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Understanding of the ship design energy efficiency and its implications in practice

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Understanding of the Ship Design Energy Efficiency and its Implications in Practice

By

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DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

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ABSTRACT

Title of Dissertation: **Understanding of the Ship Design Energy Efficiency and its Implication in Practice**

Degree: **MSc**

The EEDI value of new ships will select the ideal environment and given ship single point testing condition in order to calculate the ship's attained EEDI value and represent its design energy efficiency, however, during the actual operation process, the ship will be under the single or combined influenced of complex factors such as ship payload, ship sailing speed, sea and weather conditions, ship fouling etc., which will driving its changeable operation conditions deviated from the EEDI calculation single point condition, resulting the lack of the whole representative of the ship's design energy efficiency with only considering the EEDI value, and cannot full evaluate ship's design energy efficiency performance. In addition to that, assume the actual operation conditions are always deviated from the EEDI calculation condition, the calculation method of single point EEDI value will possibly push the ship designer as well as the ship owner solely pursue the decrease of EEDI value in order to satisfy the EEDI requirement by introducing and installing the ship energy saving design technologies, which may not perform its well-pleasing energy efficiency and mislead the design and construction of new ships. The situation will have a bad influence on the performance of ship itself design energy efficiency and does not adapt to the actual operation demand.

Based on the problem mentioned above, this dissertation will carry out studies from two aspects of theoretical analysis and practical case study. For the theoretical analysis aspects, the dissertation will provide an understanding and intensive analysis on the ship design energy efficiency concept and its nature, and give an introduction of the development of EEDI and the method of its calculation formula, present a comprehensive analysis on the EEDI calculation process, meanwhile, the dissertation also generates a discussion on the correlation as well as points of difference analysis of the ship design energy efficiency and operational energy efficiency on the basis of the connotation analysis of ship operational energy efficiency, and the reasons that trigger the deviation of ship operation energy efficiency from design energy efficiency are also analyzed. Moving forward, to make the theoretical analysis in this dissertation solid and objective, the study picked up two cases calculation by investigate and select the actual design data during the process of ship design, the calculation results of the two cases verifies the analysis and provides data support for the necessity of evaluating the ship's design energy efficiency by considering the actual need during the operation process. Through this research, this dissertation proposes to give a thorough and abundant understanding of the ship design energy efficiency by selecting more actual operation conditions to test and evaluate the design energy efficiency with a view to paying more attention to actual need and oriented to the actual operation requirements of the ship. What's more, this thesis recommends to proceed appropriate improvement of the existing EEDI evaluation system if possible, in order to provide some more objective policy guidance, which can make a contribution to promote the ship energy efficiency performance during the operation process, and finally achieve the goal of reducing the ship carbon emissions from the dimensions of ship design and ship operation. The study of this dissertation may have the reference value of providing a profound understanding of ship design energy efficiency and enrich the implications during the practice process.

KEY WORDS: Ship design energy efficiency, EEDI, EEOI, Essence analysis, evaluation, implications in practice

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LIST OF ABBREVIATIONS

AER	Annual Energy Ratio
CO_2	carbon dioxide
dwt	deadweight tonnage
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operation Indicator
EESH	Energy Efficiency per Service Hour
GHG	greenhouse gas
GT	Gross Tonnage
IMO	International Maritime Organization
ISPI	Individual Ship Performance Indicator
LNG	Liquified Natural Gas
LPG	Liquefied Petroleum Gas
MARPOL	The International Convention for the Prevention of Pollution from Ships
MCR	Maximum Continuous Rating
MEPC	Maritime Environment Protection Committee
SEEMP	Ship Energy Efficiency Management Plan
SMCR	Selected Maximum Continuous Rating
UN	United Nations
UNFCCC	United Nations Framework Convention of Climate Change
VLCC	Very Large Crude oil Carrier

CHAPTER 1

INTRODUCTION

1.1 Background information

Since the 1980s, the pressing issue of climate change and global warming has been gradually recognized and paid more and more attention to by humankind all over the world (Nordhaus, 1994). In order to tackle the climate change, the United Nations (UN) has made unremitting efforts in this area and adopted the United Nations Framework Convention of Climate Change (UNFCCC) in 1992 (Schipper, 2006). The UNFCCC has come into force on March 21st in 1994 with 197 contracting parties currently, which is universally accepted as the first established international multilateral treaty regarding to control the emission of carbon dioxide (CO_2) and other greenhouse gas (GHG), and set up the basic framework for human beings of coping with economic and social influences brought by global warming issue (Burleson, 2006).

Though shouldering over 80% of the worldwide trade amount and viewed as the most economic and energy efficient cargo transportation mode of all types (Brooks & Faust, 2018), the international shipping still needs to further improve the energy efficiency and effective emission control in a global way based on the prediction for future development condition of economy and energy. According to the predictions of the third IMO GHG study report, the CO_2 emission amount generated by world seaborn trade would increase between 50% and 250% by the year of 2050 if no effective measures were taken to control the shipping GHG emission (Smith, 2015). In fact, the shipping industry is one of the most early one to commence the negotiation of climate change response, which is mainly because the GHG emission of international shipping has the industry particularity and high degree of internationality, resulting in the technical problem of statistics (where the ship emitted the CO_2 and to whom the emission amount share will belong). In 1997, the Article 2.2 of Kyoto Protocol of UNFCCC has made authorization on the shipping GHG emission reduction, in which the Protocol required IMO to make its own efforts and contributions in order to strive for imposing restrictions or cutting down the GHG emissions generated by the industry (Oberthür, 2003).

According to different nature and characteristic of ship's energy efficiency in the process of ship design and construction as well as the actual operation, IMO has carried out discussion and policy formulation separately on energy efficiency regulations for new ships and existing ships (shown in Figure.1).

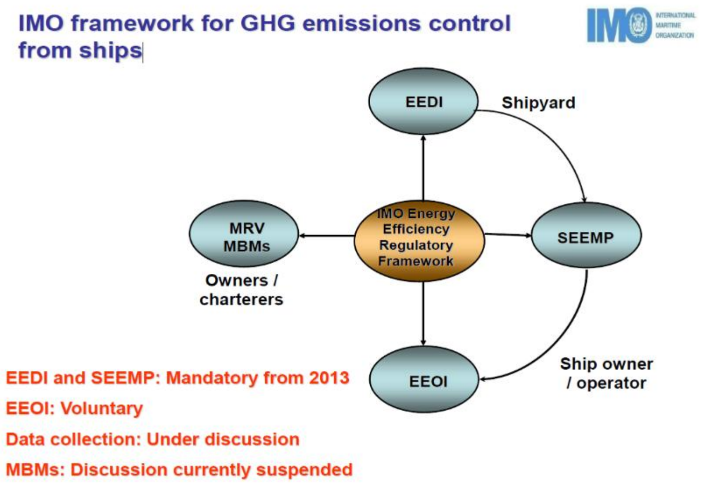

Figure 1 IMO framework for GHG emissions control from ships

（Source：IMO Course on Energy Efficient Ship Operation）

With regarding to the design and construction of new ships, IMO has adopted the very first mandatory ship energy efficiency regulations (IMO, 2011) that guiding all the member states and aiming at the entire industry in 2013, in which requirements for new ships are gradually promoting the ship energy efficiency design index up to 30% in totally three stages since the year of 2015. For the existing ships, compulsory regulations are set out for each ship to work out the Ship Energy Efficiency Management Plan (SEEMP) and realize the goal of enhancing ship energy efficiency operating performance by taking the measures from the management perspective and technical methods. The ship Energy Efficiency Operation Indicator (EEOI) (IMO, 2009) which developed in the aim of monitoring of the existing ships operational energy efficiency performance and is recommended for voluntarily using for shipping companies and ship operators.

However, a ship in operation will encounter various working conditions influenced by factors like ship draft, ship sailing speed, trim, sea conditions etc., which always deviate from her EEDI reference working conditions (referred to as "reference working condition" here after). Therefore, the EEOI values of a ship variate much and commonly different form her EEDI value. As the attained EEDI is calculated under a given working condition, such a single point value can hardly provide a whole picture of the ship's energy efficiency performance under other working conditions at the design stage. In case a ship will most of the time operate under conditions far away from the reference working condition, merely focusing on her performance under reference working condition may risk making an arbitrary design strategy at the design stage.

