

# **Dependence of ship propulsion system energy efficiency on the propeller slip, expressed through the Energy Efficiency Operational Indicator in operation.**

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**Abstract:** Under increased international requirements for reducing greenhouse gas emissions and improving the energy efficiency of maritime transport, the analysis of operational parameters affecting fuel consumption and propulsion performance has become particularly important. Propeller slip, as a parameter characterizing the losses in the conversion of rotational motion into useful thrust, is directly related to the vessel's speed, main engine power and fuel consumption. The propeller slip increasing leads to higher loading of the propulsion system and a reduction in the ship's energy efficiency. Simultaneously, the Energy Efficiency Operational Indicator (EEOI) represents a key integrated parameter for assessment of the ship's energy efficiency under real operating conditions, in accordance with the requirements of the International Maritime Organization. The interrelation between propeller slip and EEOI, established through a mathematical model, demonstrates the practical application of the considered parameters. This approach can serve as a basis for evaluation, analysis, and decision-making by the ship's command and engineering management, with the aim of optimizing operating conditions, reducing fuel consumption, and improving overall voyage efficiency.

**Key words:** propeller slip, energy efficiency, operational indicator

## **1. Introduction**

With the growing public attention to air pollution over the past decades, work has begun globally to establish a legal framework for controlling atmospheric emissions. In the maritime industry, the International Maritime Organization (IMO) has taken a leading role in developing measures to limit harmful gases emitted by ships. A key outcome of this process was the amendment of the MARPOL Convention and the introduction of Annex VI – “Prevention of Air Pollution from Ships.” This chapter came into force in 2005 and initially regulated emissions of sulfur oxides (SO<sub>x</sub>), nitrogen oxides (NO<sub>x</sub>), and volatile organic compounds that deplete the ozone layer. Although the initial focus was on the emission of harmful oxide compounds, increasing awareness of global climate change has gradually shifted attention toward carbon dioxide and greenhouse gases. The IMO's position firmly reinforces the necessity of sectoral contributions to the overall efforts in mitigating climate change. The organization faces the challenge of limiting greenhouse gas emissions from ships globally without negatively impacting sustainable development and international trade. (2)(7).

The concept of energy efficiency has emerged as a leading mechanism for reducing CO<sub>2</sub> emissions as well as fuel consumption, with the IMO approach based on improving ship efficiency through regulatory, technical, and operational measures. (2)(6).

Through its established publications and procedures forming the regulatory framework, the IMO introduces a set of instruments aimed at improving ship energy efficiency standards and reducing CO<sub>2</sub> emissions. These are basic parameters and indices that enable the monitoring and control of the energy efficiency of individual ships, based on methods for planning, data collection, analysis and evaluation. The introduced regulatory indicators, which are also interconnected, can be considered as follows:

- **EEDI (Energy Efficiency Design Index)** is a design index that assesses the potential energy efficiency of newly built ships or ships after major conversions. It shows the amount of the CO<sub>2</sub> emissions that a ship would produce in relation to the transport work under optimal design conditions. Based on the EEDI, technical standards are defined for newly designed ships.

- **EEXI (Energy Efficiency Existing Ship Index)** – it applies the same approach to existing ships in order to assess their design efficiency in relation to the new standards. For new ships or ships undergoing major conversions, the attained EEDI may be accepted as EEXI if it meets the requirements. In this way, EEDI and EEXI define the technical and design capabilities of a ship concerning energy efficiency.

- **SEEMP (Ship Energy Efficiency Management Plan)** – it is a comprehensive Plan concerning ship's energy efficiency that every ship with a gross tonnage above 5,000 GT is required to possess. It outlines the methods for collecting data on fuel consumption, cargo, and distance sailed, necessary for calculating operational efficiency indicators. The SEEMP includes objectives for improving efficiency, measures to achieve the required annual Carbon Intensity Indicator, and procedures for self-assessment and corrective actions if the ship fails to meet the standards.

- **CII (Carbon Intensity Indicator)** – it is the official operational index of Carbon intensity. It measures a ship's annual operational efficiency – the amount of CO<sub>2</sub> emissions relative to the cargo carried and the distance sailed. Based on this, the ship is assigned a specific rating, reflecting either achieved target values or unsatisfactory performance, in which case corrective actions shall be implemented through the SEEMP.

- **EEOI (Energy Efficiency Operational Indicator)** – it is an Indicator of energy efficiency for operational ships, measuring the same parameters as the CII – fuel consumption, cargo carried, and distance sailed. It serves as a voluntary index for internal monitoring and optimization of operational efficiency, implemented through the SEEMP. An improvement in the EEOI reflects that the ship is using its resources more efficiently while reducing emissions.

In summary, the EEDI/EEXI define the design potential, the SEEMP manages daily operations and data collection, the CII officially measures and evaluates performance, and the EEOI serves for internal improvement and monitoring. Together, these tools form a comprehensive framework for reducing carbon intensity and enhancing the energy efficiency of the international fleet. (2)(3)(4)(5)(6).

Technical measures aimed at improving energy efficiency in maritime transport are directly dependent on the ship's operational characteristics and the optimization of the propulsion system, the reduction of hull resistance losses, as well as the optimization of maneuverability and steering systems (course stability and autopilot).

