

Comparison of properties of marine Diesel engines run on two kinds of fuel using performance indicators

Porównanie właściwości silników okrętowych zasilanych dwoma rodzajami paliwa z wykorzystaniem wskaźników efektywności

Andrzej Adamkiewicz¹, Przemysław Deska²

^{1,2} Maritime University of Szczecin, Faculty of Mechanical Engineering

Diagnostics and Machine Repairs Department

Akademia Morska w Szczecinie, Wydział Mechaniczny, Katedra Diagnostyki i Remontów Maszyn

70-205 Szczecin, ul. Podgórna 51/53, ¹ e-mail: a.adamkiewicz@am.szczecin.pl,

² TRANSPETROL TM AS, Knud Askers vei 20B, 1383 Asker, Norway, e-mail: przemek.deska@gmail.com

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Abstract

Basing on the evolution of application of different kinds of fuel supplying main engines of gas carriers, this article justifies the need to compare the qualities of these engines. Mass-size, energy and energy-ecological effectiveness indicators have been defined. Properties of self-ignition engines run on one or two kinds of fuel have been considered. Values of key performance indicators have been estimated. On the basis of the identified sets of indicators, comparative analysis of a dual fuel engine with single fuel ones has been carried out.

Słowa kluczowe: wskaźniki efektywności, właściwości, morski silnik Diesla, układ napędowy, gazowiec

Abstrakt

Posługując się ewolucją zastosowania różnych rodzajów paliw zasilających silniki główne gazowców, w artykule uzasadniono potrzebę konfrontacji cech tych silników. Zdefiniowano wskaźniki efektywności masowo-gabarytowe, energetyczne i energetyczno-ekologiczne. Rozpatrzono cechy silników o zapłonie samoczynnym zasilanych jednym i dwoma rodzajami paliw. Oszacowano wartości kluczowych wskaźników efektywności. W oparciu o zidentyfikowane zbiory wskaźników przeprowadzono analizę porównawczą cech silnika dwupaliwowego z jednopaliwowymi.

Introduction

The increased demand for gas transported by sea at the end of the last and the beginning of the new century enforced the construction of tankers for gas transportation of exceptionally high capacities, of the 150 to 260 thousand cubic meter range. As a consequence, the necessity to remove bigger amounts of gas from cargo tankers appeared [1, 2].

The relatively low efficiency of steam turbines in LNG gas carrier propulsion systems of the first generation and technological advances in ship

building inspired the concept and the construction of gas carriers driven by self-ignition engines run on different kinds of fuel: residual marine fuel – Heavy Fuel Oil (RM), Diesel fuel (MD) and LNG transported as cargo. As a result, propulsion systems of the Diesel-electric type (DE) on ships started to be equipped in an installation for secondary gas condensation like the one on ships for transporting liquid petroleum gases.

Thanks to the development of the re-gasification technologies, there has been an increased demand for self-ignition engines which could use the sur-

plus gas when the ship is loaded and run on liquid oil when travelling with the total lack of gas in the cargo tanks. In this way the efficiency of the propulsion system has been increased and the problem of reception of gas vapour from cargo space has been solved [2]. Thus, the idea of engines run on two kinds of fuel for LNG carrier propulsion was born.

Competition and economic aspects caused that most companies manufacturing marine Diesel engines launched the production of engines for the ship main propulsion adjusted to being supplied by liquid, as well as gas fuel [3]. In this way the relatively high efficiency of propulsion systems with self-ignition engines was maintained and at the same time the problem of the vapour reception from the cargo gas was solved.

The evaluation of the technological level of the contemporary ship propulsion systems and their elements is carried out throughout different methods: with the simultaneous use of dimensional and dimensionless quantities, unitary values and universal indicators. The basic approach to choosing the indicators and defining their meanings is the expert method, whose subjective approach is due to the necessity of limiting the number of indicators and their ascribed weights. The criteria method, not burdened by the subjective outlook, uses the dimensionless indicators with an extensive degree of generalization [4].

Indicators presently used for the evaluation of the ship power systems were defined by the International Maritime Organization IMO, as well as the national research centres [5, 6, 7, 8, 9, 10, 11].