1.2 Objectives of research

The primary purpose of this research is to propose a thorough understanding of the design energy efficiency of a ship and its implications for the ship in operation. The subsequent objective will be embodied in the proposal of ship design energy efficiency evaluation method based on the actual operation need, which will be used to optimize the ship's design energy efficiency strategy during the ship design and construction process and eventually contribute to enhance the energy efficiency performance during the operation. The research task will be carried out through correlation analysis on ship design energy efficiency and operation energy efficiency by illustrating the nature of design energy efficiency, what the ship Energy Efficiency Design Index (EEDI) is and how it works in accordance with the IMO other measures of ship operation and marine GHG emissions reduction. In attempting to make the research concrete and convincible, statistics are obtained from ship design institution from the ship model testing experiment in a tank. The objective of the research is to improve the understanding of the ship's design energy efficiency under different working conditions of a ship, which will be helpful for analyzing the relationship and influence extent between a ship's design energy efficiency level and its actual operational energy efficiency performance, and also play a guiding role for ship's design, construction and operation in energy-efficiency.

1.3 Methodology

The relevant literature was widely reviewed beforehand, including appropriate IMO documents and circulars, international conventions, articles from contemporary journals, research reports from independent institutions, books and information from websites. Opinions were exchanged and advice was taken by visiting different shipping design and construction entities through consultation and discussion face to face. Furthermore, the secondary resources and statistical figures provided the necessary datasets to carry out a qualitative research, which is mainly used in addressing the main points of this dissertation. The publications relating to ship energy efficiency research are also referred to abstract the common methods and strategies for both design domain and operation domain emissions control requirements.

1.4 Structure of dissertation

This dissertation mainly consists of five chapters. The first chapter is the introduction of the whole dissertation, which provides an overall introduction of the background information, research objectives, methodology of the dissertation. Chapter two discloses the general understanding of design energy efficiency of the research by discussing the establishment of ship energy efficiency concept model and the existing evaluation method as well as indicator, concrete conclusions are made for the nature and connotation of ship design energy efficiency by analyzing the main influence factors, characteristic and some defects are also summarized based on the author's knowledge and understanding. Chapter three provides the correlation analysis of the design energy efficiency and the operational energy efficiency, scrutinizes the essence of operational energy efficiency and the evaluation indicators for the time being, summarizes the generality and analyzes deviation causes of the energy efficiency index. Chapter four mainly concentrate on the case study of the research, which provides two real ship design examples based on the real ship design statistics obtained from the investigation, and verifies the theoretical analysis from the perspective of the case study. Finally, the last chapter puts forward the overall summaries and conclusions. Generally speaking, this dissertation proposes the reference significance to enrich the understanding of ship design energy efficiency and the implications in practice.

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CHAPTER 2

Ship Design Energy Efficiency and EEDI

2.1 Definition of ship design energy efficiency

The ship design energy efficiency is the energy efficiency level which a ship can attain under the given working conditions and ideal internal and external environment. The ship design energy efficiency takes the ship's self-design level as the focal point, considering ship's environment cost (CO_2 emission) of per unit transportation created social economic benefit (transport work), focusing on different kinds of energy efficiency improving technical measures (engines, ship hull form, ship equipment and system energy efficiency etc.)

The ship energy efficiency design index (EEDI) was put forward by IMO in 2011 (IMO, 2011). As a criterion of designing and constructing for new ships, EEDI was transformed from CO_2 design index for new ships. The inherent meaning of EEDI is estimating the CO_2 emission amount of the fuel oil consumption of ship's propulsion power and auxiliary engine as it sails at a certain ship speed with the maximum loading capacity, specifically, the main engine output power is 75% of main engine's maximum continuous power and the speed of the ship is tested under no wind and no wave circumstance in a deep sea sailing condition.

Besides, IMO has developed several guidelines in order to assist in the implementing ship energy efficiency compulsory regulations, which specifically are:

(1) The guideline for calculation of commonly used reference line for energy efficiency design index (EEDI) in 2013 (Resolution MEPC.231 (65));

(2) The guideline of the calculation method for energy efficiency design index for new ships which amended in 2014 (Resolution MEPC.245 (66));

(3) The guideline for verification and certification of ship energy efficiency design index (EEDI) which amended in 2014 (Resolution MEPC.254 (67));

(4) The formulation guideline for ship energy efficiency management plan (SEEMP) in 2016 (Resolution MEPC.282 (70)).

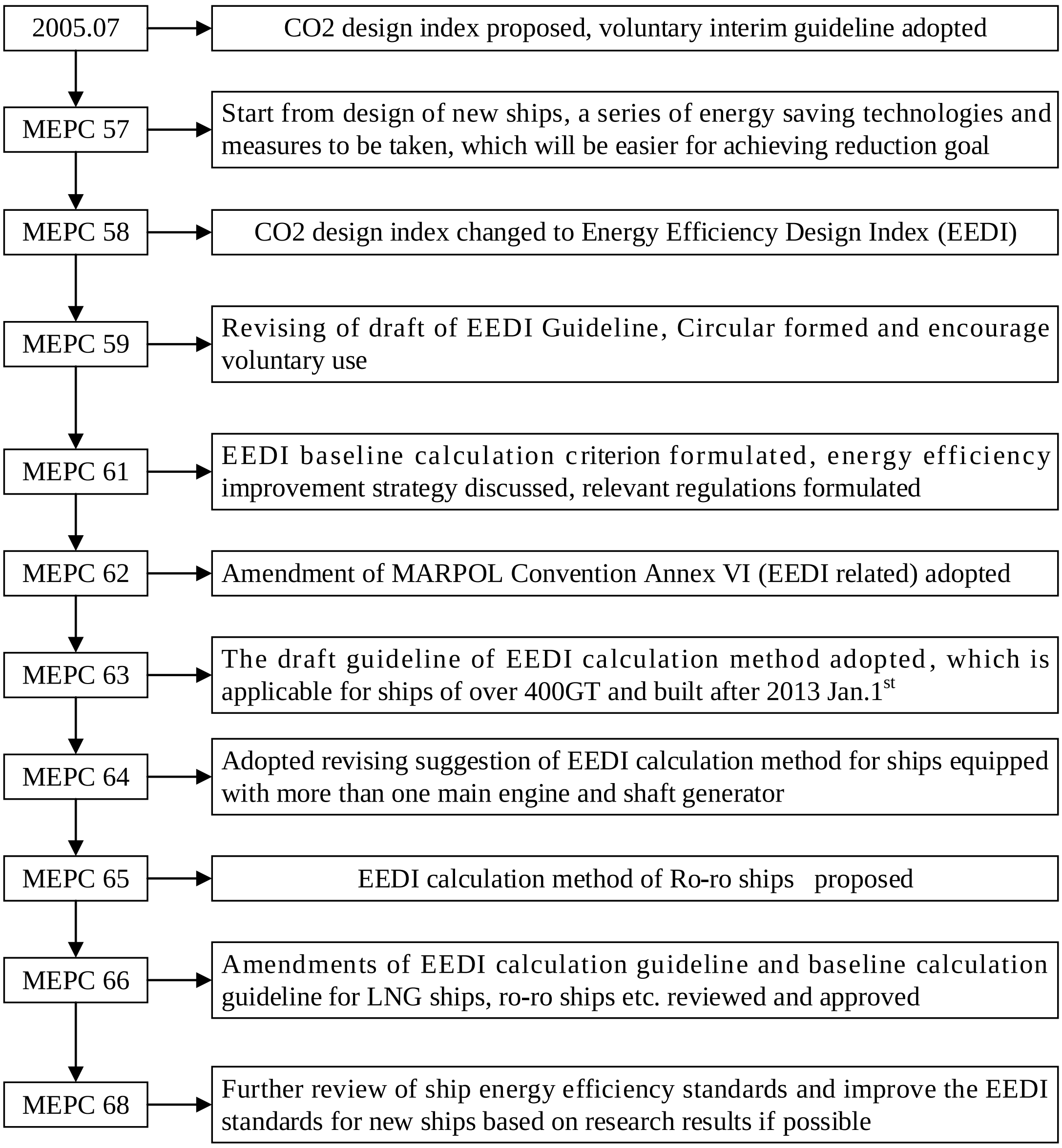

Figure 2 The development process of the EEDI regulation and the calculation formula summarized from the IMO instruments

At MEPC 69, the interim report of EEDI submitted by correspondence group were reviewed, of which the technical development condition of Phase 2 stage for implementing EEDI regulation were intensively reviewed. MEPC 70 proposed the need to give a comprehensive review for EEDI phase 3 and the possibility of discussing the introduction of EEDI phase 4, which put forward more stringent requirement for newly built ships energy efficiency. Generally speaking, IMO has always been devoting to contribute to tackle climate change from shipping prospective, especially in the design and construction process.