- **Optimization of the Propulsion System** – this is based on the enhancement of both the fundamental and operational characteristics of the propulsion system, aimed at reducing hydrodynamic resistance and converting fuel energy into useful thrust. The goal is to ensure minimal slip and maximum propulsion efficiency, which involves the main engine – shaft line – propeller. Reducing **propeller slip** means operating the ship's thruster at an optimal Specific Fuel Oil Consumption (SFOC), while minimizing energy losses, so that the majority of the input power is transformed into effective thrust. Another key factor is the proper selection and hydrodynamic optimization of the propeller, including matching the pitch, diameter, and number of blades, in order to achieve optimal forward motion and minimize hydrodynamic losses. An improperly selected propeller causes operation outside the optimal efficiency zone, leading to increased fuel consumption. Furthermore, the interaction between the hull and the propeller has a significant impact on efficiency, as uneven water flow can result in additional losses and vibrations. In this context, various energy-saving devices, such as guiding fins and nozzles, are applied to improve water flow to the propeller and enhance propulsion efficiency. From a broader theoretical perspective, the relationships between resistance, thrust, and power show that any reduction in losses within the propulsion system leads to a proportional decrease in the energy required to perform transport work. Therefore, through propeller optimization, slip control, resistance reduction, and operation of the engine in an efficient regime, fuel

consumption is reduced, and the overall energy and carbon efficiency of the ship is improved. (1)(8)(10)(11)(12).

- **Reduction of Hull Resistance** – one of the main factors determining the power required for ship propulsion and, consequently, its energy efficiency. Hull resistance comprises frictional resistance, wave-making resistance, and additional components related to the hull's shape and condition. A technical strategy for energy efficiency includes hull form optimization during the design stage, as well as maintaining a clean underwater surface during operation. Controlling fouling and hull roughness reduces the friction coefficient and, accordingly, the required thrust. Increased resistance necessitates higher power to maintain the same speed, which in turn increases propeller load and slip. As a result, efficiency decreases and fuel consumption rises. Hydrodynamic hull optimization – including selecting an appropriate block coefficient, optimizing bow and stern lines, and increasing the effective waterline length – significantly reduces resistance and improves operational performance. The condition of the hull surface also has a critical impact. Accumulation of biofouling increases friction and can lead to a substantial rise in fuel consumption. Therefore, specialized antifouling coatings are applied, and regular cleaning procedures are implemented. Modern technologies also include air lubrication systems, which create a layer of air bubbles between the hull and the water, further reducing friction. (8)(9)(10)(12)(13).

- **Optimization of Maneuverability and Steering Systems (Course Keeping and Autopilot)** – these systems have a direct impact on energy efficiency, with course maintenance playing a particularly important role. Any rudder deviation increases hydrodynamic resistance, and this relationship is nonlinear, growing significantly at larger angles. Frequent and abrupt course corrections, especially with improperly configured autopilot systems, lead to so-called “zigzag” motion, which increases the distance sailed and, consequently, fuel consumption. This, in turn, requires greater thrust from the propeller, resulting in increased slip and load on the propulsion system. In this context, proper autopilot configuration is crucial. By optimizing the regulator parameters, a balance can be achieved between steering accuracy and improved course stability, which constitutes a technical measure for enhancing energy efficiency, as it reduces resistance, stabilizes propeller operation, and limits slip increase. Modern trends include the use of adaptive and intelligent control systems that account for external factors such as waves and wind, optimizing steering in real time. This results in smoother corrections, reduced dynamic loads on the steering gear, and a substantial improvement in the ship's overall energy efficiency. (8)(9)(11)(12)(15).

Technical measures for improving energy efficiency in maritime transport rely on an integrated approach, combining propulsion system optimization, hull resistance reduction, and effective course management. The interaction between these factors determines the ship's overall operational performance, with even minor improvements in each area potentially leading to significant reductions in fuel consumption and emissions.

Operational measures consist of a set of actions aimed at the optimal use of a ship's existing technical resources, with the objective of minimizing fuel consumption and enhancing energy efficiency. These measures can be applied directly during operations and often result in significant savings without the need for substantial investment. The main areas of focus include speed management, optimization of the ship's floating condition (trim, draft, and heel), and ensuring optimal operating conditions for the propeller. (10)(13).

- **Speed Management** – it is one of the most effective ways of controlling fuel consumption, as the power required for ship propulsion is directly proportional to the magnitude of the speed. This means that even a small reduction in speed leads to a significant decrease in required power, and consequently in fuel consumption and CO<sub>2</sub> emissions. In practice, the implementation of so-called *slow steaming* can result in fuel savings in the range of 10–30%, depending on ship type and operational conditions. Optimal speed management includes consideration of weather conditions, sea state, and route planning. The use of *weather routing systems* allows the avoidance of unfavorable conditions that would otherwise lead to increased resistance and energy consumption. Maintaining a constant and optimal speed also reduces the need for

frequent engine load changes, thereby improving engine efficiency and extending its operational life. From the perspective of propeller slip, speed variations influence the advance motion and, consequently, the optimal propeller performance. Thus, slip becomes a key parameter for assessing actual energy efficiency at reduced speeds and justifies the need for its more detailed consideration in the context of evaluating propulsion strategy. (1)(10)(12)(13).