The possibility to use self-ignition piston engines run on different kinds of fuel in the propulsion systems of gas carriers, inspired the application of efficiency indicators as a means for comparison of design properties and quality of maintenance of engines in the main propulsion systems of gas carriers.

Effectiveness indicators of marine engines

Design and maintenance decisions have to be properly justified. At the tender design stage and during the maintenance of the ship propulsion system there is a need for analyses, comparison of their solutions and evaluation of functioning quality in the system of maintenance of the unit. For this reason effectiveness indicators are used at the designing stage (DI – design indicators) and maintenance effectiveness indicators also known as KPI (Key Performance Indicators), describing chosen groups of information [5, 6]. In the case of ships

they can refer for example to the propulsion system, power system or particular elements of the ship power system [5]. Each of them characterizes another group of properties connected with the performance of particular functions considered only from one point of view. Design indicators and maintenance effectiveness indicators of the ship power system are classified on the basis of the existing regulations into three categories:

- 1) economic (Ei) – having a decisive role in the ship financial results, its own crew and subcontractor costs, costs of spare parts, costs of maintenance means and first of all costs of fuel, lubricating oil, amortization and other material costs;
- 2) technical (Tj), like for example those referring to effectiveness, limits, reliability, capacity, quality:
 - mass-size (design ones – unitary mass and size) of engines, mechanisms, equipment, installations and whole engine rooms – particularly useful at the tender design stage;
 - maintenance – power system operational reliability, overloading of main propulsion engines, capability of manoeuvring, periods of time between repairs and servicing costs;
 - energy – for example efficiency, unitary fuel consumption, powers and rotational momentum deciding about the speed of the ship and consequently indirectly about its economic performance;
 - energy-ecological – determined by international conventions regulating the levels of toxic compound emissions;
- 3) organizational (Ok), for example crew structure, accepted maintenance strategy in the maintenance subsystems, structure of machines and equipment etc;

where i, j, k are the counters of properties in the sets of indicator kinds.

Besides the three listed categories of key indicators, there are many others referring to the degree of engine load, durability, longevity, repairs availability, standardization, ergonomics, acceptable degree of vibrations in the engine room, noise, microclimate, etc. For such complex and varied technical systems as ship power systems, these indicators have to be precisely defined and univocally interpreted.

In each of these groups one can distinguish indicators at the general (ship owner's) level, intermediate level (ship power system PS) and detailed level (elements such as: main and auxiliary engines, main and auxiliary boilers). Regulations [10] list

the indicators accepted as the most important ones by the Technical Committee CEN/TC 319 "Maintenance" and a suggestion was made to ascribe them to the level of decision making. However, it does not mean that ship owners or any institution using a ship is restricted in any way. Effectiveness indicators are defined and used according to particular informative demand on the side of designers and ship owners.

Mass-size indicators

A ship power system (always with excessive size and mass) has a negative effect on ship capacity and indirectly even on its speed and sailing limits. Indicators referring to the whole item for example to ship deadweight allow the comparison of mass and volume of different propulsion systems, as well as different types and sizes of ships at the general (ship owner's) level [5, 6, 12].

To determine mass and volume indicators of the power system, it is convenient to use relative values in reference to the nominal power of the engines in the ship main propulsion system, among them the ones particularly useful for comparisons and an analysis, especially at the stage of initial designing of the power system, are the indicators of its unitary mass (mass of the power system in reference to the power of the main propulsion) and the indicators of its volume. Detailed level indicators referring to the main engine are defined as follows:

- engine unitary mass:

$$g_s = \frac{m_s}{P_n} \quad (1)$$

where:

m_s – mass of the engine,
 P_n – nominal power of the engine;

- unitary area occupied by the engine:

$$a_s = \frac{L_{\max} B_{\max}}{P_n} \quad (2)$$

- unitary volume of the engine:

$$v_s = \frac{L_{\max} H_{\max} B_{\max}}{P_n} \quad (3)$$

where: L_{\max} , B_{\max} , H_{\max} maximum length, width and height of the engine, respectively, without the auxiliary suspended subunits.

Indicator (1) can be calculated for dry engines, as well as for engines with operational liquids. Traditionally for the evaluation of effectiveness at the taken geometric characteristics of engines with self-ignition at the designing stage the indicator that is

used refers to the compactness of the engine. It is defined as the ratio of operational volume of the engine to its size described as follows [7, 12]:

$$\delta = \frac{\pi D^2 S i}{4 L_{\max} B_{\max} H_{\max}} \quad (4)$$

where:

D and S – cylinder diameter and piston stroke, respectively;

i – number of cylinder.