According to the Guidelines on the method of calculating attained EEDI for new ships (MEPC.245(66)), EEDI calculation formula is applicable to passenger ships, bulk carrier (includes: bulk carrier, ore carrier, coal carrier, etc.), tanker (crude oil carrier, product tanker, chemical tanker, bitumen carrier), gas carrier (LNG carrier, LPG carrier, etc.), container ships, general cargo ships, vehicle carrier, ro-ro ships, offshore supply vessels. The EEDI calculation methods of other ship type like tow ship, research ship, off-shore vessel is now still under research. Until now, the general structure of the type of ship to which the formula applies has been formed, as shown in figure 3.

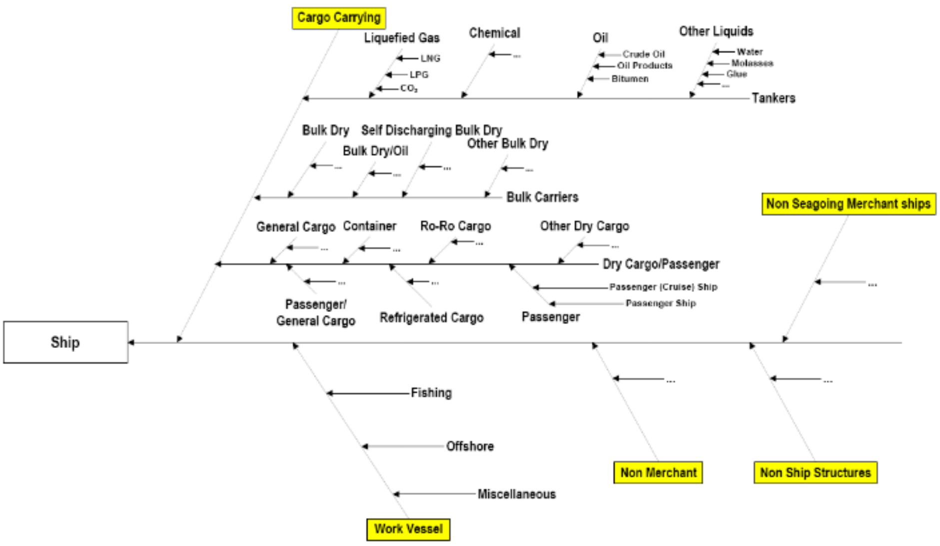

Figure 3 The applicable ship type and scope of EEDI regulation (IMO, 2011)

2.2 Calculation of EEDI

According to EEDI calculation guideline adopted by IMO (Resolution, 2013), EEDI is an indicator used for evaluating ship design energy efficiency, according to its basic principle, the final mathematical calculation formula was determined as:

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE} *\right) + \left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_i \cdot capacity \cdot V_{ref} \cdot f_w}$$

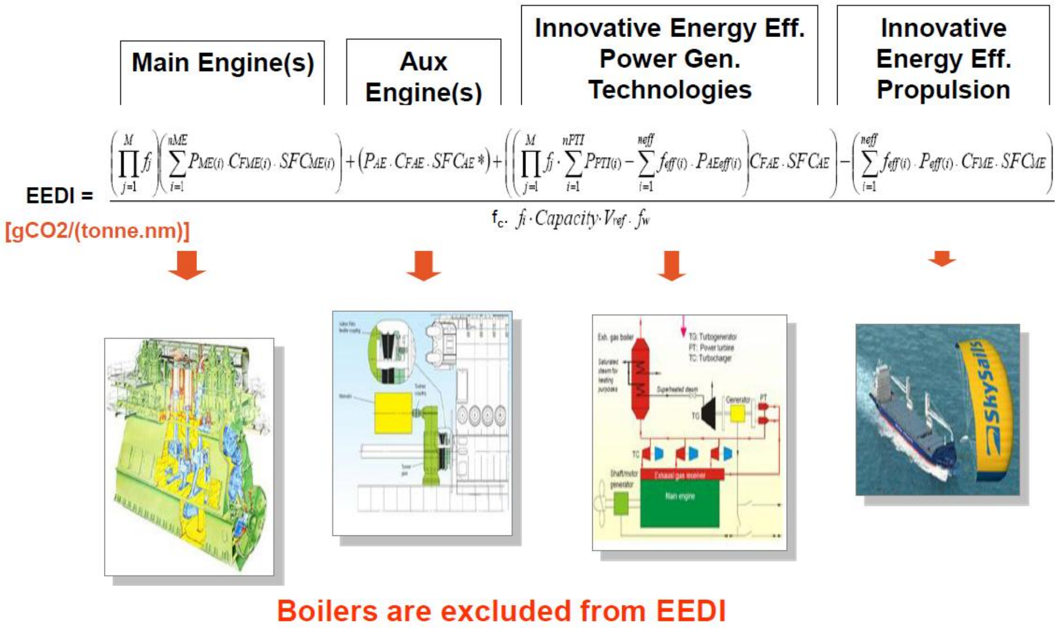

Figure 4 The EEDI calculation formula and its abridged general view

(Source: IMO Course on Energy Efficient Ship Operation)

The denominator of the EEDI calculation formula is the product of capacity and given ship speed. While the numerator of EEDI calculation formula is mainly divided into four parts:

(1) the first part of the numerator is the product of the main engine propulsion power needed for carrying such a capacity of cargo at such a sailing speed and the fuel consumed.

$$\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right)$$

(2) the second part of the numerator is the product of the auxiliary engine power and the fuel consumed; the auxiliary power is the power needed for ensuring the main engine working under the first part condition (include the necessary living power consumption).

(3) the third part of the numerator is the product of contributions of shaft power and fuel consumption of auxiliary engine on condition that the ship is installed with shaft motor and waste heat recovery system.

(4) the fourth part of the numerator represent the improvement of the ship energy efficiency which brings about by reducing the fuel oil consumption through utilizing the new energy saving technologies.

As can be seen from the formula, the sailing speed, the ship capacity and the installed power of main engine and auxiliary engine for achieving the speed all play decisive role in the EEDI for new ships, besides, the adoption of new energy saving technologies is also an effective measure for optimizing the EEDI index.

The meaning and selection method for parameters in the EEDI calculation formula is shown in the figure 5.

EEDI Formula – Parameters explained

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} * C_{FME} * SFC_{ME}\right) + \left(P_{AE} * C_{FAE} * SFC_{AE}\right) + \left(\left(\prod_{j=1}^{M} f_j * \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} * P_{AEeff(i)}\right) C_{FAE} * SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} * P_{eff(i)} * C_{FME} * SFC_{ME}\right)}{f_i * f_c * f_l * Capacity * f_w * V_{ref}}$$

Parameter	Description	Source
C_F	Non-dimensional conversion factor between fuel consumption and CO_2 emission	MEPC 245(66) "2014 Guidelines on the calculation of the Attained EEDI for new ships"
V_{ref}	Ship speed in nautical miles per hour	At design Stage- Speed-power curves obtained from model testing At final Stage- Sea Trial Report
Capacity	Computed as a function of Deadweight as indicated in 2.3 and 2.4 of MEPC 245(66) "2014 Guidelines on the calculation of the Attained EEDI for new ships"	Stability Booklet
P_{ME}	75% of the main engine MCR in kW	NOx Technical File
P_{AE}	Auxiliary Engine Power	MEPC 245(66) "2014 Guidelines on the calculation of the Attained EEDI for new ships"
P_{PTI}	75% of rated power consumption of shaft motor	
P_{eff}	Output of innovative mechanical energy efficient technology for propulsion at 75% main engine power	
P_{AEeff}	Auxiliary power reduction due to innovative electrical energy efficient technology	
SFC	Certified Specific Fuel Consumption in g/kWh	NOx Technical file
f_j	Correction factor to account for ship specific design elements. (For e.g. ice classed ships, shuttle tankers)	MEPC 245(66) "2014 Guidelines on the calculation of the Attained EEDI for new ships"
f_w	Non dimensional coefficient indicating the decrease of speed in representative sea condition of wave height, wave frequency and wind speed	
f_i	Capacity factor for any technical / regulatory limitation on capacity	
f_c	Cubic capacity correction factor (for chemical tankers and gas carriers)	
f_l	Factor for general cargo ships equipped with cranes and other cargo-related gear to compensate in a loss of deadweight of the ship	
f_{eff}	Availability factor of innovative energy efficiency technology	MEPC.1/Circ.815

Figure 5 The meaning and selection method for parameters in the EEDI calculation formula

(Source: IMO Course on Energy Efficient Ship Operation)

IMO introduces the reduction rate to gradually enhance the new built ship's design energy efficiency, i.e. the attained EEDI of every new ship should decrease by at least 10% as from 2015 compared with the base-line value. The EEDI reduction rate for the year of 2020 is at least 20% while for 2025 is at least 30%. By reducing the required EEDI value, the new ships need to take measures to improve its design energy efficiency in order to meet the IMO mandatory requirements, the new ships entering the market also have a high design energy efficiency level.

