DEVELOPMENT OF A MODEL FOR ENERGY EFFICIENCY MANAGEMENT OF A SHIP AT DIFFERENT STAGES OF ITS LIFECYCLE

Yevgeniy Kalinichenko
PhD, Associate Professor, Head of Department
Department of Navigation and Control of the Ship[1]
kalinichenko.yevgeniy1964@gmail.com

Oleksandr Shumylo
PhD, Professor
Department of Ship Power Plants and Technical Operations[1]

Mykhaylo Kourov
Postgraduate Student

[1]Odessa National Maritime University
34 Mechnikova str., Odessa, Ukraine, 65029

Abstract: The problem of increasing energy efficiency in commercial shipping has been in the focus of attention of many specialists over the past few decades. The adopted and entered into force resolutions of the International Maritime Organization (IMO) require ship-owners to develop and implement energy efficiency management plans. Considerable and increased attention is now being paid to the solution of this problem.

However, it has not yet been possible to achieve real practical results – commercial shipping already accounts for more than 3 % of greenhouse gas emissions, and this value is growing from year to year.

The reason for this effect is the practically absence of a systematic scientifically grounded approach to the issue. Management of carbon dioxide emissions into the atmosphere is mainly in the operational phase of the ship, although the foundations are laid during the design, construction, modernization and refurbishment phases.

This study is aimed at developing a comprehensive model for managing the energy efficiency of a ship throughout the entire life cycle. It is proposed to use the cost of a full cycle and the coefficient of energy efficiency as target functions of the model. A method for solving the problem of two-criterion optimization is proposed. The use of this model will be able to significantly reduce the amount of greenhouse gas emissions.

Keywords: energy efficiency, integrated mathematical model, amount of carbon dioxide emissions into the atmosphere, energy efficiency management of the ship.

1. Introduction

In recent years, the International Maritime Organization has paid considerable attention to solving the problem of improving the energy efficiency of ships. Within the framework of this work, a number of measures have been implemented and applied in practice: calculation of the ship's energy efficiency ratio, development and implementation of an energy efficiency management plan on ships, and the obligation to obtain a new international certificate from 2023. However, real practical results have not yet been achieved – merchant shipping already accounts for more than 3 % of greenhouse gas emissions, and this figure is growing from year to year.

The reason for this effect lies in the lack of a systematic science-based approach to the issue. Attempts are made to control the amount of carbon dioxide emissions during the operation of the ship, although the foundations are laid at the stages of design, construction, modernization and repair.

This study aims to develop a comprehensive model for managing the energy efficiency of a ship throughout its life cycle. It is proposed to use the cost of the full cycle and the energy efficiency factor as the target functions of the model. A method for solving the problem of two-criteria optimization is proposed. The use of this model will significantly reduce greenhouse gas emissions.

2. Methods

The problem of increasing energy efficiency in merchant shipping has been the focus of specialists' attention for the last decades. The adopted and entered into force resolutions of the International Maritime Organization (IMO) [1–4] require ship-owners to develop and implement energy efficiency management plans, which is defined as the amount of CO_2 in tones emitted by a ship during a voyage per ton of cargo transported per 1 mile. This approach made it possible to optimize the solution of a number of operational tasks, namely:

– more thorough planning of the voyage: choosing a route taking into account the weather forecast, optimizing the speed of the flight, taking into account the preliminary interaction with the ports of call;

– selection of the type of fuel and the depth of heat utilization in the ship's power plant;

– management of loading and unloading operations and ballasting in order to create an optimal trim;

– improvement of the system of technical maintenance of ship technical means, devices, systems and hull structures [10].

It should be noted that since 2008, after the 57th session of the Marine Environment Protection Committee, studies have begun on the development of measures aimed at increasing the energy efficiency of ships under construction. In the document [5], a formula was first proposed for determining the value of the constructive CO_2 index [g CO_2/(t·miles)]:

$$CO_2 \cdot \text{Index} = \frac{K_f \cdot g_e \cdot N_e}{DW \cdot v_{\max}},$$

where K_f – conversion factor that determines the amount of CO_2 in exhaust gases and depends on the type of fuel;

g_e – specific effective fuel consumption, g/(kW·h);

N_e – power of the ship power plant, kW;

DW – ship deadweight, thousand tons;

$v_{\max}$ – maximum speed of the ship, knots.