Energy parameters

A universal dimensionless measure, being also the measure of losses taking place in the power system or in some cases also taking into account information on fuel heating value, characterizing its physical and chemical properties is the effective efficiency of the engine defined by the following relation:

$$\eta_e = \frac{3600}{W_{fu} b_e} \quad (5)$$

where:

W_{fu} – lower heating value of the fuel [kJ/kg],

b_e – unitary fuel consumption [kg/(kWh)]:

$$b_e = \frac{B_h}{P_e} \quad (6)$$

B_h – hourly consumption of fuel [kg/h],

P_e – effective engine power [kW].

Depending on the range, character, requirements and the physics of the distinguished losses, efficiency can be considered as effective, usable, inner, volumetric, mechanical, general and so on [5, 12].

The level of engine technological development not only determines its being economical, but also the quantities reflecting its emission of toxic components in the exhaust.

Apart from the fuel, engine oil is another source of toxic substances in the exhaust. Its simple fractions are usually completely oxidized in combustion chambers to CO_2 and water vapour.

Macromolecular hydrocarbons from heavy fractions of petroleum oil in high temperatures of the combustion chamber are a subject to pyrolysis, where solid particles of carbon are formed in which carcinogenic polycyclic aromatic hydrocarbons are absorbed. Solid particles are the most harmful products of oil combustion in an engine. The additives themselves used in engine oils (antioxidants, washing, dispersing, anticorrosive multifunctional etc.), whose quantities can reach up to 25–30%, can be toxic. Accordingly the consumption of oil in the

engines is important not only because of economic reasons but also because of toxicity of exhaust.

For this reason, to evaluate the energy efficiency of self-ignition engines a more precise mean effective efficiency $\eta_{e\ fuel\ oil}$, which takes into account the summary heat effect of fuel and engine oil combustion, defined by the following relation, is used [7]:

$$\eta_{e\ fuel\ oil} = \frac{3600}{W_{fu} b_e + W_{oil} b_{oil}} \quad (7)$$

where:

- W_{oil} – lower heating value of oil,
- b_{oil} – unitary consumption of engine oil (products of incomplete combustion).

Due to low calorific value, small consumption of oil cannot significantly influence the value of economic indicator. However, the accumulated influence of a number of minor factors may significantly change the evaluation of technological level and the quality of Diesel engine calculated only on the basis of a limited set of indicators.

Efficiency is the energy indicator and, at the same time, also the maintenance and economic one, because the degree of energy utilization reflects the operational properties of the machine and indirectly it reflects the degree of its operational degradation in reference to its design stage at the beginning of its operation, as well as its maintenance costs.

Economic efficiency of engine maintenance (detailed degree) in a ship power system (intermediate level) in a significant degree depends on the technological level and the quality of the whole propulsion system of the ship (ship owner’s level).

At the detailed level, economic efficiency of self-ignition engine maintenance is basically decided by the costs of their operation which make up to 50% of total costs. These are among others the costs of fuel and engine oil. Thus, the conversion of chemical energy into work and also the loss of oil in the cylinders, which is the result of its combustion, is followed by the production of exhaust mostly harmful and toxic, which relates these indicators to other technical indicators including the ecological ones.

Energy-ecological indicators

Quality measures of contemporary Diesel engines should comprise parameters reflecting emission of toxic exhaust components. Exhaust is a non-homogenous solution of substances of different physical and chemical properties, classified in seven groups [13, 14]:

- nitrogen, oxygen, carbon dioxide, water vapour and hydrogen;

- carbon monoxide;
- nitrogen oxides;
- sulphur oxides;
- hydrocarbons (first of all polycycle aromatic hydrocarbons such as benzopyrene);
- aldehydes;
- carbon dust and solid particles absorbing carcinogenic substances.

Apart from the first group of substances, all the others are toxic and have a negative effect on human health and the environment. Although carbon dioxide is in the first group, it is responsible for the so called “greenhouse effect” and climate changes on Earth.