2.3 The characteristics and limitations of EEDI

The attained EEDI value of a ship is used to estimate whether the ship meet the required design energy efficiency standard by comparing the attained value with the EEDI reference value in a given ship type and ship size. However, what needs to be noted is that as a single point energy efficiency value, the ship's attained EEDI value cannot fully represent the ship's energy efficiency performance under all possible working conditions. Therefore, when implement the lowest design energy efficiency standard in practice for a given size ship, the attained EEDI cannot convey a holistic energy efficiency performance under various working conditions, which means that the ship attained EEDI value obtained under the EEDI reference working condition does not necessarily be the operating condition for a ship in service, so when a ship's attained EEDI satisfied the minimum EEDI standard, it does not necessarily mean that the energy efficiency under other operating conditions will be high consequently, and vice versa. Therefore, it is necessary to develop the design strategy based on a thorough understanding of EEDI during the process of ship design, with a view to delivering a ship better prepared for the real operation situations.

The EEDI regulation assumes that the CO_2 emission of design ship will cut down correspondingly with the reduction value of ship's attained EEDI. However, the opportunity for a ship operating under an EEDI reference working condition is really seldom. It is more often for the ship to sail in not fully loaded or a ballast voyage, however, the EEDI calculation process view the sailing speed for the whole voyage is constant, which is also not practical during operation, frankly speaking, most of the ships will choose to change the sailing speed according to the external environment change in order to achieve a better fuel oil efficiency.

The EEDI calculation formula introduces the ship's coefficient of decreasing of speed f_w factor, which aims to reflect the difference of speed of ships sailing with and without wind and waves in order to show ship's condition in the whole operation process to obtain a more rational energy efficiency value. However, as the ship operational situation changes a lot, the internal and external environment also differ in thousands of ways, it is hard to reflect the actual ship energy consumption performance, which explains why IMO still fail to figure out the determination method for f_w after the EEDI formula has been mandatory implemented.

In the amended EEDI calculation formula, the energy saving equipment are considered for EEDI calculation, which is viewed as a fair and reasonable practice. However, how to integrate the influences of different kinds of energy saving equipment in the new formula remains to be an urgent and pending problem for IMO, as there are many types of energy saving equipment with different sizes, the influence of the same kind of equipment on different ship types may not be the same, while the influence of the same kind of equipment on the same ship types with different main dimensions may not be the same either. More detailed and concrete analysis should be given on the specific ship case by case rather than simply providing a factor for estimating its general influences, which may generate tremendous difference on the results. Relevant research results show that the boss cap fins can improve the energy efficiency by 9% for a certain kind of ship, while for the other, it can only save by 3%. Therefore, the contribution of energy saving equipment for EEDI still needs to be studied furtherly. Other defects like the applicability of ship type and the relationship between other mandatory measures and EEDI are also mentioned and discussed. The EEDI formula is applicable for ship types like bulk carrier, oil tanker and containers etc. however, the design energy efficiency cannot be evaluated by sailing speed and capacity for ships like offshore supply vessels and platforms, which may bring about equity issues. What's more, some of the compulsory measures like new emission requirement of NOx and Sox, ballast water treatment equipment and damage stability requirement will all increase the oil consumption and cause the reduction of capacity, therefore, how to connect the different compulsory standards put forward by IMO and EEDI calculation formula, migrating the contradiction while protecting the mutual support, more progress is still needed for IMO.

2.4 Concluding remarks

The propose and development of ship's design energy efficiency means a lot to IMO's commitment to enhance ship's energy efficiency and cut down the CO_2 emissions. In this chapter, the definition of ship energy efficiency has been summarized, the evaluation indicator of existing energy efficiency is described thoroughly, which the propose and development of EEDI is reviewed, the applicable range and the present review conditions are expounded, in which the characteristics and limitations are summarized and concluded based on the instrument review and the author's understanding in order to lay the groundwork for the dissertation's viewpoint.

CHAPTER 3

The Correlation Analysis of Ship Design Energy Efficiency and Operational Energy Efficiency

3.1 The nature of ship operational energy efficiency and its influence factors

The ship operational energy efficiency is the energy efficiency level of a ship can perform during the actual operation process, which is under the combined influence of ship draft, ship trim, ship fouling, sea conditions etc., as influenced by various factors, the ship operational energy efficiency will normally change as the operation conditions with heavily fluctuations and random uncertainties. In fact, the ship operational performance will not only depend on the ship attained EEDI value, but also influence by the external environment factors as well as the deviation between the operational condition and the EEDI calculation condition. Various internal and external factors like ship draft, ship trim, ship sailing speed, fouling of ship hull and propeller, sailing depth will all generate influence on the final ship operational performance, which variation can be relevant to a large number of different influences that could be consider both in isolation and in combination.

(1) Fouling of the ship hull and propeller. As immersed in sea water for a long time after the ship has initiated sailing, marine organisms like shellfish, sea grass and alga are very easy to adhere to the surface of ship hull and propeller and then grow gradually and form into fouling, which cause the sags and crests of ship hull surface,

increase the roughness of ship as well as the friction resistance between ship and water, meanwhile, the output efficiency of ship propeller is also reduced, which will result in the propulsion power ship needed to increase. According to research and statistics (Schultz, Bendick, Holm, & Hertel, 2011), the ship fouling will increase the individual ship power output by 7%, which will correspondingly increase the ship oil consumption and deteriorate the operational energy efficiency performance.

(2) Sea condition and weather. The sea condition and weather will unpredictably change the ship propulsion power output. Heavy weather and rough sea conditions like sailing against the wind and huge surge will result in ship navigation resistance and increase the main engine output power, on the contrary, if a ship navigate under a favorable weather and sea condition like following wind and wave, it will significantly reduce the main engine power output and improve the ship operational performance, what's more, conditions like the external air temperature and sea water temperature will also change the ship main engine's working performance, heating load of the auxiliary engine and cargo, fouling of the ship hull and propeller etc., which will in turn influence the ship operational energy efficiency performance.

(3) Ship draft and trim condition. The ship's hydrodynamic resistance depends on the ship wet surface areas, which is highly related to ship's draft and trim condition, under different payload condition, the ship's draft will be different, while for different sailing trim attitude, the ship's navigation resistant force will vary largely, which will result in different hydrodynamic resistance and various average output power, and perform different levels of ship energy efficiency.

3.2 The existing evaluation method of ship operation energy efficiency

The Ship Energy Efficiency Operational Indicator (EEOI) was put forward by IMO in the “Guideline of voluntary use of Ship operational energy efficiency indicator” (MEPC.1/Circ.684), which is used to calculate the ratio of CO_2 emissions of a ship to its cargo/passenger turnover (the product of cargo mass and the corresponding distance travelled) in a given specific voyage or a period of time, the value of EEOI is used to evaluate the ship operational energy efficiency performance. EEOI is a relatively rational estimating indicator for evaluate the carbon intensity level of the mainstream cargo vessels (bulk carriers, oil tankers, container ships). From the view of EEOI calculation formula, the nature of EEOI is the ratio of emitted CO_2 of burning the fuel oil in theoretical (assuming sufficient burning) and the actual turnover (sometimes to be the nominal turnover) of cargo or passenger. The practical calculation formula is given in (1) energy efficiency performance in a single voyage and (2) the average energy efficiency performance of multiple voyages or in a specific period:

$$EEOI = \frac{\sum_j FC_j \times \mathrm{C_{Fj}}}{\mathrm{m}_{cargo} \times D} \tag{3.1}$$

$$AverageEEOI = \frac{\sum_i \sum_j (FC_{ij} \times \mathrm{C_{Fj}})}{\sum_i (\mathrm{m}_{cargo,i} \times D_i)} \tag{3.2}$$

where the i is the sequence number of various voyages and represents the voyage of NO. i,; j is the fuel oil type, such as HFO, MDO, LNG etc., FC_j/FC_{ij} is the fuel oil consumption amount (t) of j during the voyage i, C_{Fj} is the CO_2 conversion factor of fuel oil j, which is non-dimensional, $m_{cargo}/m_{cargo,i}$ is the cargo carried (t) or amount of work accomplished (TEU or passenger number), which can be substituted by Gross Tonnage (GT) for passenger ships, D/ Di is the voyage distance travelled (n mile) for voyage i. The lower of the ship EEOI value, the better of the ship operational energy efficiency is. As the metric of transport work of different ship type and cargo type is various, i.e. t for general cargo, TEU for containers, people for passengers etc., therefore, there are various kinds of units for EEOI, such as $kgCO_2$/t-nm, kg CO_2/ TEU-nm, $kgCO_2$/ GT-nm.