In the following years, the energy efficiency management model has been significantly improved. The main indicator was named the Energy Efficiency Design Index (EEDI) and began to take into account the level of utilization of flue gases. In addition, the new formula, given in [6], contains correction factors that allow taking into account the design features, waves and wind force, etc. The studies carried out by Deltramarine Ltd (Finland) [7] made it possible to build EEDI baselines for ships of various types.

It should be noted that a number of researchers consider it inappropriate to use EEDI to reduce greenhouse gas emissions [8], since this approach is aimed only at reducing the power of the power plant.

While recognizing the positive results from the introduction of an energy efficiency management system, it should be noted that the total effect is clearly insufficient. Statistics show that over the past decade, total CO_2 emissions have increased by almost 50 % and amounted to almost 1.5 billion tons in 2020, which is 3.3 % of total CO_2 emissions from fuel combustion. The aim of the proposed study is to develop an integrated model that will optimize the control of a ship at various stages of its life cycle, using the ship's energy efficiency coefficient as a control parameter.

3. Results

In [9], the authors propose the use of a model for calculating the cost of the life cycle of a ship to solve a number of management tasks, in particular, determining the period of the ship's decommissioning, proving the feasibility of performing modernization work, optimizing the scope and timing of repair work, etc.

The value of the total costs for all stages of the ship's life cycle, including disposal costs, is used as an objective function in this model.

The system of elements and connections that simulates the propulsive complex, other devices and systems of the ship can be represented as a graph, in which each piece of equipment corresponds to the top of the graph, and connections between equipment items or to external objects are a graph arc. Some vertices can be connected not by one, but by several oppositely or equally directed arcs. In each k-th element of the power plant equipment, the nature, quantitative dependencies and direction of the processes are controlled by the laws of thermodynamics, hydrodynamics, etc.

The dependencies between the parameters of the links can be uniquely and uniformly described by the equations of energy, consumption and hydraulic balances in the elements of equipment, as well as by the equations for changing the enthalpy of each of the types of energy carriers. The system of equations of balances in the elements of equipment establishes such a relationship between the thermodynamic and consumption parameters of the connections, which ensures the receipt of a given stationary load of the installation with certain structural and layout characteristics.

The equations for the entire installation and its external connections, referred to the same time interval, are as follows:

– the energy balance equation for each k-th piece of equipment

$$\sum_{j=1}^{J_k\text{-}N_k} (\gamma G h)_j + \sum_{n=1}^{N_k} (\gamma N)_n = 0; \tag{1}$$

– the equation of the balance of consumption for each l-th energy carrier of the k-th piece of equipment

$$\sum_{j=1}^{J_{kl}} G_j = 0; \tag{2}$$

– the equation of the hydraulic (aerodynamic) balance for each l-th energy carrier of the k-th piece of equipment

$$\left(p' \mp \Delta p - p''\right)_{kl} = 0; \tag{3}$$

– the equation of the change in the enthalpy of the l-th energy carrier in the k-th equipment element

$$\left(h' \mp \Delta h - h''\right)_{kl} = 0; \tag{4}$$

In formulas (1)–(4), the following designations are adopted:

– G – energy consumption;

– N – power of electrical or mechanical connection;

– p – pressure of the energy carrier for the outgoing (‘) or incoming (“) connection of an item of equipment;

– h – enthalpy of the energy carrier for the outgoing (‘) or incoming (“) connection of the equipment item;

– Δp and Δh – characteristics of changes in pressure and enthalpy of processes in the elements of equipment;

– γk – coefficient that takes into account the energy losses of the binder flow into the environment.

There are complex dependencies of various kinds between the parameters and technological characteristics of individual elements of the power plant equipment. Establishing these dependencies is the task of joint thermal, hydraulic, aerodynamic and strength calculation of elements. The main characteristics for the heat-power part of the installation are taken as follows:

– characteristics of the pressure change of each l-th energy carrier in each k-th piece of equipment (for heat exchangers, pipelines, collectors):

$$\Delta p_{kl} = \Delta p_{kl}\left(Z_k, Z_k^K\right); \tag{5}$$

where Z_k – set of parameters of connections of the k-th element of the installation;

Z_k^K – design parameters of the installation;

– characteristics of the change in the enthalpy of each l-th energy carrier in each k-th piece of equipment:

$$\Delta h_{kl} = \left[h'_{kl} - h\left(p''_{kl}, s'_{kl}\right)\right]\eta_{kl}, \tag{6}$$

where the values of the internal relative efficiency of the elements are determined using the corresponding submodels;

