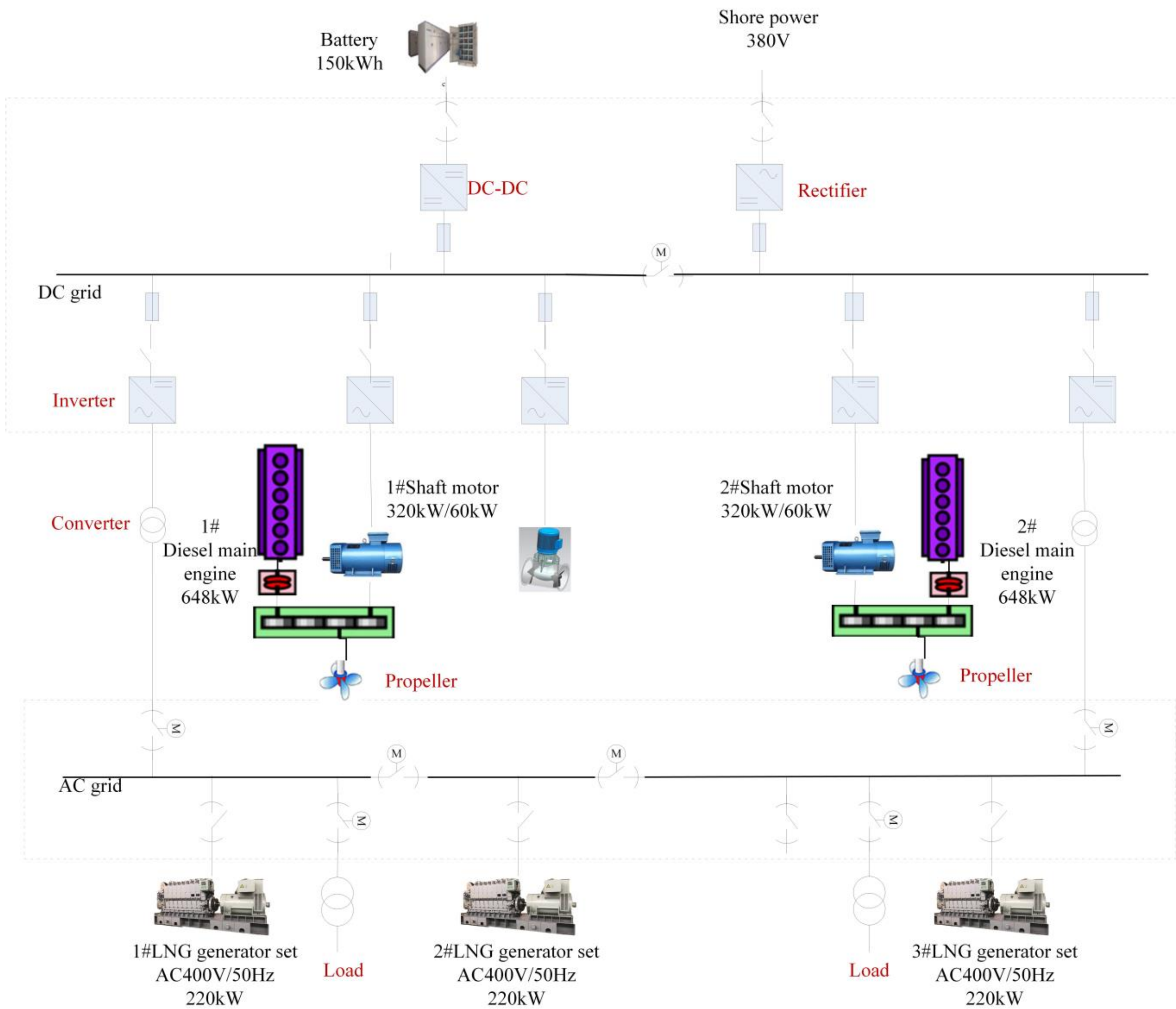

Fig. 5. Power system form of the target ship

Generally, the installed power of an inland ship main engine is much too large for meeting the power demand when sailing against the water upstream where the water velocity is high. As a result, the main engine usually works at 20–30% of the rated load most of the time. The energy efficiency of the traditional power system of inland ships is very low. Owning to the technical advantages in manoeuvring, reliability, power redundancy, and zero emission potential, the hybrid power system is more suitable for applications where the navigational environment is complicated, and the load changes in the different operating conditions are large. By adopting the parallel hybrid electric propulsion system comprising two diesel main engines, three LNG generator sets, one set of batteries, and two shaft motors, the installed power of main engine can be reduced in comparison to the traditional mechanical propulsion (Geertsma R.D et al., 2017). It can not only improve the redundancy and reliability of the power system, but also improve the economy benefit of the Yangtze River ship under low load conditions. Related research indicates that the fuel cost of the hybrid power solution is nearly 33 million CNY less than that of the diesel power solution, although the hybrid power solution requires increased initial investment and maintenance costs by 420,000 CNY (Fan A et al., 2021).

In this study, the main engine and shaft motor were connected through a gearbox, and the LNG generator set was electrically connected to the power system. The shaft motor had three different working modes, i.e. power take in (PTI), power take on (PTO), and power take home (PTH), respectively. The batteries were used during emergencies and parking.

The voyage line extended approximately 2,357.3 km from Shanghai to Chongqing, as shown in Fig. 6.

Fig. 6. Voyage line of the target ship

Based on the sailing direction, the round-trip voyage could be divided into westbound and eastbound voyages. The westbound voyage was divided into seven legs denoted W1 to W7, respectively. It took approximately 361 hours. The eastbound voyage was also divided into seven legs, denoted E1 to E7, respectively. It required approximately 220 hours.

The environmental factors can potentially affect a ship's navigational performance. The water flow can have different impacts on ship's sailing (*i.e.* promoting or hindering a voyage), and the water depth has an impact on the sailing resistance. Those factors would lead to changes in ship demand power. The representative distributions of the water depth and flow speed is shown in Fig. 7 and Fig. 8.