- **Maintaining Optimal Heel, Trim, and Draft** – the ship's buoyancy and the shape of its submerged hull significantly influence hydrodynamic resistance and propulsion efficiency. Improper trim may lead to increased resistance, particularly at higher speeds, due to unfavorable changes in hull flow characteristics. Optimization can be achieved through redistribution of cargo or ballast water in order to minimize resistance under specific sailing conditions. Heel also has a negative impact on energy efficiency, as it results in asymmetric flow around the hull and increased resistance. Even small heel angles may cause additional energy losses, especially during prolonged voyages. Maintaining even draft and optimal weight distribution ensures that the hull operates under its designed hydrodynamic conditions, thereby minimizing losses and improving overall efficiency. The direct relationship between the submerged portions of the bow and stern and the trim condition can also be expressed mathematically, providing a clear representation of achieving the required trim value that ensures minimum resistance. (8)(9)(12)(13).

$$t = d_f - d_a, \text{ where} \quad (1)$$

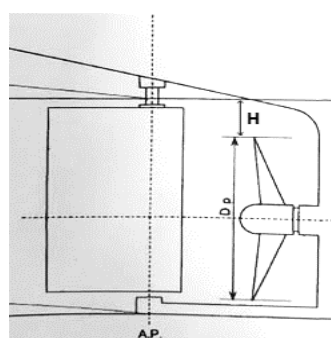
**t** – trim

**d<sub>f</sub>** – draft forward

**d<sub>a</sub>** – draft aft

- **Ensuring Optimal Operating Conditions for the Propeller** – the efficient operation of the propeller is directly related to its submergence below the waterline, which significantly affects the generated thrust, hydrodynamic losses, and the overall energy efficiency of the ship. Insufficient submergence leads to unfavorable phenomena such as air suction from the surface, cavitation, and uneven blade loading, which in turn reduces propulsion efficiency and increases fuel consumption. In practice, the minimum required propeller submergence is determined by assuming that the immersion depth should be proportional to the propeller diameter. Under normal operating conditions, the following criterion is commonly applied: see

**Fig.1**



$$H \geq (0,3 \div 0,5) D_p, \text{ where}$$

**H** – the vertical distance from the waterline to the vertical projection of the propeller (**height**);

**D<sub>p</sub>** – Diameter of the propeller.

**Fig. 1** Vertical clearance of the propeller from the waterline in vertical projection.

Insufficient propeller submergence leads to a significant increase in propeller slip and a reduction in generated thrust, which requires higher main engine power to maintain the desired speed. This directly affects energy efficiency by increasing the specific fuel consumption. Furthermore, unstable flow around the propeller results in vibrations and additional mechanical losses, which deteriorate the operational performance of the propulsion system. Maintaining optimal submergence is achieved through proper management of the ship's draft and trim, taking into account hydrometeorological conditions and operating

speed. In this regard, control of the ship's floating condition represents an important operational measure for maintaining efficient propeller performance. Proper propeller submergence ensures stable inflow to the propeller, minimizes energy losses, and enables the propulsion system to achieve maximum efficiency. (1)(8)(12)(13).

Operational measures are aimed at optimizing the performance of the propulsion system under real operating conditions, ensuring efficient use of available resources. In combination with technical measures, they contribute to improving the overall energy efficiency of the ship and reducing energy losses. In this way, more economical and sustainable operation of maritime transport vessels is achieved.

## 2. Propeller Slip – Significance, Definition, and Role in the Energy Efficiency of Ship Propulsion Systems

The ship's propulsion system ensures the conversion of mechanical energy from the main engine into thrust through the propeller, with the efficiency of this process directly depending on the interaction between the propeller and the surrounding water. One of the main parameters characterizing this interaction is **propeller slip**. (1)(10).

Propeller slip is defined as the difference between the theoretical ship speed, determined by the geometric characteristics of the propeller and its rotational rate, and the actual speed of the ship relative to the water. It arises due to hydrodynamic losses, hull resistance, and the non-ideal conversion of energy into thrust. Propeller slip is a key parameter that characterizes the efficiency of converting the rotational motion of the propulsion system into useful thrust and, consequently, into the ship's forward motion. Theoretically, if the propeller were operating in a perfectly rigid medium – analogous to a mechanical screw in a solid substance – it would advance at a *speed*  $V$ , equal to the product of the geometric *pitch*  $p$  and the *number* of revolutions  $n$ ,

$$V = p \times n \quad (\text{m/min}) \quad (2)$$

In real operating conditions, however, the water is not a rigid medium, and under the action of the rotating blades, it is accelerated backward, forming a jet behind the propeller and reducing the actual advance speed relative to the theoretical one. This difference between the theoretical and actual propeller advance is defined as propeller slip and serves as a measure of the hydrodynamic losses during propulsion. (1)(12)(13).

