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DEVELOPMENT OF BALLAST-FREE LOGISTICS MARITIME TRANSPORTATION IN ORDER TO REDUCE THE CONSUMPTION OF SHIP FUEL AND REDUCE CARBON DIOXIDE EMISSIONS – THE MAIN COMPONENT OF THE "GREENHOUSE" EFFECT ON THE PLANET

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INTRODUCTION

Until recently, sea freight transportation was carried out on the principle of delivering cargo to the customer in ahort time, not paying attention to the consumption of ship fuel and pollution of the marine environment. Recently, the International Maritime Organization (IMO) adopted Resolutions aimed at reducing the consumption of marine fuel, carbon dioxide emissions – the main component of "greenhouse" gases, reducing emissions of sulfur compounds from exhaust gases of ship power plants. Research and experimental work is being actively carried out for the purification of exhaust gases from ship power plants, which can be divided into two areas:

1) scrubber cleaning;
2) catalytic neutralization, as well as catalytic purification in combination with the utilization of heat from the exhaust gases of the SPP. Under the conditions of aong transoceanic passage of the Steinhoft container ship, a parametric relationship was established between the ship's Operational Energy Efficiency Index (EEOI) and the speed, mass of the transported cargo, and the crossing distance. Subsequently, the range of ships was significantly expanded and it was shown that, regardless of the types of ships, the EEOI, depending on the speed, weight of the cargo, and the transition distance, is described by the same patterns.

However, so far there is nouch important aspect in the literature as determining the minimum value of the operating coefficient of the vessel's energy efficiency while changing the parameters of the transition – the speed of the vessel, the mass of the transported cargo, the distance of the transition, hydrometeorological conditions.

We have established for the first time that the EEOI, depending on the speed of the vessel, has four zones: the first zone from 0.01 to 0.08 knots – the value of EEOI increases, the second zone from 0.08 to 1.8 knots – passes through a maximum, the third zone from 1.8 to 21 knots – the value of EEOI decreases, and most sharply decreases in the region of 1.8–7.0 knots, the fourth zone in the region from 21–27 knots and above there is aharp increase in the value of EEOI. The dependence of OKIES on the mass of cargo at constant values of the speed of the vessel and the distance of the sea passage can be described by hyperbole. With an increase in the mass of the transported cargo within 7,000–18,000 m.t. the values of EEOI tend to the value of the Ship Energy Efficiency Design Index (EEDI), and with the values of the mass of the cargo approaching zero, the values of EEOI tend to infinity. This means that in maritime practice it ismpossible to allow underloading (up to the values of permissible design loads) of sea vessels in the implementation of maritime cargo transportation.

The distance of the sea passage does not affect the value of EEOI.

According to apecially developed methodology, according to the data of our studies, the area of minimization of the EEOI was established.

The purpose of this work is toevelop the optimal logistics of sea freight, completely excluding ballast sea freight. This condition must be met by new designs of multi-purpose wide profile vessels capable of simultaneously transporting cargo in any state of aggregation – liquid, solid, gaseous, as well as equipment, transport vehicles, special apparatus for chemical, petrochemical, agricultural purposes.

1. Substantiation of environmental safety, economic efficiency, resource saving of ballast-free sea freight. Methods and Materials

A real transition in the Atlantic and Pacific Ocean in North and South America is considered: Miami, USA – Manzanillo, Panama – Guayaquil, Ecuador – Callao, Peru – Guayaquil, Ecuador – Manzanillo, Panama – Miami, USA[1].

The characteristics of the vessel are given in table 1.

Vessel speed and sea passage distance were measured using a Naviknot 400 Type 4718-DA doppler log. The volume of marine fuel loaded during bunkering was determined using flow meters, and the fuel consumption for a specific passage was determined by changing the level of marine fuel in the tank.

[1] Леонов В. Е. Исследования по определению области минимизации операционного коэффициента энергетической эффективности судна. *Вестник государственного университета морского и речного флота имени адмирала С. О. Макарова.* 2019. Т. 11, № 5(57). С. 910–919. DOI: 10.21821/2309-5180-2019-11-5-910-919.

Table 1

Characteristics of the vessel "Warnow Dolphin"

VESSEL'S NAME	Warnow Dolphin
FLAG	CYPRUS
PORT OF REGISTRY	LIMASSOL CYPRUS
CALL SIGN	5BTW3
OFFICIAL NO.	9395070
IMO NO.	9395070
CLASSIFICATION	GERMAN LLOYD (GL NO. 111774)
CLASS	GL 100 A5 E Container Ship, NAV-O,
SHIPOWNER	MARLOW SHIPMANAGMENT
YEAR OF BUILT	2007 Zhoushan, China
ENGINE RATED POWER	11200 kW
MAIN ENGINE TYPE	MAN B&W
PROPELLER	Controllable Pitch Propeller
SERVICE SPEED	19,4 knots.
TYPE of FUEL	IFO 380\ M 60
DISPLACEMENT	25252.7 metric tons
DEADWEIGHT	18,275.5metric tons
GROSS TONNAGE	15,375 GRT
NET TONNAGE	5983 GRT
WATER BALLAST	Total capacity 6070 m^3
LENGTH OVERALL	166.15 meters (LBP- 155.08 meters)
LENGTH FROM BOW TO BRIDGE	146.6 meters
LENGTH FROM BRIDGE TO STERN	19.5 meters
TYPE of VESSEL	CONTAINER VESSEL
CREW MEMBERS	21
MOULDED BREADTH	25.00 meters
MOULDED DEPTH	14.2 meters
MAX. DRAFT	9.5 meters

Results

The change in the speed of the ship and, accordingly, the consumption of ship fuel, depending on the share of the used power of the ship power plant (SPP) is shown in Figure 1.

According to IMO Resolution MEPC 65/INF[2], the main criterion for reducing ship fuel consumption and carbon dioxide emissions is the Ship Operating Energy Efficiency Index (EEOI), which is determined by the ratio of the mass of carbon dioxide emissions – the main component of "greenhouse" gases – formed during fuel combustion for the transition, to the distance of the transition and the mass of the transported cargo.

Calculations of the values of EEOI were carried out according to the developed program on aomputer. Computational studies were carried out in aide range of parameters of the sea passage – the distance of the passage in the range from 1,200 to 3,000 N. M., the speed of the vessel from 0.01 to 1.0 knots and from 1.0 to 27.0 knots (in different speed scales according to abscissa axis), cargo weight ranging from 1,200 to 20,000 m.t.