Emission of harmful exhaust components is characterized by:

- composition of exhaust gases C_i [%],
- emission speed E_i [kg/h],
- unitary emission e_i [kg/kWh],
- emission of a harmful component per 1 kg of fuel ε_i [kg/kg_{fuel}].

Emission of harmful exhaust components and first of all solid substances should be referred to the total consumption of fuel and oil. Table 1 presents estimated unitary values of harmful component exhaust emissions from self-ignition engines per unit of fuel [kg/kg_{fuel}] [14, 15].

Table 1. Estimated unitary values of harmful component exhaust emissions from self-ignition engines per unit of fuel [kg/kg_{fuel}] [14]

Tabela 1. Szacunkowe wartości jednostkowych emisji szkodliwych składników spalin silników o zapłonie samoczynnym na jednostkę spalane go paliwa [14]

Unitary emission of an exhaust component	Nitrogen oxides e_{NOx}	Carbon dioxide e_{CO2}	Hydrocarbons CH e_{CH}	Sulphur oxides e_{SOx}	Solid particles PM e_{PM}
kg/kg _{fuel}	c.a. 0.05	c.a. 0.027	c.a. 0.005	c.a. 0.005	c.a. 0.007

Regulations on prevention of air pollution caused by ships were formulated in Appendix VI of the MARPOL Convention 73/78 No. 10.16-1/1007. They take into account the control over substances destroying the ozone layer (these include halons, freons, sulphur oxides (SO_x), nitrogen oxides (NO_x), volatile organic compounds (VOCs) and it also presents mean weighted values of acceptable other exhaust components on a ship. The appendix also determines the limits on sulphur and nitrogen oxides emitted from ship exhaust installations and prohibits deliberate emission of harmful substances destroying the ozone layer and which can be found in the fire-fighting, or cooling system installations on ships [9, 11].

Paper [7] suggests using a toxicity indicator being a ratio of unitary fuel consumption to the sum of fuel consumption and two toxic exhaust components, given in the following form:

$$K_1 = \frac{b_e}{b_e + \sqrt{e_{\text{NO}_x} + e_{\text{CO}}}} \quad (8)$$

However, it does not include a number of normalized components, it is not very sensitive to the changes of emission of toxic exhaust components, and besides it is a dimensionless quantity.

Obtaining a dimensionless indicator requires the use of a traditional differential method [13]. When this method is used, the values of particular indicators (in this case energy-ecological effectiveness) are confronted with the limiting acceptable value of normalized toxic components given as:

$$K_2 = \sum_i^n \frac{e_i^{\text{lim}}}{e_i^r} \quad (9)$$

where:

- e_i^{lim} – limiting value of a mean weighted unitary emission of the i component of the fuel,
- e_i^r – the mean weighted real unitary emission of the i component of the fuel,
- n – number of toxic components taken into consideration in the analysis.

However, this indicator as well cannot be treated as a satisfactory one, for example in the case of a two-fold reduction of nitrogen oxides emission. Such a situation is quite realistic at the optimum regulation in the case of water – fuel emulsions and exhaust re-circulation. Then, the indicator of technological level and engine quality will also increase, it will be practically doubled giving a too high value of the indicator.

As the emission of toxic components in the exhaust is the result of fuel and oil combustion, then the energy – ecological indicator of engine excellence can be defined as a dimensionless ratio of unitary mean weighted emissions of toxic exhaust components to the respective unitary consumption of fuel and oil:

$$K = \frac{\sum_i^n e_i^r}{b_e + b_{oil}} \quad (10)$$

Taking into account the remarks connected with defining relations (8, 9, 10) for estimating the technological level and quality of marine engines, it is suggested that their ecological effectiveness indicator should be the difference between a unity and the

ration of unitary levels of emissions of toxic exhaust components with weight coefficients to the sum of fuel and oil consumption required for generating effective power:

$$K_3 = 1 - \frac{\sum_i^n w_i (e_i^r - e_i^{\text{lim}})}{b_e + w_{oil} b_{oil}} \quad (11)$$

where:

- w_i – weight coefficients of exhaust components,
- w_{oil} – weight coefficient taking into account an increased part played by lubricating oil in toxic compounds generation in relation to that of fuel.