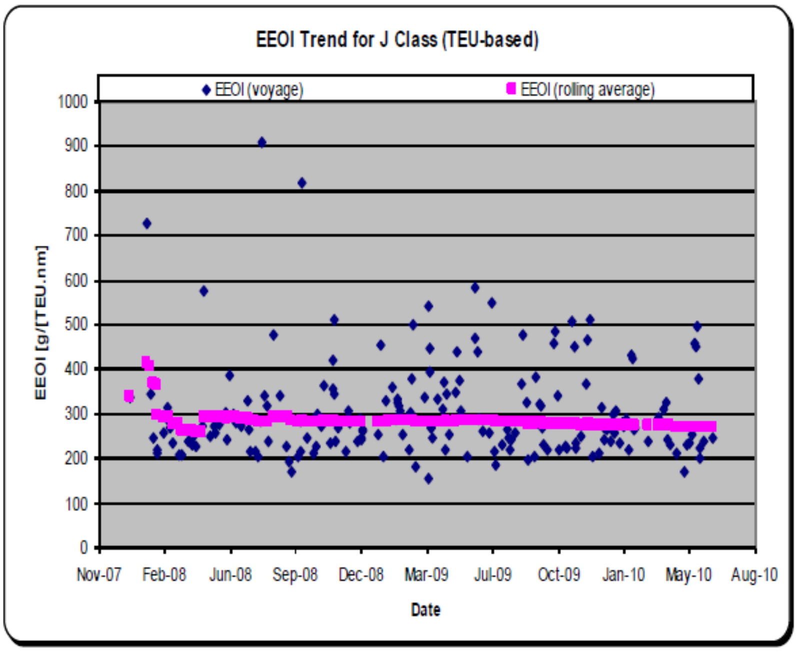

Figure 6 EEOI trend for J class container ship (IMO, 2012)

EEOI is a comprehensive reflection of ship operational energy efficiency performance, which covers the combined influence of the ship design energy efficiency level, the maintenance conditions, the utilization of payload, the weather and sea conditions. However, due to the reason of the commercial sensitivity of ships' actual freight turnover data, most of the shipping companies are pretty reluctant to disclose and submit the actual freight turnover data to the public, which may pose threat to their operating secrets and lose their competition advantages, the freight data is also excluded from the IMO data collecting system officially. Therefore, it will be more appropriate for the shipping companies and ship operators to take it as an internal energy efficiency management tool, but it is hard to propose it as a transparent policy tool to take further emission reduction measures.

In order to eliminate the commercial sensitivity of energy efficiency indicator, member states and research organizations of IMO have come up with several ship energy efficiency evaluation substitute indicators, of which the Annual Energy Ratio (AER) proposed by Japan (MEPC, 2013), Individual Ship Performance Indicator (ISPI) jointly put forward by Germany and Japan (MEPC, 2013), and the Energy Efficiency per Service Hour (EESH) proposed by United States (IMO, 2013) are typical indicators and received the common consensus. In these three substitute indicators, the ship total deadweight tonnage (dwt), the navigation voyage distance and the sailing time at sea are employed to replace the transport turnover as the transport work. Apparently, such kind of transformation can greatly simplify the statistics procedure and make full use of the IMO current data from the data collection system, which is fully supported by and available for the IMO data collection system. However, though the calculation process is simplified to a large extent for the three indicators, the evaluation results of the substitute indicators have certain degree of distortion, which means ships with higher freight payload factors turn out to have higher operational energy efficient values (which show a worse energy efficiency performance), therefore, lager uncertainties will generate when utilizing these indicators as the evaluation for ship's operational energy efficiency.

3.3 The general characteristics and distinction of ship design energy efficiency and operational energy efficiency

Though the calculation method and formula of design energy efficiency and operational energy efficiency is different, the two indicators share the task and meaning of evaluating the CO_2 emissions per unit transport work, besides, as for the common characteristics, they have the identical unit of measurement, as shown in g/(t ·nm). However, the two indicators have essential difference, which mainly shown in the following aspects:

(1) Different connotations

The evaluation of ship design energy efficiency is based on the idea of the design working condition has the representativeness of ship's design level, which is also the condition for ship to perform the maximum fuel economy, it drives the ship to a direction of better energy efficiency, therefore, once the ship completed its design and construction, it can be viewed as the constant EEDI, unless the ship undertaken huge retrofit. However, the ship operation energy efficiency is the evaluation of the real performance level, which cannot be accurately prejudged before since it is the performance evaluation after the transport activities.

(2) Different influence factors

The ship design energy efficiency is mainly affected by the ship design and construction factors, which specifically are the ship hull form, hull material used and its lightness, the main engine type selected, the energy saving technologies and equipment used etc. and manifested in the aspects of ship main engine power and design speed etc. However, along with the operation and deteriorate of the ship condition, the ship change with the main engine wear and tear, the added fouling of the ship hull, the deformation of hull etc. However, under the framework of EEDI regulation, the nominal EEDI will remain constant without considering the changing parts. For the operation energy efficiency, it is mainly affected by the design and construction factors, meanwhile, the operational energy efficiency is also influenced by different payload, sailing speed, ship trim, sea condition and weather, which performed in the different oil consumption and cargo carried, therefore, it is a indicator with huge fluctuation and uncertainty.

(3) Different applications

The design energy efficiency EEDI is utilized during the construction process of new ships, providing the ship's design energy efficiency. The EEDI is put forward in the perspective of ship energy efficiency improvement legislation, which is commonly accepted for pushing the environment protection situation, however, it may not always be representative during the actual operation. The applicable range of EEDI and EEOI is not always the same since the EEOI is used in the actual operation process. As the regulatory focus is moving from new ships to existing ships, the EEOI may be included to the mandatory regulatory system by means of other approaches as its evaluation is fluctuating and difficult to manage as EEDI.

In fact, it is commonly accepted that the operational energy efficiency performance cannot reach the design energy efficiency level. As for the reasons that operation energy efficiency deviated from the design energy efficiency, the analysis can be carried out through comparing the decomposed formula as well as the assumed conditions. The design energy efficiency and operation energy efficiency can be briefly expressed in P/WV, where P is the ship main engine's MCR, W is the ship's deadweight tonnage, V is the design speed for design efficiency while the actual output power of main engine ,the actual cargo weight carried and the real sailing speed for operation efficiency. The deviation caused by the factors can mainly be summarized into the following aspects:

(1) the ship own condition deterioration due to long time service

Along with the ship's service and machine running, ship own conditions will inevitably change due to the hull and propeller fouling, hull deformation and equipment deterioration etc., which will result in changing of the ship sailing speed and main engine output power curve, so does the EEDI reference speed change with the fuel oil consumption, and finally making the operation energy efficiency fail to reach the design energy efficiency.

(2) the sailing speed deviated from the design speed due to the slow steaming

The ship will choose a reference speed during the design process, however, as the shipping market fluctuates due to the economy conditions variation, the ship will normally choose to reduce the sailing speed in order to cut down the fuel consumption, as the main engine output power and fuel consumption has the relationship of cube with the main engine's revolution speed. As a matter of fact, the slow steaming is a hot research topic for estimating the environmental performance(Woo & Moon, 2014) , the CO_2 emission (Cariou, 2011), shipping cost (Chang & Wang, 2014), etc.

(3) the draft deviated from the full loaded draft due to different payload (O'Keeffe; & Smith, 2016)

For different payload, ship hull will have different wet surface area, which brings about different sailing resistance and the main engine output as well as the fuel consumption.

(4) other factors

Other factors such as the weather and sea conditions will increase or decrease the sailing resistance, which also arouse the research interests broadly both from the journal articles(Sozen, Alp, & Ozdemir, 2010) and scientific reports (Smith;, Prakash;, Aldous;, & Krammer, 2015; Sophia Parker, 2015) .

All the factors above will lead to the deviation of ship operation energy efficiency to design energy efficiency.

3.4 Concluding remarks

The ship operational energy efficiency is the energy efficiency level of a ship can perform during the actual operation process, which is under the combined influence of ship draft, ship trim, ship fouling, sea conditions etc. The ship's design energy efficiency is the main influence factor for the ship operation energy efficiency, so in order to have a better understanding of the design energy efficiency, the operational energy efficiency and the correlation relationship between the two need to be clarified. With a view to that, the chapter depict the nature of ship operational energy efficiency, as well as the evaluation indicators, what's more, the general characteristics and distinction of ship design energy efficiency are summarized from different prospective.