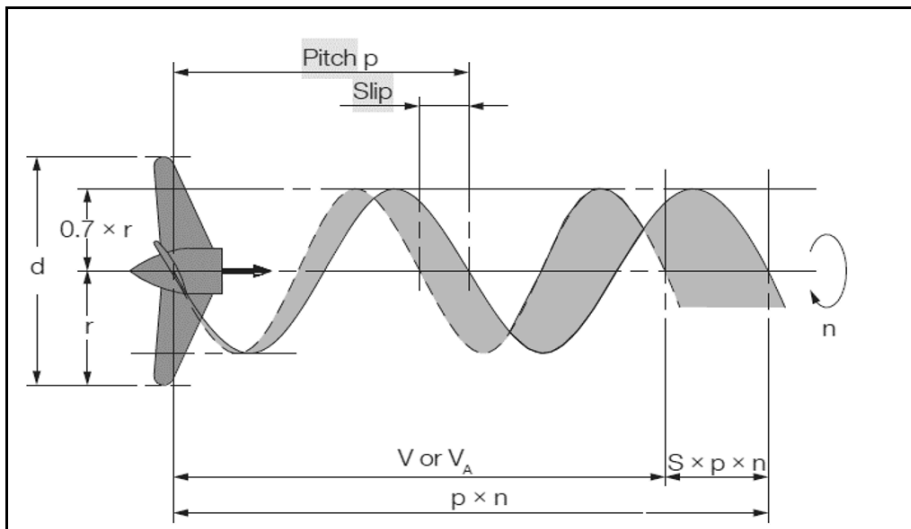


**Fig. 2** Relationship between propeller *pitch* and propeller *slip*. (10).

The geometric characteristic of a propeller that determines its potential to convert rotational motion into forward motion is the **pitch**, which represents the distance a blade would advance in one revolution in the absence of slip. Although the pitch varies along the propeller radius, in practice it is considered as a helical advance along a cylindrical surface, and an average value is introduced to account for all parameters affecting the propeller's performance. (1)(9)(10). Taking into account the dimensionality of the geometric pitch **p** (m) and the number of revolutions **n** (rev/min), the resultant speed in nautical knots may be accounted, as follows:

$$V = \frac{60}{1852} p \cdot n \quad (\text{knts}) \quad (3)$$

In practice, two types of propeller slip are distinguished – **apparent slip** - **Sa**, based on the ship's speed **V** and **real slip** - **Sr**, the latter taking into account the effect of the inflow velocity to the propeller **V<sub>A</sub>**, which is lower than the ship's speed due to the effect of the propeller **slipstream**. This further complicates the analysis, but at the same time emphasizes the role of propeller slip as an integral parameter reflecting the interaction between the hull, the propeller, and the incoming water flow. (10). See Fig. 2

$$Sa = \frac{p \cdot n - V}{p \cdot n} = 1 - \frac{V}{p \cdot n} \quad (4)$$

**Apparent slip** can be calculated by the crew in order to obtain an approximate assessment of the propeller load. The actual slip, however, usually cannot be determined by the crew, as the inflow velocity to the propeller is unknown; since this velocity is lower than the ship's speed, the actual slip is correspondingly higher. (10).

$$Sr = \frac{p \cdot n - Va}{p \cdot n} = 1 - \frac{Va}{p \cdot n} \quad (5)$$

The propeller load is proportional to slip; that is, the greater the slip, the higher the load, and vice versa. This means that an increase in resistance requires an increase in propeller revolutions in order to maintain a constant ship speed.

Propeller slip is expressed as a ratio or percentage, as follows:

$$S = \frac{Vt - Vk}{Vt} = \left(1 - \frac{Vk}{Vt}\right) \cdot 100 \% \quad (6)$$

Where: **S** – Propeller Slip in percentage; **Vt** – theoretical speed is defined as the product of the pitch and the number of revolutions per unit of time, **Vk** – actual ship's speed over the same period. Propeller slip can also take negative values, for example when strong currents or wind assist the ship's forward movement. The theoretical speed is determined as the product of the propeller's revolutions and pitch, but due to losses, the actual speed is lower, resulting in positive slip values. (1)(11).

In practice, the percentage values of propeller slip can serve as an indicator and a reliable predictor of conditions and processes related to the ship's propulsion system, the hull condition, as well as the prevailing hydrometeorological environment. Considering the coefficients in percentage terms, the following conclusions can be drawn:

- slip values of up to approximately 10 % indicate that the ship's hull is relatively clean; under calm weather conditions, this is a sign of good hull condition and optimal performance of the propulsion system;
- slip values in the range of 10–20 % indicate normal operating conditions of the propulsion system and optimal operational efficiency;

- slip values on the order of 20–30 % – under normal weather conditions – indicate a fouled hull, reduced efficiency, and increased fuel consumption. Under adverse weather conditions, this corresponds to higher resistance, that is, it becomes necessary to consider the prevailing weather and take preventive measures, such as reducing speed, correcting course and heading relative to wind and waves, and, if necessary, adjusting the sailing route;
- slip values exceeding 30 % indicate adverse weather conditions, inefficient operation of the propulsion system, high fuel consumption, and increased hull stress. Consequently, these represent unfavorable conditions for the voyage, affecting the ship, crew, and cargo, and resulting in reduced energy efficiency.

From the perspective of energy efficiency, propeller slip plays a key role, as an increase in slip leads to a reduction in the propeller's efficiency and necessitates the application of greater power to maintain the same ship speed. This makes slip an important indicator of the condition of the propulsion system and the degree of coordination between the engine, propeller, and the hull's hydrodynamic characteristics. In this regard, analyzing slip not only allows for an assessment of current efficiency but also provides a basis for optimizing operating modes, which directly impacts fuel consumption and the ship's performance. Conversely, excessively low slip values may indicate propeller overload or operation outside its optimal performance range. Therefore, maintaining an optimal slip range is essential to ensure maximum efficiency of the propulsion system. In practice, this is achieved through proper management of speed, engine revolutions, trim, and propeller immersion, as well as maintaining the hull and propeller in good technical condition. (1)(10)(12)(13).