Weight coefficients of exhaust components can be taken as a ratio of the limiting concentration of a given component to the limiting concentration of nitrogen oxide. To determine the value of weight coefficient w_{oil} , it is necessary to carry out various studies on the influence of engine oil chemical composition on the emission of particular exhaust components. The difference $(e_i^r - e_i^{\text{lim}})$ in the numerator of equation (11) shows to what extent the real toxic component emission differs from its accepted values. In the case when both values are equal, and the engine condition is in full compliance with the existing requirements, the ecological indicator will be equal to one. If emissions are lower than the normalized values, than the indicator will be bigger than one, in the reverse case it will be smaller. At the same time lowering of the hourly fuel consumption will generally lower the amount of its oxidation products, thus lowering the amount of emission of toxic exhaust components.

Regarding the remarks above, the dimensionless indicator characterizing the economy of fuel and oil consumption and taking into account the influence of exhaust toxicity on the energy-ecological level of a marine engine with self-ignition, it is evaluated according to the following relation [7]:

$$K_{ee} = \eta_{efu oil} K_3 \quad (12)$$

and after including relations (7) and (11) in the equation (12), finally the following is obtained:

$$K_{ee} = \frac{3600}{W_{fu} b_e + W_{oil} b_{oil}} \left[1 - \frac{\sum_i^n w_i (e_i^r - e_i^{\text{lim}})}{b_e + w_{oil} b_{oil}} \right]^z \quad (13)$$

where: z – weight coefficient taking into account the varied influence of fuel economics and emission of toxic exhaust components on the universal energy-ecological efficiency indicator.

Recognition of the extent of influence of fuel economics and ecology indicators on the technological level and engine quality is difficult and their influence is unequivocal.

Currently, two types of engine regulations are used: the first one – according to the criterion of minimum fuel consumption, the second one – according to the criterion of minimal emission of toxic compounds in the exhaust. Calculations of the universal energy-ecological effectiveness indicator [7] performed for the 3512B model engine manufactured by the Caterpillar company, on the basis of data from [4] showed that for each Diesel engine load, at the average effective combustion pressure, the effective unitary fuel consumption at the minimum emission of nitrogen oxides is 1.03 times bigger than that at the minimum fuel consumption, and the ratio of effective effectiveness calculated regarding the total heating effect due to fuel and oil combustion at all operational ranges is equal to 0.97 [15].

In this article, to compare the properties of dual fuel engines with the single fuel ones, the following indicators were considered: mass-size at the design stage, energy and energy-ecological ones. To exemplify the properties of the analyzed engines calculations performed with the use of the data referring to chosen engines [16, 17, 18, 19, 20, 21, 22] were used.

Dual fuel engines of contemporary gas carriers

Dual fuel engines DF can be run on distillation fuel (MDO), residual fuel (HFO) or natural gas, and the change of fuel from the distillation to the residual one and vice versa goes on without any disturbance during engine operation. So, as the engine could use gas fuel, being at the same time a self-ignition engine, ignition of the gas mixture is initiated by a small pilot dose of liquid fuel, MDO or HFO, injected to the combustion chamber. The engine can operate being run by either gas or solely by liquid fuel. Gas or fuel injection is fully controlled by the engine control system (ECS) ensuring maximum power and low emission of NO_x [23]. For the sake of this study, the properties of dual fuel engines manufactured by two companies were considered – Wärtsilä, which offers dual fuel medium-speed Diesel engines with power in the range of 2500 to 18000 kW, and MAN Diesel.

Wärtsilä launched onto the market two types of four-stroke multi-fuel engines with self-ignition for operation in power systems of ships in particular LNG carriers. The smaller of the family, the 34DF

type engine, offered in the 6L, 18V and 24V configurations can be used as the main propulsion and also as an auxiliary engine on smaller units. The bigger one, 50DF, is offered in the 18V configuration with the power of up to 17 550 kW. Table 2 presents dual fuel engines manufactured by Wärtsilä for the main propulsion of LNG carriers [21, 23].