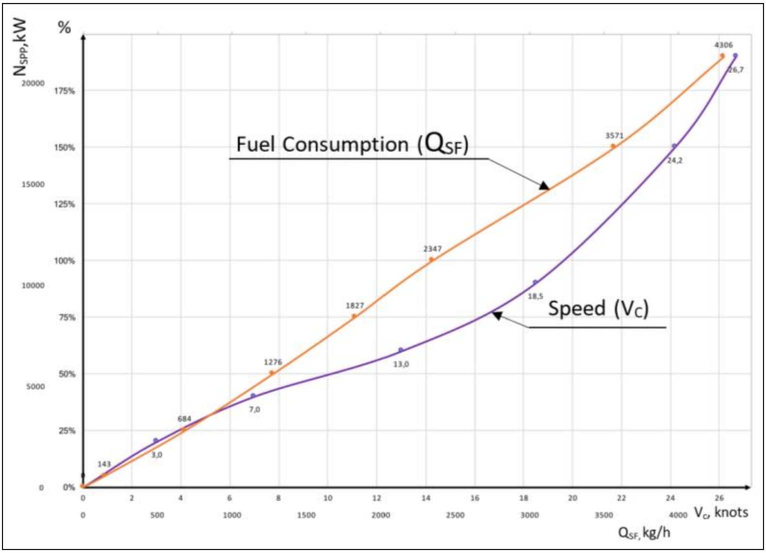

Fig. 1. Change in ship speed and ship fuel consumption depending on the share of power plant used

According to the dependence presented in Figure 1, at any speeds of the vessel, the share of the used power of the SPP and the consumption of ship fuel under these conditions, which was used in the calculations of the EEOI, were determined. The Design Energy Efficiency Index of the Vessel (EEDI)

[2] MEPC 65/INF.17 IMO Model Course on Energy-Efficient Operation of Ships. – London: World Maritime University, 2013. 61 p.

was determined by the equation: EEDI = (1 – X/100) × a × b^{-C} given in work[3].

Computational studies have established that a change in the distance of aea passage at constant vessel speed and cargo mass does not affect the value of the EEOI.

The dependence of the EEOI on the speed of the vessel and the mass of the transported cargo is shown in Figures 2 (the mass of the cargo increased from 0 to 20,000 mt along the abscissa axis), 3 (the mass of the cargo decreased from 20,000 to 0 mt along the abscissa axis). In order to trace the nature of the dependence of the EEOI on the speed of the vessel, we adopted a fairly wide range from 1.0 to 27.0 knots, and even a range from 0.01 to 0.09 knots, unrealistic for marine navigation practice, with these calculations, the transition distance and the mass of the cargo remained permanent. With an increase in the ship's speed from 0.01 to 1.0 knots and from 1.0 to 27.0 knots, we have defined four zones: the first zone from 0.01 to 0.08 knots, the value of the EEOI increases, the second zone from 0.08 to 1, 8 knots – passes through a maximum, the third zone from 1.8 to 21 knots, the value of EEOI decreases, and it decreases most sharply in the region of 1.8–7.0 knots, the fourth zone in the region from 21–27 knots and above there is aharp increase values of EEOI.

The dependence of the EEOI on the mass of the cargo at constant values of the speed of the ship and the distance of the sea passage can be described by ayperbole (Fig. 2, 3). At the maximum masses of the transported cargo (7,000–18,000 m.t.), the values of the EEOI tend to the value of the EEDI, and with the values of the mass of cargo approaching zero, the values of the EEDI tend to infinity. Based on the data given in Figures 2, 3 and additional calculations of the EEOI with the missing parameters for the speed and mass of the load, the dependencies of the total values of the EEOI were constructed with a simultaneous change in the speed and mass of the load (Fig. 4).

The values of the points of curves 2 and 3 (Fig. 4) are the sum of the EEOI, depending separately on the speed of the vessel and separately on the mass of the transported cargo – curve 2 when the mass of the cargo changes from zero to 19,000 mt (from right to left), and curve 3 from zero to 19,000 mt (from left to right). The above sum does not include EEOI depending on the transition distance, since it was found above that the distance of the transition does not affect the value of EEOI. At the point A of the

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[3] Леонов В. Е., Дмитриев В. И., Безбах О. М., Гуров А. А., Сыс В. Б., Ходаковский В. Ф. Современные информационные технологии обеспечения безопасности судоходства и их комплексное использование: Монография / под ред. проф. В. Е. Леонова. Херсон : ИЦ ХГМА, 2014. 324 с.

intersection of curves 2,3, the minimum value of the OKEES is determined, which characterizes a specific sea passage for the adopted ship design and the parameters of the sea passage. For the practical use of the results obtained by minimizing the EEOI, the minimization zone along the abscissa for the mass of the cargo (from left to right and vice versa, from right to left) was expanded by 22.2 % from point A (to the right and left), as aesult of which the area of minimization of the EEOI was obtained for of apecific sea passage studied (Fig. 4, shaded area).

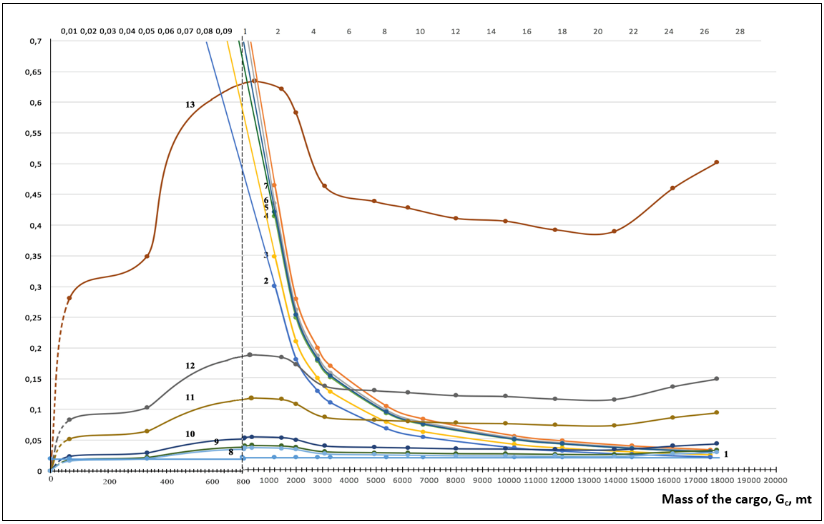

Fig. 2. Dependence of EEOI on vessel speed, knots: curves 2 – 1.6; 3 – 5.2; 4 – 8.2; 5 – 18.0; 6 – 24.0; 7 – 26.9 (knots) and mass of the transported cargo, m.t.: curves 8 – 18 000; 9 – 16 000; 10 – 12 000; 11 – 5420; 12 – 3400; 13 – 1 000. Line 1-EEDI