CHAPTER 4

Design energy efficiency evaluation of ship based on actual operational needs

4.1 Selection of the representative working conditions

Considering from the theoretical prospective, the ship's energy efficiency can be expressed as the ratio of transport work that generated from carrying cargoes or passengers and the input power of ships, specifically speaking, the transport work is the product of the actual freight transportation and the corresponding distance the ship travelled, while for the ship's input power, it is the propulsion power that generated by ship's engine through burning marine fuel. Thus, the ship energy efficiency can be expressed as follows:

$$K_{\eta} = \frac{\text{Capacity g} V}{P} = \frac{F_{Capacity} V}{P} = \frac{F_{Capacity}}{R} \frac{R V}{P} = K \eta \tag{4.1}$$

$$F_{Capacity} = \text{Capa}city\ g \tag{4.2}$$

Where the energy efficiency value Kη is the product of the sailing speed and the effective lifting force which produced by ship unit main engine power, it is also equal to the product of ship's effective ratio of lifting force and resistance force K and the propulsion coefficient η , which is a dimensionless quantity. Capacity is the deadweight tonnage of ship or the load mass of a ship, which is measured in t; g is the acceleration of gravity; V is the ship sailing speed, measured in knot; P indicates the output power of ship's main engine, which measured in kW; $F_{Capacity}$ represents the gravity force of ship's load or the effective lifting force of the ship, which is shown in kN; R is the resistance force of ship, which is also shown in kN; K is the ratio of effective lifting force and resistance force of the ship, η represents the propulsion coefficient of the ship, which is a non-dimensional quantity.

As can be seen from the formula, g is a constant, which can be cut out without influencing the calculation. The mass energy efficiency K′η as well as the mass power consumption coefficient 1/K′η

$$K'_\eta = \frac{\text{Capacity } V}{P} = \frac{K_\eta}{g} \tag{4.3}$$

$$\frac{1}{K'_\eta} = \frac{P}{\text{Capacity } V} = \frac{g}{K_\eta} \tag{4.4}$$

As can be seen from the formula, the mass energy efficiency K′η is a dimensional quantity, which indicates the product of ship sailing speed and the loaded weight of the capacity of per main engine power, while the mass power consumption coefficient 1/K′η can be shown as the required main engine power that ship sails in unit speed and unit ship capacity, which means the needed main engine power of the ship sails at per unit knot with unit tonnage cargo.

From the EEDI calculation formula, the attained EEDI value is the CO_2 emission amount of the fuel burning of the main engine and auxiliary engine that consumed when the ship sails in unit capacity and unit sailing speed. When carrying out EEDI calculation, the output power of auxiliary engine can be obtained by main engine through the empirical formula, therefore, in order to facilitate the discussion as well as the analysis, this study only choose to consider the CO_2 emission amount of the main engine, which will not have influence on the validity of the conclusion. The CO_2 emission amount of main engine can be calculated by multiply main engine specific fuel oil consumption SFC (g/kWh) and the carbon conversion factor C_F, which is the main part of the expression of EEDI, here this paper defines it as

$EEDI_{ME}$, the main engine power P should be regarded as the actual output of the main engine, what's more, only calm water external condition is considered.

$$EEDI_{ME} = (1/K'_{\eta})\ SFC\ C_F = \frac{P\ SFC\ C_F}{Capacity\ V} \tag{4.5}$$

As shown in the formula, the ship design energy efficiency is related to factors such as Capacity, ship speed V, main engine output power P, main engine's SFC and fuel C_F, Capacity and V in the formula can be viewed as independent variables, SFC is closely related to the type of ship main engine, while for the main engine type with excellent performance, the SFC of the engine is basically remaining constant. The carbon conversion factor C_F is relevant to the fuel burning by the ship, for the same ship fuel, the C_F value is always the same. The ship main engine output power P is strongly linked with Capacity, V and ship type and also the function of the three parameters. What's more. Factors such as ship's main dimension, main parameters of ship structure, ship hull form, geometrical parameter of ship propeller are all closely related to ship type, ship capacity and ship sailing speed, therefore, the $EEDI_{ME}$ can be viewed as the function of Capacity, ship sailing speed V and ship type, which can be expressed as follows:

$$\mathrm{EEDI}_{\mathrm{ME}} = f(Capacity, V, ShipType) \tag{4.6}$$

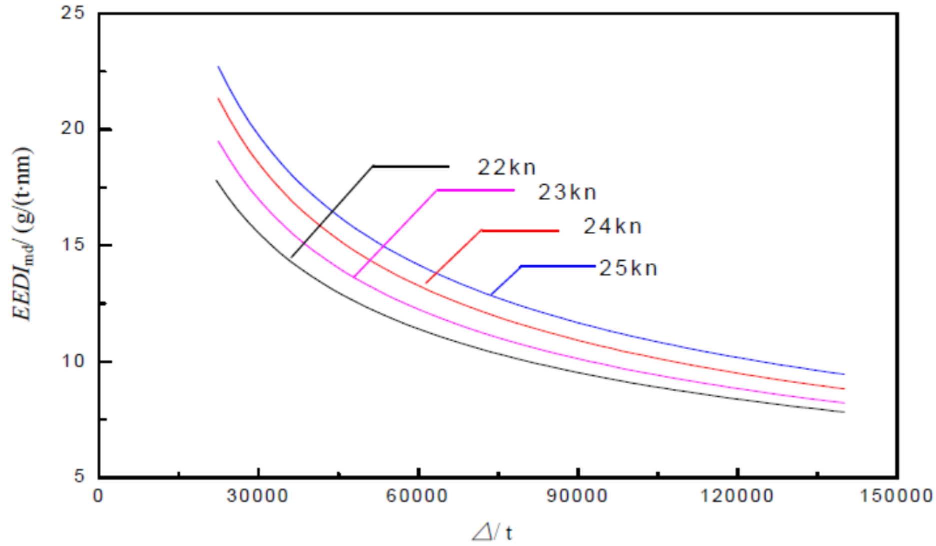

Figure 7 The calculated attained EEDI values of new ship under different capacity and design speed

As can be known from the above analysis, the understanding and evaluation of ship design energy efficiency is partially appropriate (or may be termed fully) to be only summarized and calculated as the curve of deadweight tonnage as the independent variable under the 75% of main engine MCR, but to introduce deadweight tonnage as independent variable and sailing speed as parameter, in order to fully show the design energy efficiency profile in the light of different types of ships. As a matter of fact, during the process of actual use and operation, it is necessary and appropriate to consider design energy efficiency of multi operation conditions in different stages through analyzing the sailing speed in common use with different payload condition as well as the proportion accounted in the voyage during real operation process, which will comprehensively evaluation the ship design energy efficiency level and provide guidance for ship designing and the future operation in order to reduce the carbon emissions from the shipping sector.

4.2 Case analysis

In order to use the statistics to verify the theoretical analysis, the dissertation has obtained the design parameters and ship model experiment data from the ship design institutions through the investigation of actual ship design and different EEDI strategy selection process with the purpose of verifying the theoretical analysis part and make the research more objective and quantitative.

This dissertation selected two typical design cases of new ships, i.e. a container ship and a very large crude oil carrier (VLCC). The case verification is carried out by comparing different design strategies regarding EEDI. For the sake of commercial confidentiality, the identification of the sample ships as well as the associate stakeholders are masked, and the data are also mildly modified through a consistent process without undermining their inherent features.

Case 1: A container ship for operating between ports of Europe and China

In this case, a container ship under design is taken as an example. The main parameters of the selected ship are provided in Table. 1. In addition, the output power and specific fuel oil consumption (referred to SFOC hereafter) under various working load of the main engine are also provided by the engine supplier, as present in Table2.

Table. 1 Parameters of Case 1 ship

Ship parameter	**Value**
Ship deadweight tonnage (t)	42260
Ship main engine Selected Maximum Continuous Rating (SMCR) (kW)	20880
75% of SMCR (kW)	15660
Specific Fuel Oil Consumption of 75% of SMCR (g/kWh)	156.9
The auxiliary engine power converted from the EEDI calculation condition (kW)	772.1
The oil consumption of auxiliary engine under EEDI calculation condition (t)	213

Table. 2 Fuel oil consumption under different power load of Case 1 ship

Engine Load (%SMCR)	Engine Output Power(kW)	SFOC（g/kWh）
100	20880	163.3
95	19836	162.2
90	18792	161.3
85	17748	159.4
80	16704	157.7
75	15660	156.9
70	14616	156.0
65	13572	156.1
60	12528	157.3
55	11484	158.5
50	10440	159.8

45	9396	161.2
40	8352	162.6
35	7308	164.3
30	6264	165.3
25	5220	167.3
20	4176	169.3
15	3132	173.4
10	2088	183.5

Two EEDI strategies at this design stage, referred to as Option A and Option B, can be followed as presented in Table 3.