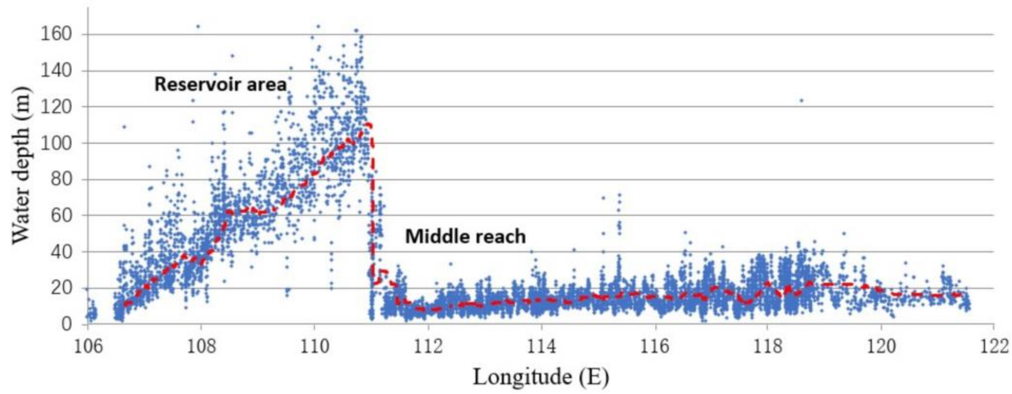

Fig. 7. Water depth distribution of the Yangtze River

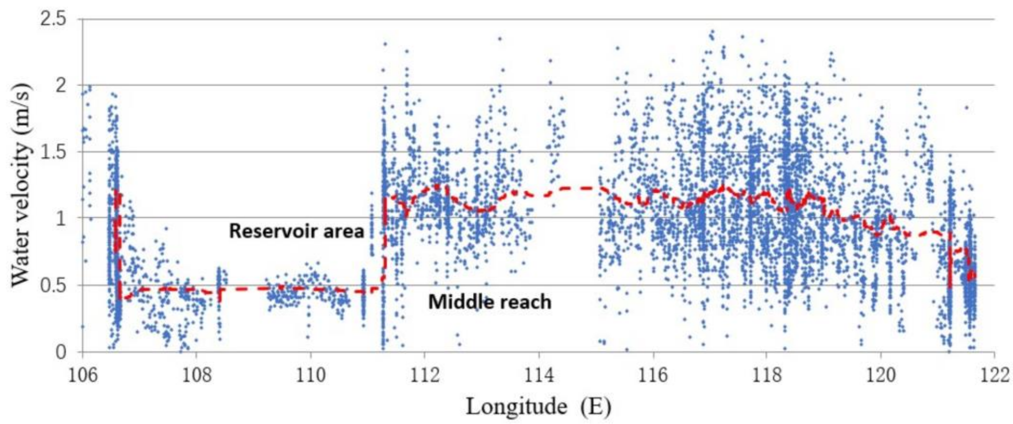

Fig. 8. Water flow speed distribution of the Yangtze River

As reflected in Fig. 7 and Fig. 8, the eastbound and westbound voyage had significant differences in water flow speed. In the westbound voyage, the power system needed to provide high power when sailing against the rapidly flowing region. Therefore, only the main engine propulsion mode was adopted in parts of the westbound voyage, and specifically in the leg(s) where the water flow speed was high. Under normal conditions, the LNG generator sets provided the main power supply.

According to the statistics, on the whole eastbound voyage, the PTH mode (LNG generator sets only) was used, while on the westbound voyage, among the whole sailing time (413.2 h), the PTH mode runs for 361 h, and the PTI mode (diesel main engines and LNG generator sets in parallel) runs for 52.2 h. The percentages are 87.4 % and 12.6 % respectively. The batteries are only used during emergencies and parking. Thus, the main working mode of the parallel hybrid electric propulsion system, PTH mode, is investigated in this study.

3.2. Two-phase energy efficiency optimisation of the target ship

The process of the two-phase energy efficiency optimisation method is shown in Fig. 9.