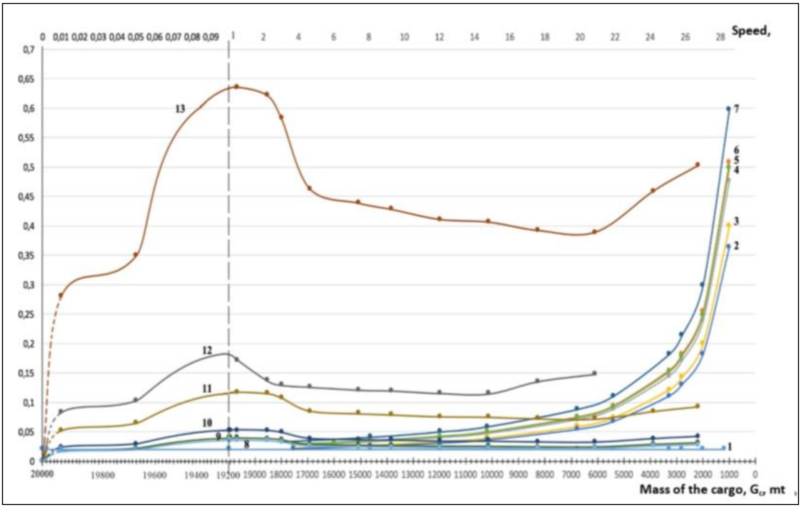

Fig. 3. Dependence of EEOI on vessel speed, knots: curves 2 – 2.5; 3 – 6.1; 4 – 12; 5 – 22; 6 – 24.5; 7 – 28.2 (knots) and mass of the transported cargo, m.t.: curves 8 – 18 000; 9 – 16 000; 10 – 12 000; 11 – 5420; 12 – 3400; 13 – 1 000. Line 1-EEDI.

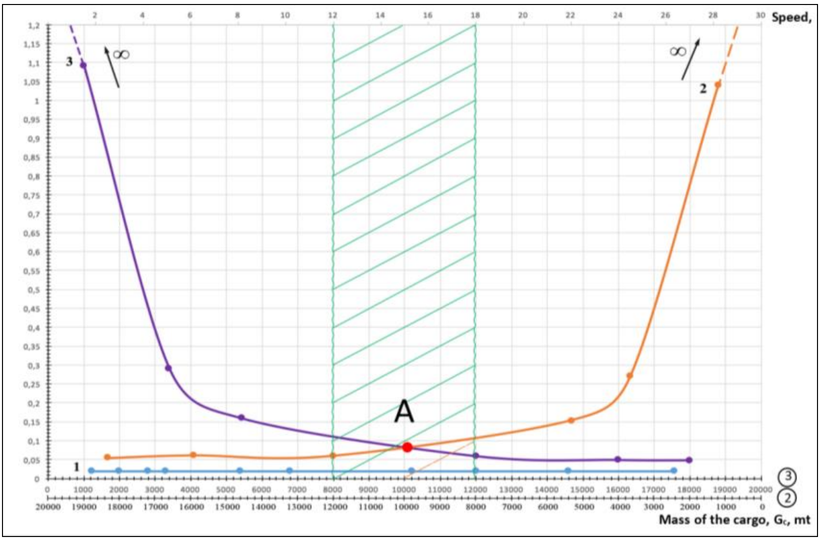

Fig. 4. Minimization area of the EEOI. Line 1-EEDI

Discussion

As a practical recommendation based on the results of the studies performed, the parameters of the sea passage were established, at which the minimum values of EEOI are achieved, namely: the speed of the vessel should be within 12–18 knots, the mass of the transported cargo should be within 8,000–12,000 m.t. (Fig. 4).

On the basis of the conducted research, an important conclusion follows – in marine practice, ballast passages should not be allowed, since with the mass of the cargo tending to zero, the value of the EEOI tends to infinity (∞), and this has an extremely negative effect on the economic and environmental indicators of the sea passage (?).

In the scientific and technical literature, there is extremely limited information about complex vessels capable of sea transportation of cargoes of various physical and chemical properties. Let's dwell on some of them.

The work[4] describes the vessel "OBO–Oil–Bulk–Ore cargo vessel". This is apecial design of ships designed for the carriage of goods in liquid and dry states. OBO type vessels are more flexible than single-purpose vessels, and meet market conditions and increase the profits of sea freight.

OBO ships were most popular in 1955–1980. The largest vessel for the above period is M/V Derbyshire 180,000 dwt. The operation of these vessels for 25 years brought profit to the maritime industry and they certainly fulfilled their role as annnovative technical solution for that period of time. Over time, the shortcomings of these vessels became more and more noticeable, especially in the face of aharp increase in the scale and tonnage of sea freight. As aesult, OBO-type vessels have become unpopular and there are currently a small number of such vessels in the navy.

The article[5] describes the vessel "PROBO carrier–Product–Ore–Bulk-Oil". "PROBO carrier–Product–Ore-Bulk–Oil" with a deadweight of 49,000 m.t. was the first ship built in 1985 by the South Korean company "Hyundai" by order of the Norwegian shipping company. "PROBO carrier - Product–Ore–Bulk–Oil" was an integral complex that includes an automation system, computer equipment and satellite navigation systems. These vessels were designed to carry a wide range of cargoes such as crude oil, refined and crude products, wheat, coal, aluminum, cement, grain, caustic soda, timber, containers, as well as over seven types of liquid cargoes. The main characteristics of these vessels are: length 182.8 m, length between perpendiculars 175 m, beam 31.95 m, deadweight 49,070 mt, draft

[4] Anand N. Van Duin. JHR. Ontology based multi-agent system for urban freight transportation. *International Journal of urban sciences*. 2014. Vol. 18. P. 133–153.

[5] Bhusiri S. Qureshi A.G/ Taniguchi E/ The trade of between fixed vehicle costs and time-dependent arrival in aouting problem. *Transportation Research*. 2014. P. 12–22.

13.09 m, carrying capacity – for granular materials 50,940 m^3, for crude oil – 51,935 m^3, 954 TEUs. The vessel is equipped with a 12,800 HP Hyundai B and W L80 MCE main engine. at arankshaft speed of 83 min^{-1}, the design service speed of the vessel is 15.3 knots with a power plant of 10,880 HP.

Taking into account the IMO requirements for reducing the consumption of marine fuel, the economic efficiency of maritime cargo transportation is achieved, and in parallel, the environmental one is the reduction of carbon dioxide emissions. Suggested recommendations are:

1) on existing ships – 1.1) determine and ensure the minimum values of the EEOI of maritime cargo transportation; 1.2) exclude ballast sea passages;

2) to prepare the technical and economic bases for the development of multi-purpose, multi-purpose vessels and their implementation in the fleet.