Table 2. Dual fuel engines for the main propulsion of LNG carriers manufactured by Wärtsilä [21, 23]

Tabela 2. Silniki dwupaliwowe firmy Wärtsilä napędu głównego zbiornikowców LNG [21, 23]

Engine model	Rotational speed [r/min]	Mean effective pressure [MPa]	Power [kW]
W 6L34DF	750	2.0	2 700
W 9L34DF	750	2.0	4 050
W 12V34DF	750	2.0	5 400
W 16V34DF	750	2.0	7 200
W 6L50DF	514	2.0	5 850
W 8L50DF	514	2.0	7 800
W 9L50DF	514	2.0	8 775
W 12V50DF	514	2.0	11 700
W 16V50DF	514	2.0	15 600
W 18V50DF	514	2.0	17 550

Besides the above presented engines, Wärtsilä also offers engines of the 20DF type, which are manufactured in the following configurations: 6L, 8L and 9L. However, due to smaller power they are only used in current generating units.

MAN Diesel offers low-speed two-stroke dual fuel engines of the ME-GI type, of 11 900 to 26 160 kW [16], with the gas injection technique involving a multi-stage compressor (30.0 MPa) or a high pressure LNG pump (25.0 MPa), and a gas vaporizer. Table 3 presents dual fuel engines manufactured by MAN Diesel for the main propulsion of LNG carriers [22].

Table 3. Dual fuel engines manufactured by MAN Diesel for the main propulsion of LNG carriers [22]

Tabela 3. Silniki dwupaliwowe firmy MAN Diesel napędu głównego zbiornikowców LNG [22]

Engine model	Rotational speed [r/min]	Mean effective pressure [MPa]	Power [kW]
6L51/60DF	500	1.905	6 000
7L51/60DF	500	1.905	7 000
8L51/60DF	500	1.905	8 000
9L51/60DF	500	1.905	9 000
12V51/60DF	500	1.905	12 000
14V51/60DF	500	1.905	14 000
16V51/60DF	500	1.905	16 000
18V51/60DF	500	1.905	18 000

The medium-speed four-stroke engines found practical application in ship propulsion systems. In two-stroke engines at cargo exchange, in the combustion chamber at axial washing a part of the air-gas mixture gets lost, which increases losses and at the same time costs of their operation.

Choice of engines for comparative analysis

Choice of engines for comparative studies was carried out with the view to ensure comparability of analysed results. Three self-ignition engines with possibly closest technical and constructional parameters were chosen.

The 9L50DF engine manufactured by Wärtsilä was chosen as a model dual fuel engine, as it is one of the most often used engines for the main propulsion system of LNG carriers. It is a four-stroke irreversible turbo Diesel engine with direct liquid fuel injection and indirect gas fuel injection. Its properties were compared with single fuel engines manufactured two companies – Wärtsilä 9L46 and MAN Diesel 9L48/60B. Both these engines are four-stroke irreversible turbo Diesel engines with interstage cooling and direct fuel injection. Table 4 presents basic technical data of engines renown as criteria type for ensuring comparability of results [18, 19, 20].

Analysis of results of efficiency indicator calculations

Exemplification of results of chosen mass-size, energy and energy-ecological indicators defined and presented in the article was carried out basing on literature data [18, 19, 20] for the above chosen engines. Values of some indicators were not calculated because of the lack of reliable data and also the impossibility of their comparison with single fuel engines. Table 5 shows the values of indicator calculation results.

The obtained absolute values of indicators show that:

- dual fuel engines in comparison to single fuel ones have bigger unitary mass – equation (1),
- they occupy a bigger area and take up more space – equations (2) and (3),
- they are less compact (4), which is due to the more developed structure of installations servicing dual fuel engines in the machine compartment itself, and
- they are less efficient – equations (5) and (7).

However, they differ in the same way from the Wärtsilä and MAN Diesel engines, i.e.: they have better ecological properties – equation (8) in comparison to engines supplied solely with liquid fuel.