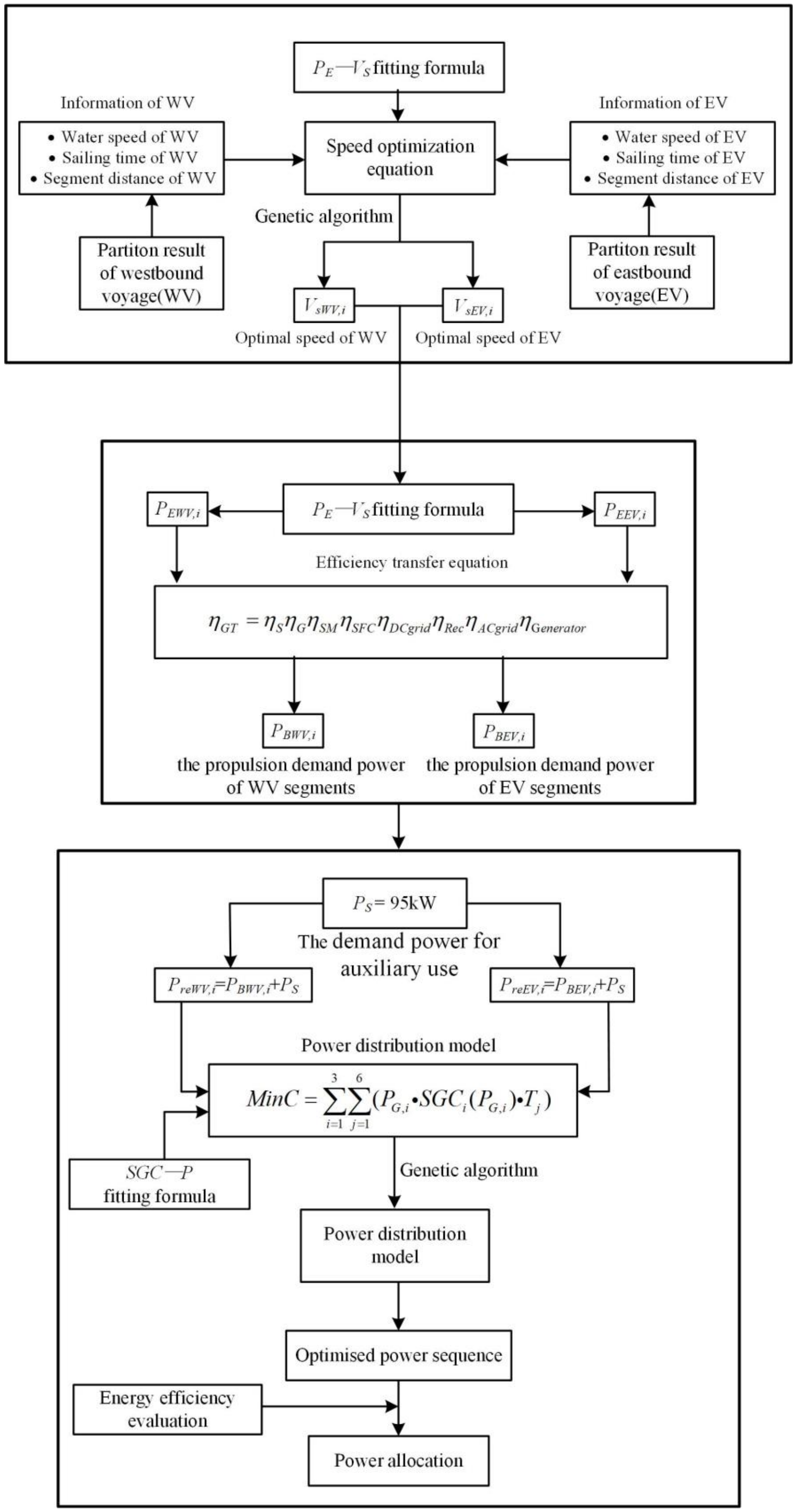

Fig. 9. Two-phase optimisation process of the target ship

3.2.1. Speed optimisation of the target ship

The optimised speed for each leg is calculated for westbound and eastbound voyage. Table A.1 lists the designed navigational parameters of the target ship, in which the distance of each leg d_i, water flow speed V_W, scheduled sailing time T, designed speed V_{sD}, fuel consumption FC, and gas consumption GC of each leg are provided.

Owing to the target ship still being under construction, the power demand prediction model is established using a regression analysis method based on the propulsion data of the propeller, as shown in Table A.2. According to Equation (7), a cubic