In conclusion, propeller slip serves as an integral indicator of the propulsion system's efficiency, with its analysis enabling the diagnosis of the ship's operational condition and the identification of opportunities to reduce energy losses. Monitoring this parameter is an essential component of measures aimed at improving energy efficiency in maritime transport.

### 3. Energy Efficiency Operational Indicator (EEOI) – Definition, Role, and Formulation

The primary regulatory document introducing the Operational Energy Efficiency Indicator for existing ships is **MEPC.1/Circ.684 – Guidelines for Voluntary Use of the Ship Energy Efficiency Operational Indicator (EEOI)**, issued in 2009. (3).

This circular is the formal outcome of the meeting of the members of the Marine Environmental Protection Committee (MEPC) of the International Maritime Organization, held during its 59th session from 13–17 July 2009, where the decision was made to introduce the voluntary use of the Ship Energy Efficiency Operational Indicator (EEOI). The document provides a calculation methodology, defines the required input data (fuel consumption, emission factors, cargo carried, and distance sailed), and sets out the principles for its voluntary application. It emphasizes that the EEOI serves as a tool for monitoring the actual carbon intensity of shipping operations, expressed as the amount of CO<sub>2</sub> per ton-mile. Its main function is to provide a comparable and quantitative basis for evaluating the ship's operational efficiency over time. The EEOI does not impose mandatory limits but acts as a managerial and analytical instrument that can support decision-making and operational optimization. (3).

An important role in institutionalizing the EEOI is also played by **MEPC.1/Circ.683**, which regulates the development of the **Ship Energy Efficiency Management Plan (SEEMP)** for both new and existing ships. The SEEMP aims to improve the ship's energy efficiency through four steps: *planning, implementation, monitoring*, and *analysis (evaluation and improvement)*. These elements are key to the continuous cycle of enhancing the ship's energy management. *Planning* is the most critical stage of the SEEMP, as it defines both the current state of the ship's energy consumption and the expected improvement in its energy efficiency. Therefore, it is recommended that sufficient time be devoted to the planning phase to develop a

plan that is as suitable, effective, and applicable as possible. The final part of the planning stage involves setting objectives, which can be formulated in various ways, for example as an annual fuel consumption target or as a specific target value of the Energy Efficiency Operational Indicator (EEOI). Regardless of their form, the objectives should be measurable and easy to understand. **Monitoring** the ship's energy efficiency, described in the document as one of the key elements of the plan, should be conducted quantitatively using an established and preferably internationally recognized method. One of the main tools for this purpose is the EEOI, which is referenced directly in both the planning and monitoring stages of the SEEMP, providing a quantitative measure of the energy efficiency of a ship and/or fleet in operation. The EEOI can serve as a baseline tool for tracking performance, as it allows for the assessment of actual fuel consumption relative to the transport work performed. (3)(5).

The procedures discussed so far present the **Energy Efficiency Operational Indicator (EEOI)** as one of the key terms defining requirements for ship energy efficiency and the reduction of carbon dioxide emissions from maritime transport. The indicator provides a quantitative measure of a ship's actual operational efficiency, taking into account fuel consumption, cargo carried, and distance sailed. Although the EEOI is not mandatory, it plays a crucial role as a core parameter in ship energy efficiency management procedures. It is used for planning and monitoring within the framework of the SEEMP, providing insight into the practical implementation of measures outlined through **EEDI (technical energy efficiency of new ships)**, **EEXI (energy efficiency of existing ships)**, and **CII (operational carbon intensity)**. In this way, the EEOI serves as a central metric for operational efficiency, complementing and supporting other regulatory and technical energy efficiency requirements. (3)(4)(5).

MEPC.1/Circ.684 provides a simplified definition of the Indicator, namely as the ratio between **the mass of CO<sub>2</sub> emissions (M)** and **the transport work** performed:

$$EEOI = \frac{M_{CO_2}}{\text{transport work}}, \text{ where} \quad (7)$$

**M(CO<sub>2</sub>)** – the mass of carbon dioxide (CO<sub>2</sub>) emitted over a given period,

**Transport work** – the product of **the cargo carried (in tonnes)** and **the distance sailed (in nautical miles)**.

This indicates the amount of CO<sub>2</sub> emissions per unit of transport work performed and serves as a quantitative tool for assessing the ship's energy efficiency. (3)(14).

Expressed in formula form, the Energy Efficiency Operational Indicator (EEOI) is presented in the Annex to MEPC.1/Circ.684. This provides guidance for calculating the EEOI based on actual ship operational data. Key data sources can include the ship's logbook, engine logbook, and other official records. These data allow for accurate tracking of fuel consumption, cargo carried, and distance sailed, which are necessary for quantitatively determining the ship's operational energy efficiency using the EEOI.