Table 4. Technical data of engines chosen for the analysis
Tabela 4. Dane techniczne silników wybranych do analizy

Parameter	Label	Unit	9L50DF dual fuel engine	Wärtsilä 9L46 single fuel engine	MAN B&W 9L48/60B single fuel engine
Power from the cylinder	P_1	kW	950/975	975	1150
Mean effective pressure	p_e	MPa	2.0	2.43	2.58/2.65
Cylinder diameter	D	mm	500	460	480
Piston stroke	S	mm	0.443	0.481	0.476
Rotational speed	n	obr/min	500/514	500/514	514/500
Mean piston speed	v_s	m/s	9.7/9.9	9.7/9.9	
Effective power	P_e	kW	8550	8775	10 350

Table 5. Listing of calculated values of effectiveness indicators
Tabela 5. Zestawienie obliczonych wartości wskaźników efektywności

Indicator	Label	Equation	Unit	9L50DF dual fuel engine	Wärtsilä 9L46 single fuel engine	MAN B&W 9L48/60B single fuel engine
Unitary mass	g_s	1	kg/kW	21.64	15.157	14.106
Occupied unitary area	a_s	2	m ² /kW	$4.446 \cdot 10^{-3}$	$4.015 \cdot 10^{-3}$	$3.670 \cdot 10^{-3}$
Unitary volume	v_s	3	m ³ /kW	0.0243	0.0203	0.0197
Indicator of construction compactness	δ	4	[–]	$4.0934 \cdot 10^{-3}$	$4.8676 \cdot 10^{-3}$	$4.7990 \cdot 10^{-3}$
Effective efficiency (liquid fuel)	η_e	5	[–]	0.443	0.481	0.476
Effective efficiency (gas fuel)	$\eta_{e\ gas}$	5	[–]	0.442	–	–
Effective efficiency (plus oil losses)	$\eta_{e\ fu\ burn}$	7	[–]	0.442	0.48	0.474
Energy-ecological indicator of exhaust toxicity	K_1	8	[–]	0.003	0.04	0.04

Table 6 presents the values of indicators for single fuel engines related to respective values for dual fuel engines, thus evaluating the above formulated conclusions.

Table 6. The values of indicators for single fuel engines related to respective values for a dual fuel engine of the 9L50DF type
Tabela 6. Wartości wskaźników silników jednopaliwowych odniesione do wartości wskaźników silnika dwupaliwowego 9L50DF

Related indicator	9L46 / 9L50DF	9L48/60B / 9L50DF
Unitary mass	0.7004	0.6518
Occupied unitary area	0.9031	0.8250
Unitary volume	0.8354	0.8107
Indicator of construction compactness	0.9865	0.9726
Effective efficiency	1.0858	1.0745
Energy-ecological Indicator of exhaust toxicity	13.33	13.33

Conclusions

Development of propulsion systems of gas carriers leads to the application of piston engines and the use of turbine propulsion is decreasing. For this reason, there is a need to supply self-ignition engines with different kinds of fuel. Modification of the so-far applied propulsion systems for running on gas fuel requires such extensive changes in the construction of engines and their auxiliary systems that manufacturers do not offer such solutions. This justifies the need to create a mathematical tool to enable the evaluation of piston engines in the propulsion systems of gas carriers.

Effectiveness indicators can be such a measure as they are chosen, defined and applied in each case for a special individual informative requirement regarding:

- the function performed by the unit;
- stage of life of the ship (design, construction, operation – maintenance, modernization – main repairs);
- the level of transmitted information – general (ship owner's), intermediate (ship power system), detailed (engines, boilers, pumps).

From among the possible categories of effectiveness indicators, the ones that were considered, were the representative for the categories technical indicators for the needs of initial designing and for the choice of engines for the propulsion systems. This approach was dictated by the aim of the study and a limited availability of information for estimating the values of indicators. The indicators defined in this article showed the extent of requirements for detailed information, not always available

in a direct way, thus indicating the direction of further research in the discussed matter.

Comparison of energy efficiency for single fuel engines and for dual fuel ones shows that the latter are characterized by lower efficiencies. It is the same when the engine operates on liquid fuel and on gas fuel, however, for comparable load ranges it is always lower for engines supplied with liquid fuel. This conclusion requires further analysis from the point of view of the physics of combustion process. The values of energy-ecological indicator of exhaust toxicity show that dual fuel engines are more environmentally friendly, which gives them a significant dominance over single fuel ones.

Fuel and engine oil consumption and emission of harmful substances in exhaust gases dependant on the quality of the combustion process of the applied kinds of fuel and lubricating oils may be estimated by one universal dimensionless effectiveness indicator characterizing the economics of fuel and oil consumption with regard to the influence of exhaust toxicity – equation (13). However, the relation between fuel economics and emission of toxic compounds in exhaust is unusually complex and will require further research.

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