polynomial is used to obtain the mathematical relationship between P_E and V_S, as shown in Equation (18), where R^2 is 0.9994.

$$P_E(V_S) = 28.58V_S^3 + 109.8V_S^2 + 217.1V_S + 181.3 \quad (18)$$

3.2.2. Energy management of the target ship

With regard to the parallel hybrid electric power system of the target ship as shown in Fig. 5, its energy transmission efficiency can be calculated according to Equations (12) and (13). The value of each component's efficiency is shown in Fig. 10.

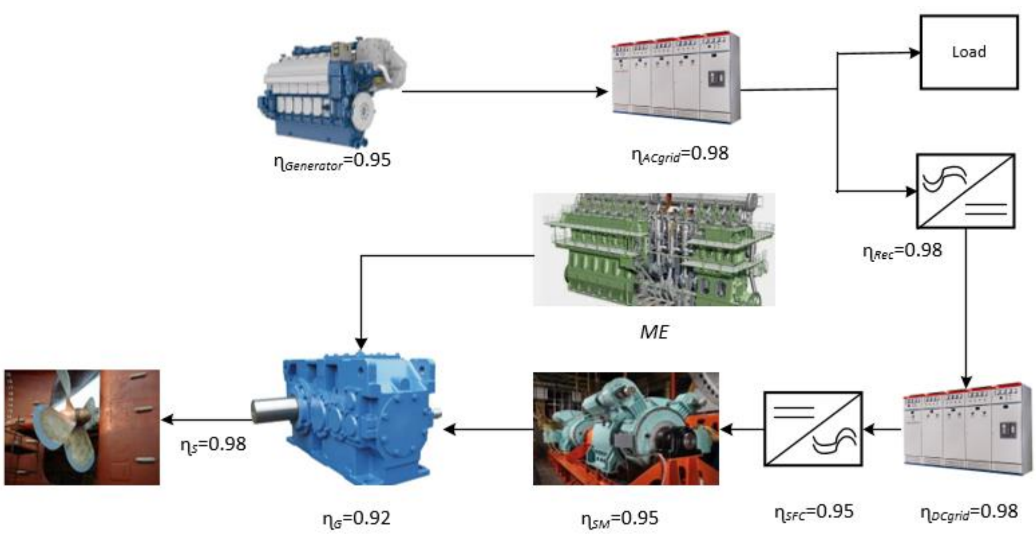

Fig. 10. Transmission efficiency of power system components

Based on Equation (12), the demand power for the propulsion P_T can be calculated; the demand power for auxiliary use (P_s) is 95 kW.