It is difficult to solve clause 1.2 on tankers and chemical-gas carriers), however, we have worked out the issue in relation to the tanker fleet in terms of the implementation of oncoming sea cargo transportation: “oil, oil products ↔ natural fresh water” for regions that, on the one hand, have significant reserves hydrocarbon raw materials, and on the other hand, experiencing a significant shortage in natural fresh water[6].

In[7], the range of ship types was significantly expanded and it was shown that, regardless of the types of ships, the EEOI, depending on the speed, cargo weight and distance of the transition, is described by the same patterns.

A real transition was considered, which was carried out along the route: Algeciras, Spain (03/10/2020), – Marsaxlokk, Malta (03/13/2020) – Livorno, Italy (03/16/2020) – Genoa, Italy (03/17/2020) – Barcelona, Spain (03/20/2020) – Valencia, Spain (03/22/2020) – Fort-de-France, Martinique (04/01/2020) – Pointe-a-Pitre, Guadeloupe (04/02/2020) – Caucedo, Dominican Republic (04/03/2020) – Cartagena, Colombia (04/06/2020) – Kingston, Jamaica (04/08/2020) – Houston, USA (04/12/2020) – Veracruz, Mexico (04/15/2020) – Manzanillo, Panama (04/21/2020) – Moin, Costa Rica (04/23/2020) – Cartagena, Colombia (04/25/2020) – Algeciras, Spain (05/05/2020). The total transit time is 56 days.

Vessel speed and sea passage distance were measured using a DS-60 Doppler log. The volume of marine fuel loaded during bunkering was

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[6] Леонов В. Е. Пути повышения эффективности морских грузоперевозок. Монография. / В. Е. Леонов, В. И. Дмитриев. М. : МОРКНИГА, 2019. 299 с. С. 248.

[7] Леонов В. Е., Сердюк А. Д. Исследования параметрической связи EEOI судна в условиях реального морского рейса. Научные проблемы водного транспорта. Нижний Новгород : Волжский государственный университет водного транспорта. 2020. Вып. 65. С. 105–116. DOI: https://doi.org/10.37890/jwt.vi65.133

determined using flow meters, and the fuel consumption for a particular crossing was determined by the change in the level of marine fuel in the tank.

The technical characteristics of the vessel and the ship power plant are given in table 2.

Table 2

Characteristics of the vessel and power plant

Vessel name	m/v Katherine
Vessel type	Container Vessel
Port of registration	Majuro, Marshall Islands
Call sign	V7ZU2
Official number	4914
IMO number	9641235
MMSI	538004914
Owner	Ikaros Marine LLc
Manager	Technomar Shipping Inc.
Date of construction	30 April 2013
Total length, м (LOA)	270,07 m
Length between perpendiculars, м (LBP)	258,00 m
Estimated width, м	42,80 m
Estimated depth, м	24,80 m
Maximum draft, м	14,52 m
Maximum surface height, м	61,9 m (with mast tilted: 58,5 m)
Displacement, т	103698 tons
Deadweight, т	80274 tons
Total tonnage, т (GT)	71021 tons
Net tonnage, т (NT)	40452 tons
Classification Society	RINA
Shipbuilding company	Hyundai Samho Heavy Industries Co. Ltd, Korea
Main engine	One (1) Huyndai MAN B&W 8S80ME-C9-2/ 33670 kW at 78 rpm
Bow thruster	2500 kW / 3000 HP
Auxiliary engines	3350 kW, 2850 kW (4) Hyundai Himsen H32/40
Propeller type	Fixed, right handed type
Marine fuel	Marine Diesel Oil (MDO)
Specific fuel consumption	174,15 g/kWh 100 % at shop test
Daily fuel consumption	104 tons / day
Number of crew members	21

Melina S30 brand fuel was used as marine diesel fuel: density at 15 °C – 0.884 kg/l, ignition temperature 260°C, kinematic viscosity at 40 °C – 105.4 cSt.

The studies were carried out according to the methodology given in[8].

Based on the characteristics of the adopted Ship Power Plant (SPP), the parametric dependence of the consumption of marine diesel fuel and ship speed on the share of used power was determined by calculation and analytical method (Fig. 5).

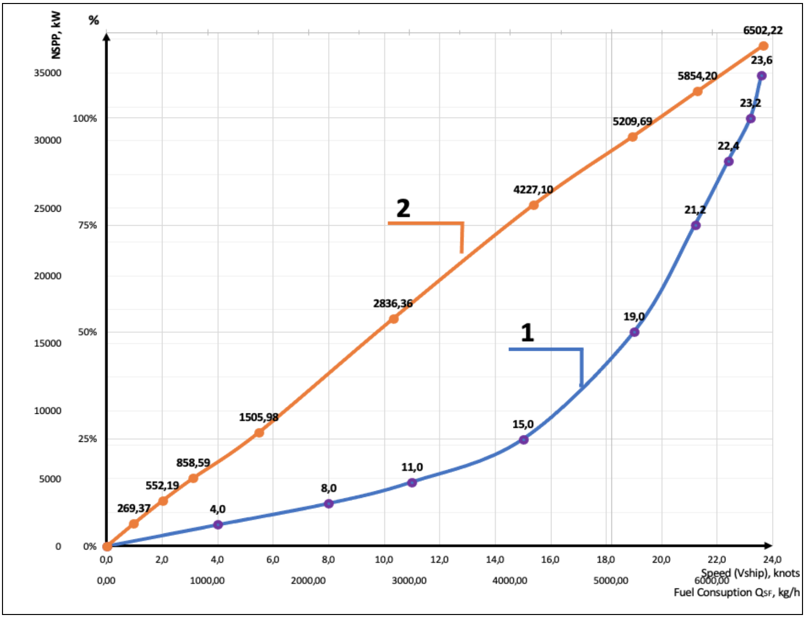

Fig. 5. Variation in vessel speed (curve 1) and ship fuel consumption (curve 2) depending on the share of used power of the SPP.

On the basis of the performed studies, it was found that the distance of the sea crossing has practically no effect on the EEOI (Fig. 6).

The dependence of the EEOI on the mass of the transported cargo is described by hyperbolas (Fig. 7 and Fig. 8).

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[8] Леонов В. Е. Исследования по определению области минимизации операционного коэффициента энергетической эффективности судна. *Вестник государственного университета морского и речного флота имени адмирала С. О. Макарова.* 2019. Т. 11, № 5(57). С. 910–919. DOI: 10.21821/2309-5180-2019-11-5-910-919.