– characteristics of the average flow rate of the l-th energy carrier in each k-th piece of equipment (for heat exchangers, pipelines, etc.):

$$W_{kl} = W_l\left(Z_k, Z_k^K\right); \tag{7}$$

– characteristics of the highest wall temperature for each q-th structural part of each k-th piece of equipment made of material of type m:

$$t_{qmk} = t_{qm}\left(Z_k, Z_k^K\right); \tag{8}$$

– characteristics of the absolute or relative wall thickness of each q-th structural part of each k-th piece of equipment made of material of type m:

$$\beta_{qmk} = \beta_{qm}\left(Z_k, Z_k^K\right); \tag{9}$$

– characteristics of the consumption of metals and other m-x materials for each q-th part in each k-th piece of equipment [11]:

$$G_{qmk} = G_{qm}\left(Z_k, Z_k^K\right). \tag{10}$$

The influence of the remaining parameters of the installation Z and Z^K, which are not related to this k-th piece of equipment, on the characteristics of this piece of equipment is implicitly manifested through their relationship with the parameters of this piece of equipment. The characteristic expressions take into account the operating conditions of the installation at both nominal and partial loads.

For given types and materials of equipment elements or their structural parts, limiting conditions are imposed on the characteristics of the type, reflecting the requirements for manufacturability and long-term reliable operation of the installation.

The value of the cost function for all stages of the life cycle, taking into account discounting, will be:

$$C_\Sigma = C_{DB} + \sum_{t=1}^{\Phi}\left[\frac{1}{(1+k)^t}\cdot C_E\right] + \sum_{t+1}\left[\frac{(1+I_T)^t}{(1+k)^t}\cdot C_F\right] + \sum_{t=1}^{T}\left[\frac{1}{(1+k)^t}\cdot C_R\right] + \frac{C_U}{(1+k)^T}, \tag{11}$$

where C_{DB} – costs of designing and building the ship, its commissioning;

C_E – operating costs (crew maintenance, insurance, property tax, operating costs during operation);

C_F – cost of fuels and lubricants (fuel), which is calculated taking into account the intrinsic value of inflation – I_T;

C_R – repair costs, including the cost of replacement parts and repair materials;

C_U – cost of ship recycling;

K – discount factor.

$$EEDI = \frac{\left(\Pi_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{MEi} C_{FMEi} SFC_{MEi}\right) + P_{AE} C_{FAE} SFC_{AE}^{*}}{f_i \cdot \text{Capacity} \cdot V_{ref} \cdot f_w} + \\ + \frac{\left(\sum_{i=1}^{nRTI} P_{PTI(0)} - \sum_{i=1}^{nWHR} P_{WHRi}\right) C_{FAE} SFC_{AE} - \left(\sum_{i=1}^{neff} f_{eff} P_{eff} C_{eff} SFC_{MEi}\right)}{f_i \cdot \text{Capacity} \cdot V_{ref} \cdot f_w}, \quad (12)$$

where V_{ref} – sheep speed;

Capacity – ship displacement;

f_i, f_j, f_W – factors that take into account the effect of displacement, design features and conditions of waves and wind, respectively;

P_{MEi} – design power of the main engine, equal to 75 % of its rated power minus the power consumed by the shaft generator (if any);

P_{AE} – design power of auxiliary engines;

$P_{PTI(0)}$ – power equal to 75 % of the rated power consumed by each propeller electric motor excluding mechanical losses (this indicator should be taken into account when there is a hybrid propulsion system with a combined propeller drive);

P_{WHR} – electrical power as a result of heat recovery from the main engines;

SFC_{AE} – specific effective fuel consumption by main and auxiliary engines;

C_{FMEi}, C_{FAEi} – CO_2 emissions from the main and auxiliary engines;

f_{eff} – coefficient of efficiency of innovative technologies for energy production;

P_{eff} – power developed as a result of the use of innovative technologies for energy production;

C_{eff} – CO_2 emissions as a result of the use of innovative energy production technologies;

SFC_{ME} – specific effective fuel consumption, determined on the basis of universal characteristics. The types and parameters of the main engines were obtained from the Lloyds Register HIS Fairplay (LRFP – Lloyds Register HIS Fairplay) database in accordance with the International Standard ISO 3046-1 with a tolerance of +5 %.

$P_{PTi(0)}$ – power, calculated based on the assumption and regression analysis of the data. In case the ship is equipped with a controllable pitch propeller (CPP), it is assumed that there is a device for transferring mechanical power from the main engine to the CPP, connected to the line of the shaft or gearbox. The parameters of the device were taken on the basis of estimates based on specific data, depending on the type of ship in the form of regression curves. If the boat is equipped with a fixed pitch propeller, it is assumed that this device does not exist [8].