According to Equation (14), the energy management model for the target ship can be established, as shown in Equation (19) as follows:

$$MinC = \sum_{i=1}^{3}\sum_{j=1}^{6}(P_{G,i} \cdot SGC_i(P_{G,i}) \cdot T_j) \tag{19}$$

Here, $P_{G,i}$ is the output power of the i^{th} generator, i=1,2,3; SGC_i is the specific gas consumption of the i^{th} generator under the corresponding power; and T_j is the sailing time for each leg, j=1,2,3,4,5,6.

The generator set type of the target ship is CQFJ220J-WY LNG. The specific gas consumption of the engine is shown in Table A.3. A quartic polynomial is used to obtain the mathematical relationship between SGC and $P_{G,i}$, as shown in Equation (20), where R^2 is 0.9938.

$$SGC(P_{G,i}) = 0.000000195P_{G,i}{}^4 - 0.0001469P_{G,i}{}^3 + 0.03985P_{G,i}{}^2 - 4.579P_{G,i} + 381.7 \tag{20}$$

It is assumed that the energy efficiency performance of each generator is initially the same, and that the power is distributed in the order of 1st generator, 2nd generator, 3rd generator.

4. RESULTS AND DISCUSSION

The genetic algorithm is used to calculate the results for the speed optimisation and power management. The optimal gas consumption (G_{CO}) of each leg is calculated. The other optimal results are compared with the corresponding values in Table A.1. A comparative analysis is then conducted.

4.1 Optimisation for westbound voyage

A comparison of the power and speed for westbound voyage is shown in Fig. 11.

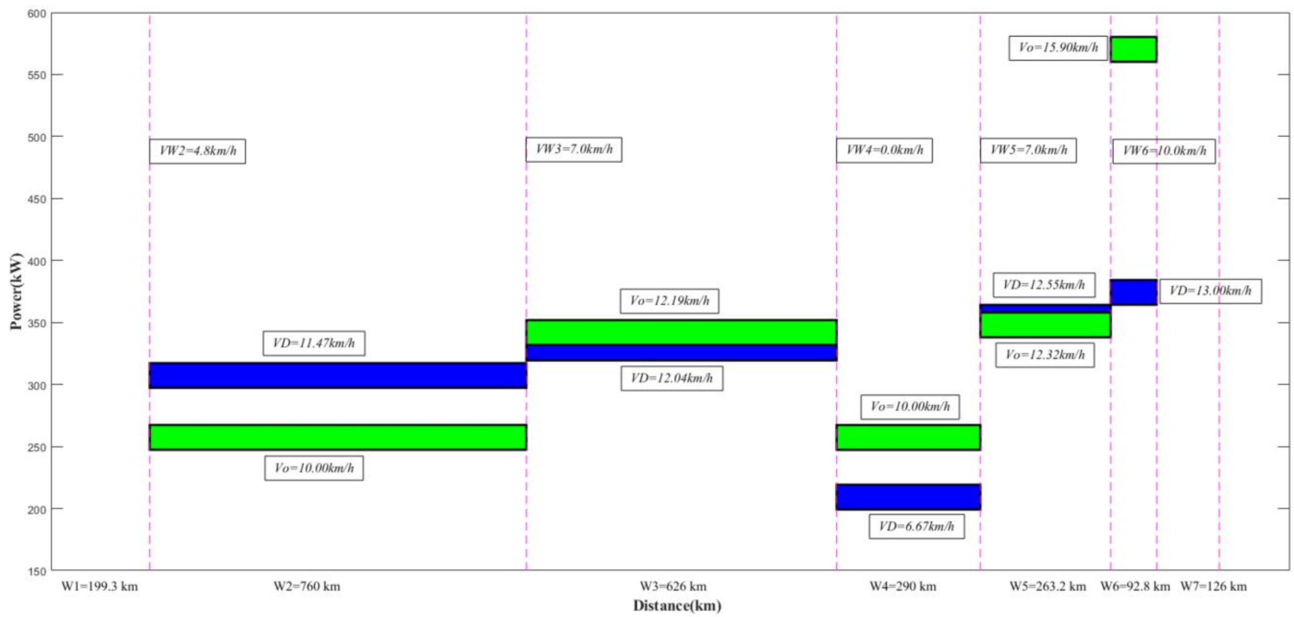

Fig. 11. Power and speed comparison of westbound voyage legs

The results regarding the power allocation for westbound voyage are shown in Table 3.