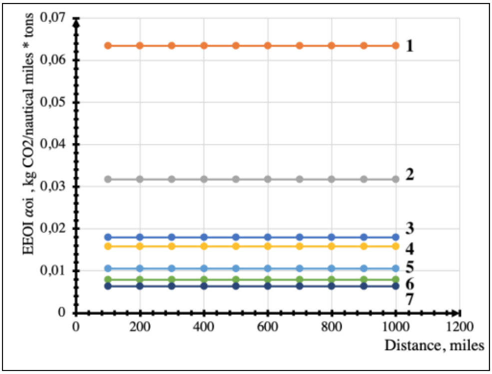

Fig.6. Dependence of EEOI on the transition distance at aessel speed of 14.8 knots and the mass of the transported cargo, t: Line 3 – EEDI

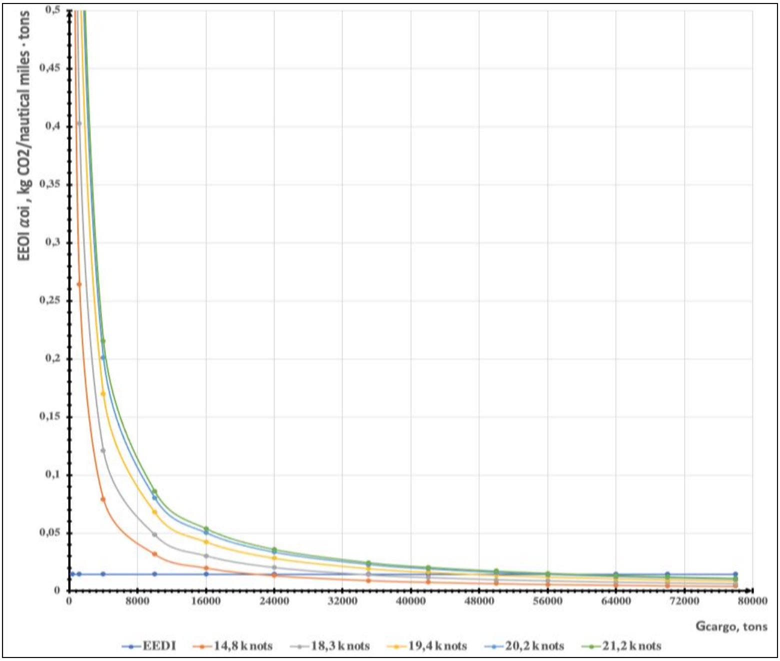

Fig. 7. Dependence of EEOI on the mass of the transported cargo at aessel speed of 14.8 knots, 18.3 knots, 19.4 knots, 20.2 knots, 21.2 knots. Hyperbolas are respectively arranged from bottom to top (direct line – EEDI)

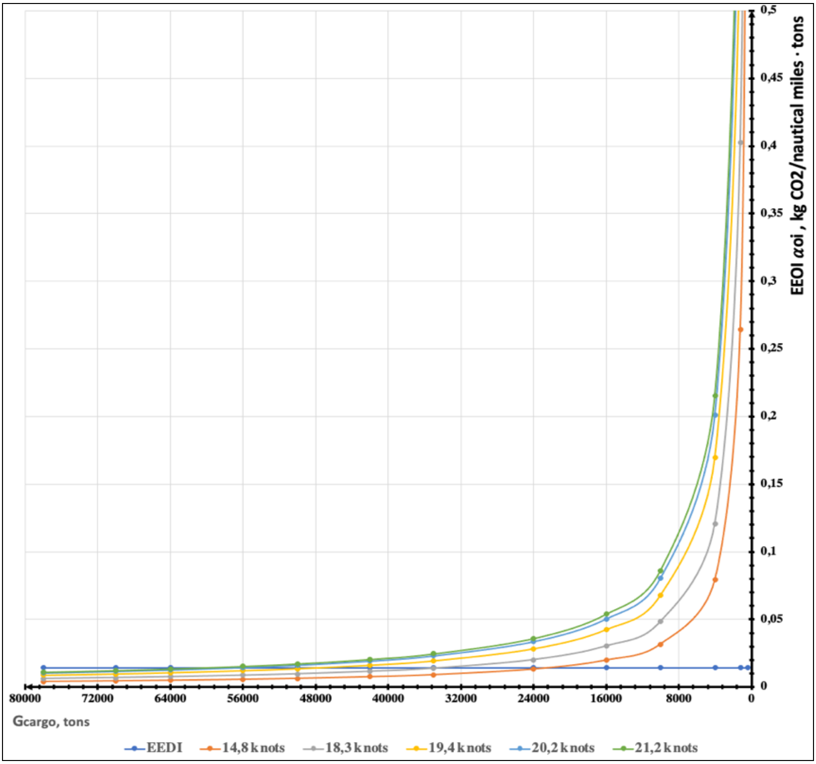

Fig. 8. Dependence of EEOI on the mass of the transported cargo at aessel speed of 14.8 knots, 18.3 knots, 19.4 knots, 20.2 knots, 21.2 knots. Hyperbolas are respectively arranged from bottom to top (direct line – EEDI)

The dependence of the EEOI on the speed of the vessel is described by aomplex dependence with a maximum at 4.5 knots and a minimum at 8.0 knots (Fig. 9).

Dependences of EEOI on the speed of the vessel and the mass of the transported cargo are shown in Figures 10 and fig. 11. In Figure 10, the mass of the transported cargo increased from 0 to 80,000 tons on the abscissa, and in Figure 11, the mass of the transported cargo decreased from 80,000 tons to zero on the abscissa.

To analyze the nature of the dependence of the EEOI on the speed of the vessel, we adopted a wide range of speeds – from 0.01 knots. up to 24.0 knots. With these calculations, the transition distance and the mass of the transported cargo remained constant.

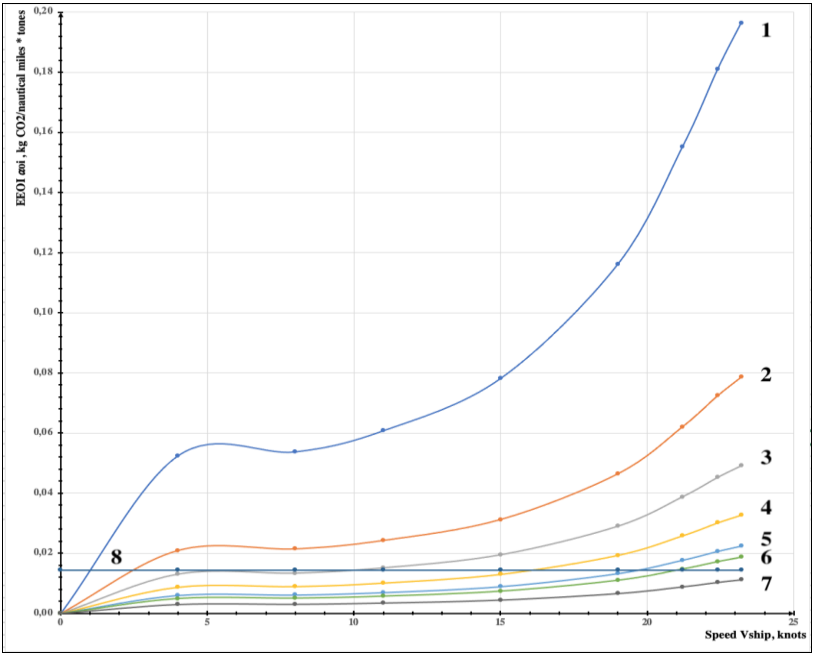

Fig. 9. Dependence of the EEOI on the speed of the ship at aistance of 500 nautical miles and the mass of the transported cargo, t: Line 8 – EEDI