Formulas for Calculating the EEOI (3)(14):

1) For calculating the EEOI for a single voyage:

$$EEOI = \frac{\sum_j FC_j \cdot CF_j}{M_{\text{cargo}} \cdot D} \quad (8)$$

2) For calculating the average value of the Indicator over a specific period or a number of voyages:

$$\text{Average EEOI} = \frac{\sum_{i,j} FC_{ij} \cdot CF_j}{m_{cargoi} \cdot D_i} \quad (9)$$

where:

- **j** – type of fuel oil;
- **i** – number of voyages;
- **FC ij** – the weight of fuel oil consumption **j** for a voyage **i**;
- **CFj** – specific coefficient accounting the ratio between the weight of fuel oil over the weight of emitted CO<sub>2</sub> due to burning of the relevant weight of fuel oil **j**;
- **m cargo** – the mass of cargo carried (in tonnes) or transport work performed (number of TEUs or number of passengers) or GT of the passenger vessels;
- **D** – the distance sailed (in nautical miles) for the period of transporting the cargo (TEUs or passengers).

The unit of the EEOI depends on the measure of cargo carried or transport work performed – tonnes CO<sub>2</sub>/(tonnes • nautical miles), tonnes CO<sub>2</sub>/(TEU • nautical miles), tonnes CO<sub>2</sub>/(person • nautical miles), etc.

It should be noted that the second equation does not represent a simple arithmetic average of the EEOI for individual voyages (**i**). It means, the overall EEOI for a given period (a year for example) is not calculated as a simple arithmetic average of the EEOI for each individual voyage. Instead, the total CO<sub>2</sub> emissions for all voyages are summed and divided by the total transport work performed during the same period.

**CF** is a dimensionless conversion factor that links fuel consumption, measured in grams, to CO<sub>2</sub> emissions, also measured in grams, based on the carbon content of the fuel. The value of CF depends on the type of fuel and indicates how many grams of CO<sub>2</sub> are produced from the combustion of one gram of fuel. This coefficient is essential for calculating the EEOI, as it converts actual fuel consumption into the amount of CO<sub>2</sub> emitted, which forms the basis of the operational energy efficiency indicator. It should also be noted that the chemical composition of the fuel varies in carbon content, which affects the relationship between fuel consumption and CO<sub>2</sub> mass. CF values differ for different types of marine fuels. Additionally, international regulations impose limits on fuel content depending on the area in which a ship is operating. (3)(14). See fig. 3

| Type of fuel                     | Reference                       | Carbon content | C <sub>F</sub><br>(t-CO <sub>2</sub> /t-Fuel) |
|----------------------------------|---------------------------------|----------------|-----------------------------------------------|
| 1. Diesel/Gas Oil                | ISO 8217 Grades DMX through DMC | 0.875          | 3.206000                                      |
| 2. Light Fuel Oil (LFO)          | ISO 8217 Grades RMA through RMD | 0.86           | 3.151040                                      |
| 3. Heavy Fuel Oil (HFO)          | ISO 8217 Grades RME through RMK | 0.85           | 3.114400                                      |
| 4. Liquified Petroleum Gas (LPG) | Propane                         | 0.819          | 3.000000                                      |
|                                  | Butane                          | 0.827          | 3.030000                                      |
| 5. Liquified Natural Gas (LNG)   |                                 | 0.75           | 2.750000                                      |

Fig. 3 Table of Carbon Content for Different Fuel Types. (3).

In conclusion, the introduction of the **Energy Efficiency Operational Indicator (EEOI)**, developed by the International Maritime Organization (IMO), represents an important step toward improving energy

efficiency and reducing emissions in maritime transport. Although established as a voluntary tool, its implementation provides significant benefits for shipping companies, individual vessels, and the global shipping industry as a whole. The indicator allows for the quantitative measurement of CO<sub>2</sub> emissions per unit of transport work, providing a foundation for analysis, optimization, and sustainable management of ship operations.

#### **4. Interconnection between the Ship's Energy Efficiency Operational Indicator (EEOI) and Propeller Slip – A Mathematical Model of the Relationship**

Propeller slip is a key operational parameter that characterizes the efficiency of converting the rotational motion of the propulsion system into useful thrust and the ship's forward motion. It is defined as the difference between the theoretical advance of the propeller per revolution and the actual advance of the ship in the water. The causes of slip include hydrodynamic losses, turbulence, and interaction between the hull and the propeller, while hull resistance and operational conditions must also be considered. Therefore, slip is regarded as an integral indicator of propulsion system efficiency, reflecting the forces acting during the ship's forward motion and the hydrodynamic characteristics of the vessel. An increase in slip leads to a reduction in the main engine's propulsive efficiency, meaning lower propulsion performance. To maintain the same speed with higher slip, more power is required, which results in increased fuel consumption. The main engine's efficiency depends on the efficiencies of the hull, propeller, and their interaction; thus, any increase in slip reduces the overall energy efficiency of the ship. In this sense, slip serves as an indicator of losses in the propulsion system, manifested through increased required power and higher fuel consumption. (1)(11)(13).

An increase in propeller slip can be caused by various factors, such as hull fouling, adverse meteorological conditions, improper matching between the main engine and the propeller, and deviations in the ship's course. All of these circumstances lead to an increase in hull resistance, which requires greater thrust from the propeller and, consequently, results in a higher value of this parameter. This means that slip can be used as an operational indicator for assessing the condition of the propulsion system and for monitoring changes in the ship's energy efficiency under different operational conditions. (1)(13).