Table 3

Results of Power Allocation for Westbound Voyage

Leg / Items	W2	W3	W4	W5	W6	Total
P_{GD} (kW)	297.3	319.4	199.2	344.2	364.3	
N_D	2	2	1	2	2	
GC (t)	6.61	7.8	1.7	3.2	2.2	21.51
P_{re} (kW)	247.4	331.9	247.3	338.0	560.2	
N_O	2	3	2	3	3	
P_1(kW)	123.7	110.7	123.7	112.7	198.0	
P_2(kW)	123.7	110.6	123.6	112.7	197.9	
P_3(kW)	0	110.6	0	112.6	164.3	
GC_O (t)	6.96	7.73	1.38	3.15	1.73	20.95
Reduction rate: $(GC\text{-}GC_O)/\ GC$				2.60%		

In the above, P_{GD} is the designed total power of the generator sets; N_D is the designed amount of LNG generator sets in work; P_{re} is the optimised total power of the generator sets; N_O is the optimised number of LNG generator sets in work; P_i is power of the i th generator set (i = 1,2,3); and GC_O is the optimised gas consumption.

According to the results of westbound voyage, the optimised total sailing time T_O is 360.8 h, i.e. not much different from the scheduled time T of 361 h. However, the cumulative power consumption is reduced from 53,687.25 kWh to 52,765.20 kWh, a reduction rate of 1.72%. In addition, there are differences in the amount of generator sets in work before and after optimisation. The cumulative gas consumption is reduced from 21.51 t to 20.95 t, a reduction rate of 2.60%.

4.2 Optimisation for eastbound voyage

The comparison of power and speed for eastbound voyage is shown in the Fig. 12.