Table3 EEDI strategies for Case 1 ship

	Option A	Option B
Required EEDI	18.43	
Attained EEDI	13.86	13.76
Vref	19.9	20.04

For each EEDI strategy option, the engine power output corresponding to different ship speeds can be obtained through tank experiments, as presented in Table. 4.

Table. 4 Engine power output vs. ship speed for Case 1 ship

Ship speed Vs (kn)	Engine power output P（kW）	
	Option A	Option B
12	5659	6158
15	6761	7321
17	8678	9159
18	10374	10722
19	12719	12732

20	15992	15495
21	20332	19142

According to the operation profile provided by the ship owner, the expected allocation of ship speed during the specific voyage (the total voyage distance is 13000 nm), in conjunction with the corresponding fuel oil consumption (SFOC) is shown in Table. 5:

Table. 5 Operation profile of Case ship 1

Operation Profile		SFOC	
Speed Vs (kn)	Time proportion α %	Option A	Option B
12	8%	165.2	164.3
15	49%	163.9	163.3
18	25%	159.2	158.8
20	18%	156.8	156.5

Then, the total fuel oil consumption for the voyage can be calculated as follows:

$$FC_{Total} = \frac{D}{\sum_i V_i \alpha_i} \times \sum_i P_{SFOC_i} \times SFOC_i \times \alpha_i$$

Where D is the total distance of the voyage, V_i stands for the different sailing speed, α_i is the time proportion undergoing speed V_i, P_{SFOC_i} the engine power output corresponding to V_i, $SFOC_i$ is the specific fuel oil consumption under the engine power output P_{SFOC_i} as given in Table. 6

The calculated total fuel oil consumption for the two EEDI options are reported in Table. 6

Table. 6 Total fuel oil consumption for the voyage

Option A（t）	Option B (t)
1173	1211

In this case, the total fuel oil consumption, consequently the converted CO_2 emissions, for the voyage of Option A is less than Option B, though the ship would hold a better EEDI value following Option B. Such a result is mainly caused by the largely majority of time operating at a speed far below the design point, where a relatively lower design speed tends to take the advantage.

Case 2: A VLCC for operating between ports of Middle East and China

In this case, a VLCC under design is taken as an example. The main parameters of the selected ship are provided in Table. 7. In addition, the output power and specific fuel oil consumption (referred to SFOC hereafter) under various working load of the main engine are also provided by the engine supplier, as present in Table8.

Table. 7 Parameters of Case 2 ship

Ship parameter	**Value**
Ship deadweight tonnage	323150
Ship main engine Selected Maximum Continuous Rating (SMCR)	24800
75% of SMCR	18600
Specific Fuel Oil Consumption of 75% of SMCR	156.8
The auxiliary engine power converted from the EEDI calculation condition	871.1
The oil consumption of auxiliary engine under EEDI calculation condition	216

Table. 8 Fuel oil consumption under different power load of Case 2 ship

Engine Load (%SMCR)	Engine Output Power (kW)	SFOC (g/kWh)
100	24800	163.7
95	23560	162.5
90	22320	161.5
85	21080	159.5
80	19840	157.7
75	18600	156.8
70	17360	155.9
65	16120	155.9
60	14880	157.1
55	13640	158.3
50	12400	159.6
45	11160	161.0

40	9920	162.4
35	8680	163.9
30	7440	165.0
25	6200	167.0
20	4960	170.0

Two EEDI strategies at this design stage, referred to as Option A and Option B, can be followed as presented in Table 9.

Table 9 EEDI strategies for Case 2 ship

	Option A	Option B
Required EEDI	2.25	
Attained EEDI	1.918	1.944
Vref	15.6	15.39

For each EEDI strategy option, the engine power outputs corresponding to different ship speeds and loaded conditions, as well as the specific fuel oil consumption, are provide in Table. 10 to Table13.

Table. 10 Engine power output vs. ship speed for Case 2 ship

(Option A whilst laden)

Speed Vs (kn)	Option A，Whilst laden	
	Ps (kW)	SFOC (g/kWh)
11	6690	165.5
12	8625	163.3
13	10877	160.4
14	13451	157.4
15	16469	154.8
16	20086	156.7
17	24343	161.8

Table. 11 Engine power output vs. ship speed for Case 2 ship

(Option A in ballast)

Speed (kn)	Option A，In ballast	
	Ps (kW)	SFOC (g/kWh)
13	7482	164.5
14	9777	162.0
15	12637	158.7
16	16141	155.1
17	20453	157.6
18	25732	163.6

Table. 12 Engine power output vs. ship speed for Case 2 ship

(Option B whilst laden)

Ship speed Vs (kn)	Option B， Whilst laden	
	Ps (kW)	SFOC
10	5317	168.5
12	9040	162.9
13	11410	159.9
14	14105	156.8
15	17201	154.9
16	20864	157.9
17.5	27938	163.6

Table. 13 Engine power output vs. ship speed for Case 2 ship

(Option B in ballast)

Ship speed Vs (kn)	Option B， In ballast	
	Ps (kW)	SFOC (g/kWh)
kn	kW	g/kWh
11	4310	171.1
12.5	6495	165.6
14	9453	162.1
15	11862	159.2
16	14843	156.0
17	18689	155.6
18.5	26543	163.8

According to the operation profile provided by the ship owner, the expected sea speeds whist laden and in ballast, in conjunction with the corresponding daily fuel oil consumption (SFOC), is shown in Table. 14 The distance of the one-way voyage is 6500nm).

Table. 14 Operation profile of Case ship 2

Operating Condition	Selected Speed Vs (kn)	Main engine output power for selected speed Ps	
		Case A	Case B
Full loaded	15	16468	17201
Ballast	16	16141	14842

Then, the total fuel oil consumption for the voyage can be calculated as follows:

$$FC_{Total} = \frac{D}{V_{laden} \times 24} \times DFOC_{laden} + \frac{D}{V_{ballast} \times 24} \times DFOC_{ballast} \qquad (4.1)$$

Where D is the distance of the one-way voyage, V_{laden} and $V_{ballast}$ stand for the sailing speed whilst laden / in ballast, $DFOC_{laden}$ and $DFOC_{ballast}$ stand for the daily fuel oil consumption whilst laden / in ballast.

In Eq.(4.1), the daily fuel oil consumption is calculated as $DFOC = SFOC \times P_{SFOC} \times 24$, where P_{SFOC} the engine power output under certain loaded condition, $SFOC$ is the specific fuel oil consumption under given engine power output as provided in Table. 13

The calculated total fuel oil consumption for the two EEDI options are reported in Table. 15

Table. 15 Total fuel oil consumption for the voyage of Case 2 ship

Option A	Option B
Case A (t)	Case B (t)
2259.1	1957.6

In this case, the total fuel oil consumption, consequently the converted CO_2 emissions, for the round-trip voyage of Option B is less than Option A, though the ship would hold a better EEDI value following Option A. Such a result is mainly caused by the factual operation feature, i.e. the roughly half-and-half proportion of the fully loaded and ballast condition, which can be deemed as a significant deviation from her EEDI working condition.

4.3 Concluding remarks

Generally speaking, as a technical approach, the EEDI chooses the typical working condition to represent ship's energy efficiency from the design technology perspective, pushing the ship to possess a relatively high energy efficiency before it provides service for shipping market through gradually increasing the energy efficiency requirements, which has made huge progress without doubt for cutting down the CO_2 emissions from the shipping sector. However, as a matter of fact, ships will encounter and be influenced by various changeable situations during the operation process, as proved by the fluctuation of the EEOI, which is an indicator for ship operation energy efficiency, influencing factors mainly come from the ship payload, the actual sailing speed selected, the performance deterioration of ship engines and fouling of the hull and propeller duet to long time navigation, the weather and sea conditions, etc. All the influence factors resulting in the operation working conditions deviated from the EEDI reference working condition, making the ship fail to perform what it should have maintained design energy efficiency level, which may cause the unfavorable conditions of making an arbitrary design strategy at the design stage if the policy maker and ship designer merely focusing on ship energy efficiency performance under reference working condition. As analyzed from the formula derivation and shown in the EEDI design case of the ship design institution, therefore, the dissertation propose to if it is possible to optimize and evaluate the ship design energy efficiency based on actual operation needs to a large degree, it will benefit the perform and improvement of ship energy efficiency, which will contribute to a large extent for the ship energy efficiency performance and shipping industry carbon emission reduction.