The EEOI (Energy Efficiency Operational Indicator) was developed by the International Maritime Organization as a tool for assessing a ship's energy efficiency during operation. It represents the ratio between carbon dioxide emissions and the transport work performed, thereby reflecting the efficiency of fuel use during the ship's operation. The indicator is used as part of an energy efficiency management system, which aims to assist ship operators in optimizing operational modes and reducing greenhouse gas emissions. EEOI takes into account the influence of multiple factors, including the ship's speed, cargo load, fuel consumption, and distance traveled. This means that any change in the operational parameters of the propulsion system, including propeller slip, can affect the indicator's value. Lower EEOI values indicate better energy efficiency, while an increase in the indicator signifies a decline in the ship's operational efficiency. (3)(5)(6)(7).

The relationship between propeller slip and the operational indicator manifests through the effect of slip on the ship's speed and fuel consumption. As slip increases, the efficiency of the propeller decreases, which necessitates more power to maintain the same speed. This leads to higher fuel consumption and, consequently, increased carbon dioxide emissions. At the same time, increased slip can reduce the ship's actual speed, decreasing the distance traveled over a given period. As a result, the EEOI value rises, indicating a deterioration in energy efficiency. (1)(6)(13).

Therefore, the relationship between the operational indicator and propeller slip can be considered as the consequence of functional dependencies related to fuel consumption, ship speed, and the effective operation of the propeller. These parameters are reflected in the energy efficiency of the main engine and the overall

propulsion system, taking into account the propeller shaft torque and the slip itself. From this, the following functional dependencies can be derived:

**Fuel consumption = f (slip)**

**Vessel's Speed = f (slip)**

**EEOI = f (Fuel consumption, vessel's speed)**

Therefore, **EEOI = f(slip)**, that is, the operational energy efficiency indicator of the ship, under certain dependencies, is a function of the propeller slip. In this way, the indirect relationship between the two parameters is demonstrated, which aids in the early detection of deterioration in operational performance. While EEOI provides a summarized assessment of energy efficiency over a given period, slip can be used for real-time monitoring of the propulsion system. Their combined use enables more precise management of the operational modes of the propulsion system, as well as improvement of the ship's overall energy efficiency.

The mathematical model representing the relationship between the propeller slip and the ship's Energy Efficiency Operational Indicator (EEOI) can be presented as follows, taking into account the following sequential steps: (1)(6)(10)(11)(13):

### 1) Slip of ship's propeller

From formula (4) it follows that:  $Slip = \frac{p.n - V}{p.n} = 1 - \frac{V}{p.n}$  then:

$$V = (1 - Slip). p.n \quad (10)$$

### 2) Distance sailed

$$S = V.T \quad (11)$$

$$S = (1 - Slip). p.n. T \quad (12)$$

T – time as a period of sailing (in minutes or hours);

### 3) Power calculated from Torque

$$P = 2\pi n. Q \quad (13) \quad , \text{ where:}$$

P – power of the propulsion;

Q – magnitude of torque (quantity).

### 4) Fuel Oil Consumption

$$FC = SFOC. P. T \quad (14) \quad , \text{ upon substitution, it follows:}$$

$$FC = SFOC. 2\pi n. Q. T \quad (15) \quad , \text{ where:}$$

FC – Fuel Consumption;

SFOC – Specific Fuel Oil Consumption.

### 5) EEOI – Energy Efficiency Operational Indicator

$$EEOI = \frac{FC.CF}{Mcargo.S} \quad (16) \quad , \text{ upon substitution, it follows:}$$

$$EEOI = \frac{SFOC. 2\pi n. Q. T.CF}{Mcargo.(1-Slip). p.n. T} \quad (17) \quad , \text{ upon cancelling of n and T, it follows:}$$

$$EEOI = \frac{2\pi.SFOC.Q.CF}{Mcargo.(1-Slip).p} \quad (18)$$

Formula (18) expresses the relationship between EEOI and slip (Slip), showing how changes in slip affect the value of the operational energy efficiency indicator. Consequently, the following dependence can be established:

$$EEOI \sim \frac{Q}{(1-Slip)} \quad (19)$$

Formula (19) expresses the direct dependence of EEOI on the propeller slip (**Slip**). It follows that an increase in propeller slip leads to a corresponding increase in the ship's Energy Efficiency Operational Indicator during operation.

The obtained relationship shows that slip and torque are two key parameters determining a ship's energy efficiency. As slip increases, the efficiency of power conversion decreases, which leads to a higher required torque and, consequently, increased fuel consumption. This results in a higher EEOI value and a deterioration of energy efficiency. This relationship is particularly valuable because slip (**Slip**) can be easily measured as a percentage, torque (**Torque**) is automatically obtained from instruments, and the operational indicator (**EEOI**) is calculated using the provided formulas and relationships. *Therefore, slip can be used as an early indicator of deteriorating energy efficiency.*

## 5. Conclusion and Findings

The energy efficiency of a ship's propulsion system is of critical importance for the modern commercial shipping fleet, considering both its economic and environmental aspects. In the context of increasing international requirements for reducing greenhouse gas emissions and optimizing fuel consumption, analyzing operational parameters that affect the ship's performance is particularly important. In this regard, propeller slip (**Slip**) and the Energy Efficiency Operational Indicator (**EEOI**) play a significant role, as they provide both meaningful and interrelated information on the efficiency of the propulsion system, both in the short term and over the long term.