With an increase in the ship's speed from 0.01 knots. up to 24.0 knots four zones have been identified:

1) the first zone – from 0.01 knots. up to 4.0 knots – the value of EEOI increases;

2) the second zone – from 4.0 knots. up to 4.8 knots – the value of EEOI passes through a maximum (speed equal to 4.5 knots);

3) the third zone – from 4.8 knots. up to 8.0 knots – the value of EEOI decreases (EEOI is minimal at apeed of 8.0 knots);

4) the fourth zone – from 8.0 knots. up to 24.0 knots – a sharp increase in EEOI.

The dependence of the EEOI on the mass of the cargo at constant values of the speed of the vessel and the distance of the sea passage is described by hyperbolas (Fig. 10 and Fig. 11). With the maximum weights of the transported cargo (60,000 tons and more), the values of the EEOI tend to the EEDI, and with the values of the weight of the cargo approaching zero, they tend to infinity.

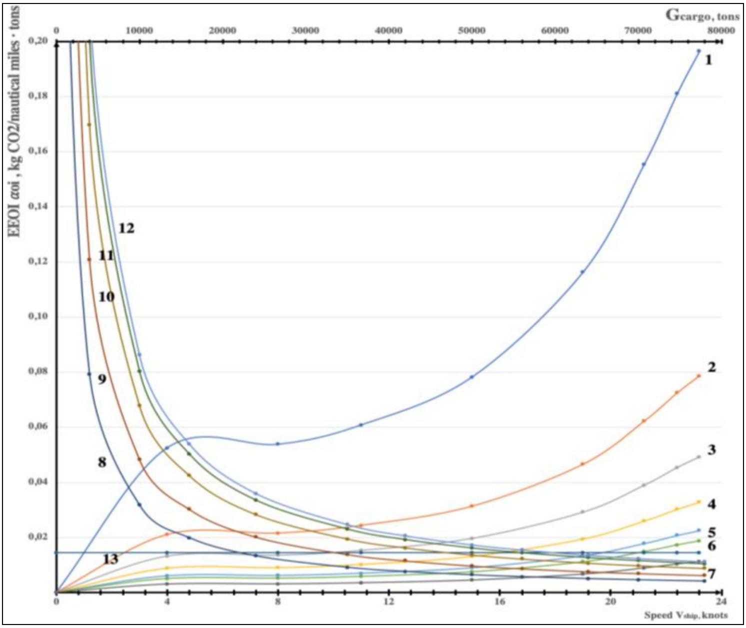

Fig. 10. Dependence of EEOI on vessel speed (curves 1 – 4,000 t, 2 – 10,000 t, 3 – 16,000 t, 4 – 24,000 t, 5 – 35,000 t, 6 – 42,000 t, 7 – 70,000 t) and weight of transported cargo (8 – 14, 8 knots, 9 – 18.3 knots, 10 – 19.4 knots, 11 – 20.2 knots, 12 – 21.2 knots), line 13 – EEDI

Based on the data shown in Figures 10, 11, dependencies were plotted for the total values of the EEOI with a simultaneous change in the speed and mass of the load (Fig. 12).

Intersection point A of lines 2 and 3, shown in Figure 12, characterizes the minimum value of the operational energy efficiency factor of the ship/flight and, accordingly, the minimum ship fuel consumption Gmin, mt, and the minimum carbon dioxide emission of 3.114× Gmin, mt.

According to the methodology given in[9], the zone of minimization of the OKEAS is defined – zone A. As aesult of the analysis and generalization of the experimental data, the following conclusion can be drawn: cargo 48 000–60 000 mt, sea passage distance is not limited.

[9] Леонов В. Е. Исследования по определению области минимизации операционного коэффициента энергетической эффективности судна. *Вестник государственного университета морского и речного флота имени адмирала С. О. Макарова.* 2019. Т. 11, № 5(57). С. 910–919. DOI: 10.21821/2309-5180-2019-11-5-910-919.

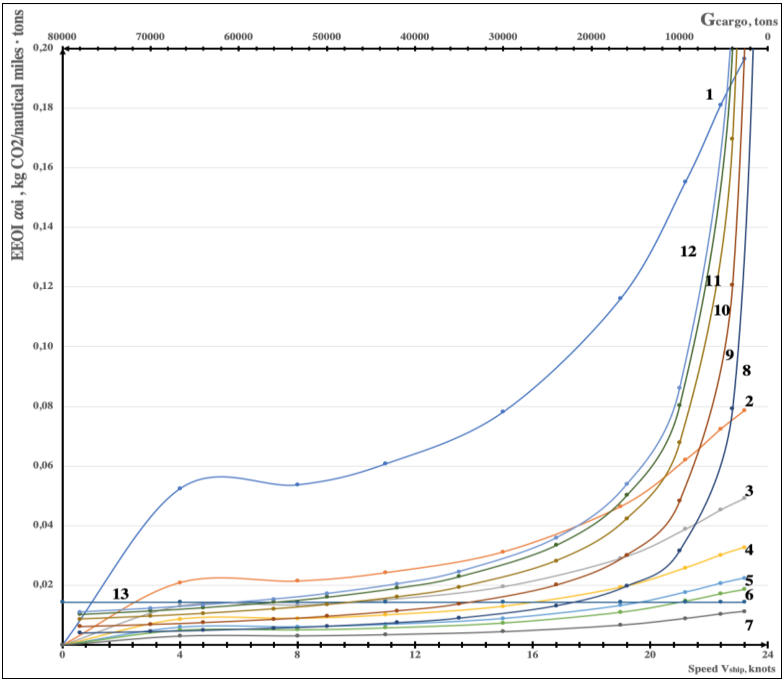

Fig. 11. Dependence of EEOI on vessel speed (curves 1 – 4,000 t, 2 – 10,000 t, 3 – 16,000 t, 4 – 24,000 t, 5 – 35,000 t, 6 – 42,000 t, 7 – 70,000 t) and weight of transported cargo (8 – 14, 8 knots, 9 – 18.3 knots, 10 – 19.4 knots, 11 – 20.2 knots, 12 – 21.2 knots), line 13 – EEDI

Maritime transport, as anntegral part of man-made systems, leads to the following negative consequences:

1) deficiency of natural oxygen contained in the atmospheric air;
2) exhaustion of non-renewable resources of hydrocarbon origin;
3) an increase in the cost of maritime freight transportation;
4) intensive pollution of the marine environment;
5) the rapid development of the planetary “greenhouse” effect.