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CHAPTER 5

SUMMARY and CONCLUSIONS

The shipping greenhouse gas (GHG) emission reduction action as well as its reduction mechanism establishment is the significant component of the response for global climate change and the founding of the structure of global climate governance. The improvement of ship energy efficiency level and the performance is one of the important solutions to realize the goal of cutting down ship GHG emission, as is also a highly being emphasized issue and an important direction for carrying out missions for marine environmental protection committee (MEPC) of International Maritime Organization (IMO). As a matter of fact, IMO has initiated intensive discussions separately on gradually enhancing the energy efficiency and performance of the new designed and constructed ships as well as the existing ships in the light of the different characteristic of ships during the design and construction process as well as the actual operation process. The ship Energy Efficiency Design Index (EEDI) is the existing indicator developed by IMO with the view to evaluating the design energy efficiency level of new ships. IMO has adopted the amendment of Annex VI of International Convention for the Prevention of Marine Pollution by Ships in the year of 2011, which provides the compulsory requirement for the EEDI value of new ships built for the year 2013 and thereafter with the purpose of controlling the CO_2 emissions of ships from the source of design and construction through improving the

EEDI levels of new ships. To be specific, the EEDI regulation makes great efforts to offer a fair and basic evaluation indicator, making it as a basic indicator of equity and comparing the different ship's design energy efficiency level while checking whether the ship has met the lowest energy efficiency standards set by IMO regulations.

Ship design energy efficiency is considered from the viewpoint of ship own design and construction level, to calculate the environment cost (CO_2 emission amount) of per ship produced socio-economic benefit (transport work) without concerning the ship's actual operation conditions, what just be considered is all kinds of the energy efficiency improvement technologies and measures which used during ship design stage. The EEDI is an indicator of evaluating the energy efficiency design level and calculating the energy efficiency design value. The ship attained EEDI formula calculates ship CO_2 emission amount under the specific situations of ideal external conditions (without wind and wave, sailing in deep sea area) and the ship working condition (75% MCR main engine output, sailing under the maximum loading capacity with a tested speed), the attained ship energy efficiency index value is used to evaluate the design energy efficiency level of a certain ship type with ship tonnage.

In conclusion, this dissertation provides a comprehensive discussion on the definition and influence factors of ship energy efficiency and reviews the propose and development of EEDI. What is worthy to be confirmed, the EEDI plays a significant role in improving the energy efficiency for new built ships, through selecting the reprehensive working condition, EEDI will become a specific tractive force with a view to driving the enhancement of ship's energy efficiency performance. However, this dissertation also provides a more intensive understanding of ship's design energy efficiency by theoretical analysis as well as the verification for the actual examples, the conclusion is that even though the present EEDI value calculation and selection is

generally acceptable and has made huge contributions to the improvement of ship energy efficiency, the attained EEDI, which is a single point value calculated under a given working condition, can hardly provide a whole picture of the ship's energy efficiency performance under other working conditions at the design stage, since merely focusing on ship performance under reference working condition may risk making an arbitrary design strategy at the design stage, it is meaningful to have a thoroughly understanding of ship design energy efficiency and its implication in practice, under the condition of meeting the requirement of present EEDI required value. It will benefit the ship's energy efficiency performance of whole life process if more actual operation conditions and more actual needs are considered and optimize the ship's design energy efficiency strategy during the ship design and construction process.
What's more, this dissertation also recommends to proceed appropriate improvement of the existing EEDI evaluation system if possible, in order to provide some more objective policy guidance, which can eventually contribute to enhance the energy efficiency performance during the operation, and finally achieve the goal of reducing the ship carbon emissions both from the dimensions of ship design and ship operation.

This paper has some limitations. The study presents a thoroughly understanding of ship energy efficiency by theoretical analysis and real case analysis, however, it is limited by the small number of ship design case and ship type and the limited research time, besides, for the sake of commercial confidentiality, the identification of the sample ships as well as the associate stakeholders have to be masked, which makes the dissertation more like limited to theory.

REFERENCES

Brooks, M. R., & Faust, P. (2018). 50 Years of Review of Maritime Transport, 1968-2018: Reflecting on the Past, Exploring the Future. Retrieved from https://unctad.org/en/PublicationsLibrary/dtl2018d1_en.pdf

Burleson, E. (2006). Multilateral Climate Change Mitigation. USFL Rev., 41, 373.

Cariou, P. (2011). Is slow steaming a sustainable means of reducing CO2 emissions from container shipping? Transportation Research Part D: Transport and Environment, 16, 260-264. doi:10.1016/j.trd.2010.12.005

Chang, C.-C. C., & Wang, C.-M. M. (2014). Evaluating the effects of speed reduce for shipping costs and CO2 emission. Transportation Research Part D: Transport and Environment, 31, 110-115. doi:10.1016/j.trd.2014.05.020

IMO. (2009). Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator (EEOI). Retrieved from MEPC.1/Circ.684:

IMO. (2011). Amendments to the Annex of the Protocol of the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto (Inclusion of regulations on energy efficiency for ships in MARPOL Annex VI). Retrieved from Resolution MEPC.203(62):

IMO. (2013). Proposal of the United States to Enhance Energy Efficiency inInternational Shipping. Retrieved from MEPC 65/4/19:

MEPC. (2013). Further details of possible metric options to develop further technical and operational measures for enhancing the energy efficiency of international shipping. Retrieved from London, UK:

Nordhaus, W. D. (1994). Managing the global commons: the economics of climate change (Vol. 31): MIT press Cambridge, MA.

O'Keeffe;, E., & Smith, T. (2016). A Case Study of Fuel Monitoring and Efficiency Indicators for INTERTANKO. Retrieved from London, UK: https://u-mas.co.uk/Projects

Oberthür, S. (2003). Institutional interaction to address greenhouse gas emissions from international transport: ICAO, IMO and the Kyoto Protocol. Climate Policy, 3(3), 191-205.

Resolution, M. (2013). 231 (65), 2013 Guidelines for Calculation of Reference Lines for Use with The Energy Efficiency Design Index (EEDI). Adopted on, 17.

Schipper, E. L. F. (2006). Conceptual history of adaptation in the UNFCCC process. Review of European Community & International Environmental Law, 15(1), 82-92.

Schultz, M., Bendick, J., Holm, E., & Hertel, W. (2011). Economic impact of biofouling on a naval surface ship. Biofouling, 27(1), 87-98.

Smith, T. W. P. J., J. P. ; Anderson, B. A. ; Corbett, J. J. ; Faber, J. ; Hanayama, S. ; O'Keeffe, E. ; Parker, S. ; Johansson, L. ; Aldous, L. ; Raucci, C. ; Traut, M. ; Ettinger, S. ; Nelissen, D. ; Lee, D. S. ; Ng, S. ; Agrawal, A. ; Winebrake, J. J. ; Hoen, M. ; Chesworth, S. ; Pandey, A. (2015). Third IMO GHG Study 2014. United Kingdom: International Maritime Organization.

Smith;, T., Prakash;, V., Aldous;, L., & Krammer, P. (2015). The Existing Shipping Fleet's CO2 Efficiency. Retrieved from International Maritime Organization (IMO): https://www.ucl.ac.uk/bartlett/energy/publications/2015/may/existing-shipping-fleets-co2-efficiency

Sophia Parker, C. R., Tristan Smith, and Ludovic Laffineur. (2015). Understanding the Energy Efficiency Operational Indicator: an empirical analysis of ships from the Belgian Shipowners' Association. Retrieved from https://www.safety4sea.com/wp-content/uploads/2015/09/RBSA-Understanding-the-EEOI-Summary-2015_08-.pdf

Sozen, A., Alp, I., & Ozdemir, A. (2010). Assessment of operational and environmental performance of the thermal power plants in Turkey by using data envelopment analysis. Energy policy, 38(10), 6194-6203. doi:10.1016/j.enpol.2010.06.005

Woo, J. K., & Moon, D. S. H. (2014). The effects of slow steaming on the environmental performance in liner shipping. Maritime Policy & Management, 41(2), 176-191. doi:10.1080/03088839.2013.819131

BIBLIOGRAPHY

Nakazawa, Takeshi. (2018). *Impact of Maritime Innovation and Technology*. Unpublished lecture handout, Dalian Maritime University, Dalian, China.

Second IMO GHG Study 2009, International Maritime Organization (IMO) London, UK, April 2009; Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W., Yoshida, K.