Propeller slip represents an important operational parameter that characterizes the efficiency of converting the rotational motion of the propeller into useful thrust. It is defined as the difference between the theoretical advance of the propeller in a rigid medium and the actual movement of the ship in a water environment. As a result, part of the energy transmitted from the engine to the propeller is lost due to water acceleration, turbulence, and hydrodynamic losses. Consequently, the actual speed of the ship is lower than the theoretical speed, resulting in the occurrence of slip. An increase in this parameter reduces the efficiency of the propulsion system, as maintaining a given speed requires higher power from the main engine. This leads to an increase in torque, higher engine load, and increased fuel consumption. In this context, propeller slip serves as a direct indicator of emerging issues in the operation of the propulsion system, including hull fouling, propeller damage or contamination, adverse meteorological conditions, increased hull resistance, or improper coordination between the engine and propeller. (1)(10)(13).

On the other hand, the Energy Efficiency Operational Indicator (EEOI) represents an integrated parameter used to assess the energy efficiency of a ship under actual operational conditions. This indicator is based on the ratio between fuel consumption, carbon dioxide emissions, and the transport work performed, allowing a quantitative evaluation of the ship's efficiency over a given period. The EEOI was introduced by the International Maritime Organization as part of measures to reduce emissions and improve the energy efficiency of ships and is directly linked to the implementation and application of the ship's Energy Efficiency Management Plan (SEEMP). (4)(5)(6)(7).

A key feature of these two indicators is their interrelationship through the ship's speed, fuel consumption, and required power. An increase in propeller slip leads to a reduction in the effective speed of the ship at a given propeller rotation rate. To maintain the desired speed, the engine must increase power output, resulting in higher fuel consumption. Increased fuel consumption, in turn, raises the EEOI value, indicating a decline in the ship's energy efficiency. Therefore, slip can be considered an operational indicator of future changes in EEOI and an early warning of reduced propulsion system efficiency. The practical significance of these indicators is particularly relevant for the two primary crew members in management positions – the ship's captain and the chief engineer. From an engineering perspective, the chief engineer uses slip as an indicator of the technical condition of the propulsion system. Sudden changes in its value may signal increased hull resistance, fouling, propeller damage, engine issues, or deviations in operating conditions. This allows for timely technical measures, such as hull cleaning, propeller polishing, optimization of operating regimes, or preventive maintenance. Meanwhile, the captain utilizes slip information to optimize navigational decisions. Under adverse weather conditions, heavy seas, or headwind navigation, slip increases, leading to higher fuel consumption. In such situations, the captain may alter the course, reduce speed, or select a more efficient route to optimize energy efficiency. The EEOI provides more aggregated information and is used to evaluate operational efficiency over a defined period. The chief engineer uses this indicator to assess the technical condition of the engine, propeller, and hull, while the captain applies EEOI for analyzing the effectiveness of chosen sailing regimes, including optimal economical speed for the voyage (slow steaming), course deviations, and route selection, taking into account local meteorological conditions and navigational characteristics. Thus, the combined use of slip and EEOI provides a comprehensive view of the ship's energy efficiency. Slip delivers real-time operational information, while EEOI offers a long-term assessment of efficiency. This approach enables not only the identification of potential problems but also the optimization of operating regimes and reduction of fuel consumption, allowing the ship's command team to make informed managerial decisions for effective economic and environmental measures concerning the optimal loading and operation of the propulsion system.

Based on the conducted analysis, the following key conclusions can be drawn:

- 1) Propeller slip represents an important operational parameter that directly affects the efficiency of the propulsion system and fuel consumption.
- 2) The EEOI operational indicator is an integral measure that enables a quantitative assessment of the ship's energy efficiency under actual operational conditions.
- 3) There is a direct interrelation between propeller slip and EEOI through the ship's speed, fuel consumption, and required engine power.
- 4) Propeller slip can be used as an early indicator of deteriorating energy efficiency, which subsequently reflects on the EEOI values.
- 5) The combined use of propeller slip and EEOI allows for more effective management of the propulsion system and improvement of energy efficiency, supporting the ship's command team in making accurate and timely decisions.

The present analysis shows that propeller slip and the operational indicator provide valuable information about the ship's energy efficiency. However, there are also other parameters that may be the subject of future research in order to achieve a more comprehensive assessment of propulsion system efficiency, both independently and in interaction and integration with EEOI under the respective operating conditions.

Among these, the following aspects may be considered:

- 1) The influence of hull resistance and fouling on energy efficiency;

- 2) The impact of autopilot operation and rudder deviations on fuel consumption;
- 3) Optimization of main engine operating modes;
- 4) The influence of meteorological conditions on voyage energy efficiency;
- 5) Analysis of the impact of propeller response on energy efficiency under different loading conditions;
- 6) The influence of heel and trim on energy efficiency.

Further research in these areas would enable the development of an integrated energy efficiency monitoring system to support decision-making by both the ship's captain and the chief engineer. This would lead to more efficient ship operation, reduced fuel consumption, and lower harmful emissions, in line with modern requirements for the sustainable development of maritime transport.

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