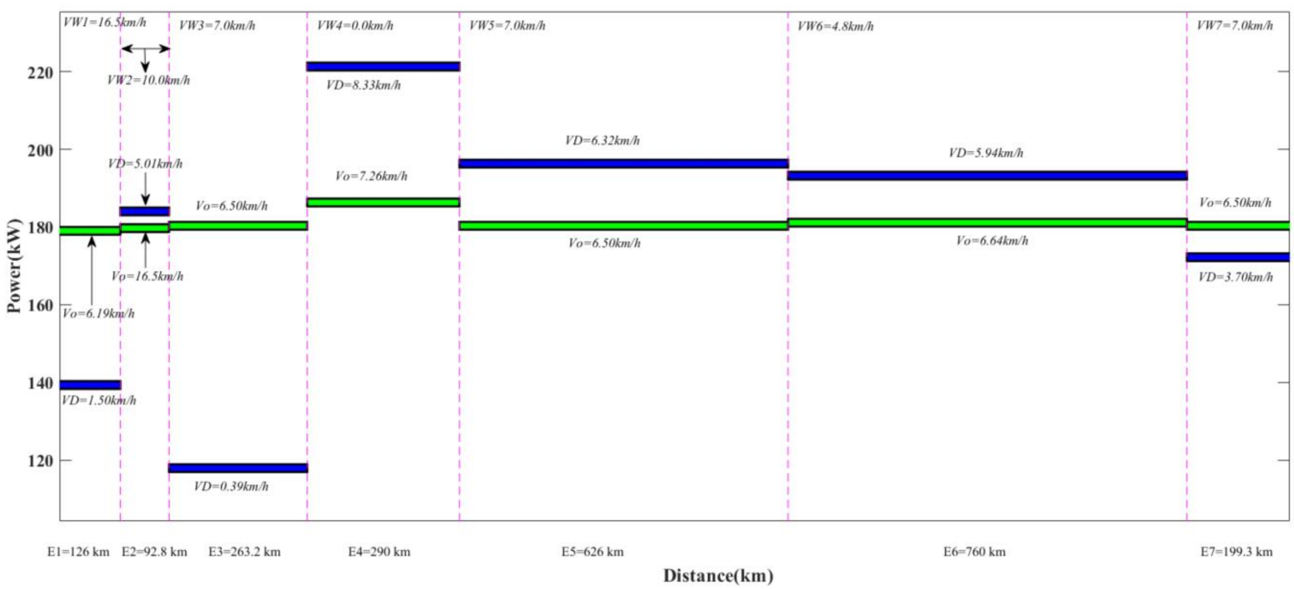

Fig. 12. Power and speed comparison of eastbound voyage legs

The results regarding the power allocation for the eastbound voyage are shown in Table 4.

Table 4

Results of Power Allocation for Eastbound Voyage

Items \ Leg	E1	E2	E3	E4	E5	E6	E7	Total
P_{GD} (kW)	138.3	183.0	116.9	220.3	195.3	192.2	171.2	
N_D	1	1	1	2	1	1	1	
GC (t)	0.19	0.22	0.8	1.5	1.8	2.68	0.62	7.81
P_{re} (kW)	178.0	178.7	179.3	185.3	179.3	180.1	179.3	
N_O	1	1	1	1	1	1	1	
P_1(kW)	178.0	178.7	179.3	185.3	179.3	180.1	179.3	
P_2(kW)	0	0	0	0	0	0	0	
P_3(kW)	0	0	0	0	0	0	0	
GC_O (t)	0.19	0.20	0.69	1.46	1.63	2.35	0.52	7.04
Reduction rate: $(GC\text{-}GC_O)/\ GC$						9.86%		

For the eastbound voyage, the optimised sailing time T_O is 198.23 h and the scheduled time T is 220 h, showing a significant reduction. The cumulative power consumption is reduced from 12,656.72 kWh to 11,303.84 kWh, a reduction rate of 10.69%. Before optimisation, two generator sets are used in leg E4, and one set is used in other legs. After optimisation, only one set is used for the entire voyage. As all of the optimised power values are less than the maximum allowed power of a single set, the 1st generator takes down all of the output power. The cumulative gas consumption is reduced from 7.81 t to 7.04 t, a reduction rate of 9.86%.

In conclusion, the cumulative gas consumption reduction is 4.54% on the round-trip voyage. If the LNG price is calculated based on 701.8 dollars/t, the fuel cost can be reduced by 933.4 dollars. For each year, 11200.7 dollars can be saved for a single ship (assuming 12 round-trip voyages).

According to the above results for the two-phase energy efficiency optimisation, the following observations can be made.

1) The gas consumption in the westbound voyage is larger than that in the eastbound voyage. On the westbound voyage, the ship needs more power to overcome the resistance of the water flow; in contrast, on the eastbound voyage, the ship sails along with the water flow; therefore, the power demand and gas consumption are significantly reduced.

2) The gas consumption reduction rate for the westbound voyage is much smaller than that for the eastbound voyage. The main reason is the difference between the optimised sailing time and scheduled sailing time.

3) There are differences in the amount of sets working in the corresponding legs. The amount of sets to be used is determined according to the energy management model. Owing to the different speeds before and after the optimisation, the power demands of the LNG generator sets are different. Therefore, for different legs, the numbers of sets in work are different.

5. CONCLUSION

Compared with diesel and other single-energy power systems, a parallel hybrid electric power system has multiple operating modes (such as PTI, PTO, and PTH), and a wider range of output power. It has advantages such as high efficiency, good manoeuvrability, and power redundancy. The hybrid form is more suitable for applications where the sailing conditions are random and complex, and/or where the load of the ship changes significantly. To solve the energy efficiency optimisation problem for parallel hybrid electric powered ships, a two-phase energy efficiency optimisation method is proposed, based on speed optimisation and energy management. The speed optimisation can reduce the required power of the propeller from the demand side, and the energy management can reduce the cumulative power consumption of the power system from the supply side. For the speed optimisation, the minimum cumulative power consumption of the propeller is taken as the objective function, whereas for the energy management, the minimum energy consumption of the parallel hybrid electric power system is taken as the objective function. A genetic algorithm is used to solve the two optimisation problems. The case study shows that the proposed two-phase energy efficiency optimisation can reduce the emissions and costs of the ship. As the target ship is still under construction, the proposed research method requires the collection of actual operating data for verification after the ship is launched. Further studies should be conducted, such as considering full working modes of the parallel hybrid electric power system, providing a dynamic prediction of the demand power, and a dynamic distribution optimisation of the output power.