Thus, the presented model includes two objective functions (11), (12), and the region of its admissible solutions is formed by the system of equations and inequalities (1)–(10).

4. Discussion

A method for solving the problem of energy efficiency. The performed analysis of modern complex power plants shows the presence of a nonlinear nature of the dependences between thermodynamic and consumption parameters, nonlinearity of the dependences of the characteristics of equipment elements and their limitations, as well as the nonlinearity of the dependence of the target function on the same sets of parameters. Consequently, this problem belongs to the class of nonlinear programming problems in their most general formulation.

In the proposed model (1)–(12), a number of parameters have a continuous character of change, or the assumption of the continuity of change in the considered area is admissible for them. The rest of the design parameters of individual equipment elements have a pronounced discrete nature of the change. Therefore, it is advisable to divide the problem of complex optimization of the ship's energy efficiency into two parts: first, to determine the optimal values of continuously changing parameters, and then to optimize the discrete parameters. The following sequence for solving this problem is proposed:

– preliminary analysis of options for a ship of various dimensions, equipped with different types of propulsion;

– for each of the options, the choice of various types of power plants, ship systems and devices;

– calculation of the EEDC, the minimum value of which will allow to determine the optimal composition of the power plant;

– using formula (12) as an additional constraint using the linear programming method with an objective function (11) to make the final calculation of the main characteristics, parameters and operating modes of the ship.

5. Conclusions

The use of the proposed model makes it possible to improve the quality of the ship's energy efficiency management and, in a complex, solve the problems of minimizing the costs of a ship-owning company, reducing the amount of greenhouse gas emissions and maintaining the required level of safety in commercial shipping.

References

1. Elg, M. (2014). Energy Efficiency related Rules and Regulations – EEDI and Ship Design. EEDI and other EEE Rules and Regulations, 55.
2. Fourmer, A. (2006). Controlling Air Emission from Marine Vessels: Problems and Opportunities. University of California Santa Barbara, 91.
3. Anink, D., Krikke, M. (2009). The IMO Energy Efficiency Design Index. A Netherlands Trend Study. Centre for Maritime Technology and Innovation, 52.
4. Botelis, E. (2012). Integrated Propulsion Systems. The CIMAC Circle at the 2012 SMM, 34. Available at: https://www.cimac.com/cms/upload/events/circles/circle_2012/Boletis_20120906_cimac_smm3.pdf

5. Parmenova, D. G. (2017). The hull shape of a vessel, ensuring the safety of navigation and increasing the energy efficiency. Ship power plants, 37, 111–118. Available at: http://nbuv.gov.ua/UJRN/seu_2017_37_12
6. IMO (2010). Reduction of Green House Gas emissions from Ships, Report of the Working Group on Energy Efficiency Measures for Ships. Paper MEPC 6I/WP.10. International Maritime Organization, London.
7. Deltamarin Ltd. Study on tests and trials of the Energy Efficiency Design Index as developed by the IMO. Deltamarin EEDI Study for EMSA - Final Report.docx (2011). Raisio, 159.
8. 2013 Guidelines for calculation of reference lines for use with the energy efficiency design index (EEDI) (2013). Resolution MEPC. Annex 14. Available at: https://www.classnk.or.jp/hp/pdf/activities/statutory/eedi/11_231(65).pdf
9. Ivanchenko, A., Petrov, A., Zhivlyuk, G. (2015). Energy efficiency of ships and regulation of greenhouse gas emissions. Vestnik Gosudarstvennogo Universiteta Morskogo i Rechnogo Flota Imeni Admirala S.O. Makarova 3 (31), 103–112. doi: https://doi.org/10.21821/2309-5180-2015-7-3-103-112
10. Pizinciali, L. V., Shahov, A. V. (2015). Upravlenie stoimost'yu zhiznennogo cikla sudna. Odessa: Feniks, 114.
11. Sistemniy analiz. Available at: https://intuit.ru/studies/courses/3651/893/lecture/32037?page=2

Received date 12.09.2021
Accepted date 17.11.2021
Published date 29.11.2021

How to cite: *Kalinichenko, Y., Shumylo, O., Kourov, M. (2021). Development of a model for energy efficiency management of a ship at different stages of its lifecycle. Technology transfer: fundamental principles and innovative technical solutions, 17–20. doi: https://doi.org/10.21303/2585-6847.2021.002176*