In [8], for the first time, it was proposed to use synthetic oxygen as anxidizer for ship fuel instead of atmospheric air on board a ship in order to reduce ship fuel consumption and carbon dioxide emissions.

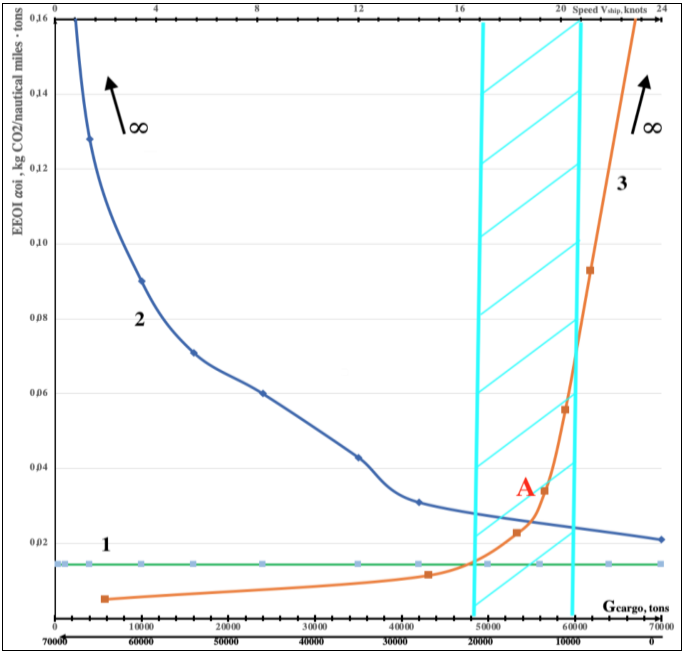

Fig. 12. Minimization area of EEOI (shaded area A)

Thus, if oxygen is used instead of air, then the share of perfect useful work will increase by 25 % and amount to 50 %, while in air it isnly 25 %, i.e. the contribution to the useful work of the SPP will double. In addition, the emission (release) of nitrogen oxides with the exhaust gases of the SPP will be completely excluded.

The task that lies in our proposed new technical solution is asollows:

1) replace the air used in all oxidizing processes, in particular in ship power plants, with oxygen;

2) to create a new technology for producing synthetic oxygen from carbon dioxide and water.

The proposed method is focused on using water (H2O) and/or carbon dioxide (CO_2) as aeedstock for producing oxygen. It should be noted that these products of deep oxidation have a high oxygen content, respectively, in water – 88.8 % wt., in CO_2 – 72.7 % wt., and in atmospheric air only about 21 %[10].

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[10] Леонов В. Е. Использование кислорода в качестве окислителя судового топлива вместо воздуха для судовых энергетических установок / В. Е. Леонов, А. А. Гуров. *Вестник Государственного университета морского и речного флота*

Thus, the main task of the study, the purpose of which is toetermine the area of minimum values of the EEOI of aeal sea crossing, depending on the main parameters that change during this transition, has been solved.

Depending on the speed of the vessel, the mass of the transported cargo, the distance of the passage, the zone of the minimum value of the Operational coefficient of the vessel's energy efficiency is determined. One of the most significant indicators that affect the value of the Operational Energy Efficiency Factor of ahip is the weight of the ship's load and the speed of the ship. When performing empty ballast passages, the value of the ship's Operational Energy Efficiency Factor tends to infinity, which does not meet the requirements of resource saving and, accordingly, leads to increased consumption of ship fuel and high emissions of carbon dioxide, the main component of "greenhouse" gases.

From this follow practical recommendations – to avoid ballast transitions, to achieve the maximum allowable loading of the vessel (not exceeding the design load), to choose the optimal economically justified speed of the vessel.

The main directions for further research can be focused in the following areas:

1) expanding the range of studies of different types of ships and sea crossings;

2) study of the influence of the parameters of hydrometeorological conditions on the change in the EEOI;

3) conducting feasibility studies on the creation of multi-purpose, multi-purpose ships, excluding ballast transitions;

4) complete replacement of atmospheric air with synthetic oxygen;

5) creation of fundamentally new scientific directions for the production of synthetic oxygen using raw materials with a large reserve ratio.

2. Development of logistics routes for ballast-free sea transportation

Since there are ship power plants in navigation, the desire of shipowners and shipbuilders to create economic propulsion is understandable. At the same time, in our century, all kinds of propulsion units available at this stage of development have been tried, starting with a sail, an internal combustion engine and ending with propulsion units powered by atomic energy. It isot possible to analyze the advantages and disadvantages of each type of propulsion within one work. Therefore, we focus on one very important topic: environmental protection.

имени адмирала С. О. Макарова. 2020. Т. 12. No 3. С. 583–590. DOI: 10.21821/2309-5180-2020-12-3-583-590.

Each type of ship brings certain harm to the atmosphere and the ocean, so the world community, and in particular the IMO, is making certain efforts to reduce harmful emissions into the atmosphere and ocean. Within the framework of this work, we will leave in brackets non-transport vessels, such as tugs, supply vessels, technical fleet, etc. since they occupy not a significant part of the fleet.

Let's turn to transport ships. Any shipowner, as already mentioned, tries to reduce fuel costs, including by setting the economic course of the vessel. Moreover, many companies understand this concept in their own way, while pursuing, basically, the final profit.

For example, refrigerated ships and especially banana carriers do not think about fuel consumption at the crossing. The main thing for them is the good speed of the vessel and, accordingly, the timely delivery of cargo to its destination.

The new IMO requirements for the implementation of the SMPEP plan and in particular the implementation of the Ship Operational Energy Efficiency Index (EEOI) and the Ship Energy Efficiency Design Index (EEDI), have created certain difficulties for ships (shipowners). This has already been mentioned above.

One of the positive solutions to these problems is the appointment of aeasonable speed of the vessel, the loading of the vessel and the avoidance of ballast passages, and in the future the renewal of the fleet, a reasonable tonnage and type of ships under construction. Bulk carrier and tanker ships suffer the most from ballast crossings.