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APPENDICES

Table A.1 Designed Condition File of Target Ship

Route	Leg	d_i (km)	V_W (km/h)	V_{GD} (km/h)	V_{sD} (km/h)	Mode	P_{ME} (kW)	SFC_{ME} (g/kWh)	P_{GD} (kW)	N_C	SGC_G (g/kWh)	T (h)	GC (t)	FC (t)
	Departure	0	0.0	0.00	0	Power take home (PTH)			144.8	3	194	1.0	0.08	
	E1	126	16.5	18.00	1.5	PTH			138.3	1	193	7.0	0.19	
	E2	92.6	10.0	15.01	5	PTH			183.0	1	197	6.2	0.22	
	E3	263.2	7.0	7.39	0.36	PTH			116.9	1	193	35.6	0.80	
EV	E4	290	0.0	8.33	8.33	PTH			110.2	2	195	34.8	1.50	
	Crossing the dam	0	0.0	0.00	0	Shutdown			32.3	1	255	72.0	0.59	
	E5	626	7.0	13.32	6.29	PTH			195.3	1	196	47.0	1.80	
	E6	760.2	4.8	10.74	5.94	PTH			192.2	1	197	70.8	2.68	
	E7	199.3	7.0	10.72	3.7	PTH			171.2	1	196	18.6	0.62	
	Inbound	0	0.0	0.00	0	PTH			144.8	3	194	1.0	0.08	
	Departure	0	0.0	0.00	0	PTH			144.8	3	194	1.0	0.08	
	W1	199.3	7.0	11.01	18.04	PTI	840	195.7	110.6	2	195	18.1	0.78	2.98
	W2	760	4.8	6.67	11.47	PTH			148.7	2	195	114.0	6.61	
	W3	626	7.0	5.00	12.04	PTH			159.7	2	195	125.2	7.80	
	Crossing the dam	0	0.0	0.00	0.00	Shutdown			32.3	1	255	72.0	0.59	
WV	W4	290	0.0	6.67	6.67	PTH			199.2	1	196	43.5	1.70	
	W5	263.2	7.0	5.55	12.60	PTH			172.1	2	196	47.4	3.20	
	W6	92.6	10.0	3.00	13.00	PTH			182.1	2	197	30.9	2.22	
	W7	126	16.5	3.70	20.20	Power take in (PTI)	1094	200	184.8	2	197	34.1	2.48	7.45
	Inbound	0	0.0	0.00	0.00	PTH			144.8	3	194	1.0	0.08	

In the above, EV is the eastbound voyage; WV is the westbound voyage; V_{GD} is the speed over ground; *VsD* is the designed ship speed; P_{ME} is the power of the main engine; SFC_{ME} is the specific fuel consumption of the main engine; P_{GD} is the designed power of the LNG generator set; N_D is the starting number of LNG generator sets; SGC_G is the specific gas consumption of the LNG generator set; T is the sailing time; GC is the designed gas consumption; FC is the designed fuel consumption.

Table A.2 Propulsion Data of Propeller

Ship speed （km/h）	Effective power of hull （kW）	Ship speed （km/h）	Effective power of hull （kW）
3	6.8	12	206.8
4	13.2	13	255.2
5	22.8	14	317.9
6	36.1	15	377.3
7	53.6	16	456.5
8	75.8	17	542.3
9	102.6	18	652.3
10	132.2	19	777.7
11	167.2	20	932.8

Table A.3 Specific Gas Consumption of The Generator Set

Power (kW)	Specific gas consumption (g/kWh)	Power (kW)	Specific gas consumption (g/kWh)
40	255	140	193
50	234	150	195
60	219	160	195
70	210	170	196
80	204	180	197
90	200	190	197
100	196	200	196
110	195	210	196
120	191	220	195
130	190		