If we analyze the volume of traffic by type of cargo, Figure 13, we can conclude

that with a general increase in the amount of cargo transported, the largest amount is transported by chemical cargo, liquid and dry bulk cargo. Such shipments are carried out by specialized vessels (chemical carriers, bulk carriers, tankers, LPG). And these are just the ships that "suffer" from ballast transitions. After slow growth over the previous two years, container traffic increased by 6.4 % in 2017. At the same time, dry bulk transportation increased by 4.0 % compared to a 1.7 % increase in 2016. Crude oil shipments rose by 2.4 % compared to 4 % in 2016, while oil product and gas shipments combined increased by anstimated 3.9 %. Historically, developing countries have been the main suppliers of low unit value bulk commodities, but their role has changed in recent years. Developing countries have become the world's leading exporters and importers. 2014 was a milestone, when the share of developing countries in the total volume of landed (import) cargo for the first time exceeded their share in the total volume of loaded (export) cargo. This change highlights the strategic role of developing countries as the main driver of global maritime transport, as well as their growing participation in global value chains.

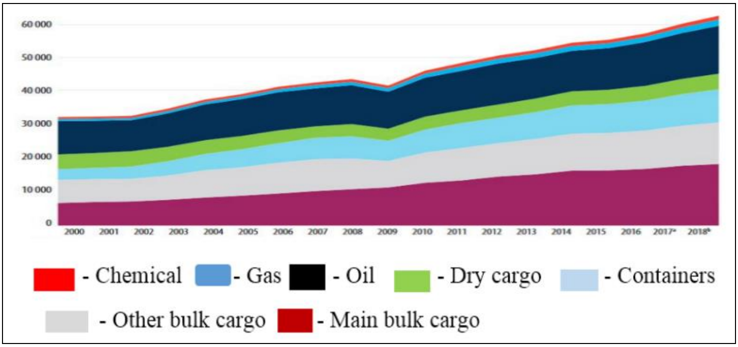

Figure 13 – Cargo turnover by sea transport by type of cargo, 2000–2018 (billion ton-miles)

The resulting regression models allow us tostimate the annual increase in the turnover of the corresponding cargoes (pessimistic and optimistic forecast):

– for chemical cargoes from 27.9 to 29.7 billion ton-miles;
– for gas from 63 to 68.7 billion ton-miles;
– for oil from 198.8 to 233.1 billion ton-miles;
– for containers from 340.3 to 362.9 billion ton-miles;
– for basic dry bulk cargoes from 659.9 to 696.81 billion ton-miles;
– for other dry cargo from 270 to 312.1 billion ton-miles.
– for the total cargo traffic from 1584.1 to 1679.1 billion ton-miles.

On the basis of the models obtained, it islso possible to forecast (extrapolate) the volume of maritime cargo transportation for the coming years. The corresponding estimates show that for the period from 2019 to 2023, the volumes of transportation of the corresponding types of cargo will increase:

– for chemical cargoes by 2.4 – 2.6 %;
– for gas by 3.4 % – 3.8 %;
– for oil by 1.5 % – 1.6 %;
– for containers by 3.2 % – 3.6 %;
– for the main dry bulk cargoes 3.3 % – 3.7 %;
– for other dry cargoes: 2.3 – 2.4 %.
– for the general cargo traffic: 2.7 % – 2.9 %.

Traffic volumes are expected to increase across all sectors, with containerized and dry bulk traffic growing the fastest.

Liquid cargo transportation is also expected to grow, albeit slightly slower than other market segments, in line with the previous trend[11].

From the above analysis follows the logical conclusion that with an increase in the tonnage of the world fleet, pollution of the air and water basins of the Earth increases. Based on the content of this article, it makes sense to clarify the concept of the economic speed of the vessel, especially when sailing in ballast. It iselieved that the economic speed is the speed at which the balance of the speed itself and fuel consumption is carried out. Under the new circumstances and following the new IMO requirements for the SMPEP plan, it makes sense to introduce the notion of reasonable speed, which will balance the ship's speed, fuel economy and respect for the protection of the environment, i.e. maintaining the Ship's Operating Energy Efficiency Index (EEOI) and the Ship's Design Energy Efficiency Index (EEDI) in the normal range.

CONCLUSIONS

On the basis of the performed research works in the conditions of real sea passages, the regularities of the Operating Coefficient of Energy Efficiency of the Vessel were established depending on the speed of the vessel, the mass of the transported cargo, the distance of the sea passage. The purpose of these studies is toinimize the EEOI while varying the main parameters of the sea crossing – the speed of the vessel, the mass of the cargo, the distance of the transition.

For the first time, the complex nature of the influence of the ship's speed on the EEOI was established, which made it possible to determine in each specific case the most optimal ship's speed, depending on the transition conditions, the type of ship's power plant, the changing power and ship's fuel consumption.

The high parametric sensitivity of the Operational Energy Efficiency Coefficient of the Vessel is determined depending on the mass of the transported cargo. At low loading masses of the ship tending to zero, the Operating Energy Efficiency Factor of the Vessel tends to infinity, i.e. to the most unfavorable operating mode of the vessel in terms of ship fuel consumption (economic criterion) and carbon dioxide emissions (environmental criterion).

On the basis of the research data obtained, we recommended to accept for practical implementation the development and development in maritime practice of multi-purpose vessels that allow for ballast-free sea

[11] Абрамов А. Д. Математические модели трендов роста морских грузоперевозок для отдельных типов грузов. URL: https://ksma.ks.ua/wp-content/uploads/2021/02/Конференция_2019_Том_1

transportation. In our opinion, it isxpedient to develop multi-purpose vessels according to the principle of the phase state of the transported goods, namely:

1. Transportation of any cargo in aiquid state, regardless of their physical and chemical properties.
2. Transportation of any cargo in aaseous, liquefied state, regardless of their physical and chemical properties.
3. Transportation of any goods in the solid state, regardless of their physical and chemical properties.
4. Transportation of equipment, apparatus, metal structures, metal products and metal waste.
5. Introduce the concept of aeasonable ship speed, i.e. the balance of the speed itself, fuel consumption and environmental protection.

SUMMARY

The International Maritime Organization has legalized and introduced into the practice of maritime transport the term Vessel Operating Energy Efficiency Factor (EEOI), the purpose of which is toeduce ship fuel consumption (economic criterion) and carbon dioxide emissions, the main marker of the “greenhouse” effect (environmental criterion).

On the basis of the performed research works carried out in the conditions of aeal long-term sea passage, the zones of minimization of the EEOI were determined depending on the speed of the vessel, the mass of the transported cargo, and the distance of the passage. It has been determined that the accepted speed of the ship and the loading of the ship have a significant impact on the value of EEOI. In the case of ballast transportation, the value of EEOI tends to infinity, which is extremely unfavorable from the standpoint of economic and environmental criteria. On the basis of the studies performed, practical recommendations have been formulated to ensure ballast-free sea transportation using multi-purpose ships.

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