STUDY OF THE FACTORS DETERMINING THE ENERGY EFFICIENCY OF PASSENGER SHIPS IN OPERATION

Iliyan Donev[1]

[1]*Technical University – Varna*

Abstract

The paper deals with the key factors that influence energy efficiency in the process of operating passenger ships. The research uses the theory of planning the experiment, which makes it possible to obtain mathematical models describing the interrelationships between various factors (speed, cooling water temperature, air temperature and others) and to improve the level of energy efficiency indicators EEOI of ships. A distinction is made between commercial decisions in voyage planning and maritime decisions in voyage execution by comparing speed and route choices. Lloyd's requirements for energy efficiency are mainly based on innovations in the mechanical part of the ship's electrical system. The analysis shows that in order to obtain the desired 'energy efficiency' it is necessary to formulate and define such indicators, criteria and methods that reflect the essence of the electrical processes in the ship's power system and, accordingly, the consideration of the influence of the factors.

Keywords: energy efficiency, energy efficiency indicator, theory of experiment design, voyage planning and execution, speed optimization.

INTRODUCTION

The International Maritime Organization (IMO) requires shipowners to improve energy efficiency in the operation of ships. The two most common definitions of energy efficiency in ship operations are the annual efficiency ratio (AER; IMO, 2021) and the operational energy efficiency index (EEOI; IMO, 2009). Both AER and EEOI disaggregate the ship's annual CO2 emissions by a measure of annual transport work. EEOI uses actual loads carried and distances traveled to calculate transport work, while AER relies on the vessel's rated load capacity (deadweight) and distances travelled. The EEOI thus takes into account the capacity utilization of ships, which the AER ignores. The analyzes carried out on board an IB-type passenger ship show that when considering the operational indicators for energy efficiency EEOI, random weather conditions are not taken into account and the various factors between which there are complex dependencies are not taken into account. Ship electrical power systems are a set of generating sources, power supply system and electric loads that are diverse in their nature and modes of operation.

EXPOSITION

The theory of planning the experiment is one of the widespread research engineering approaches, giving the opportunity to obtain mathematical models describing the interrelationships between the various factors and their influence on certain studied quantities. The model must describe a real object and cannot be modeled on a non-existent physical object.

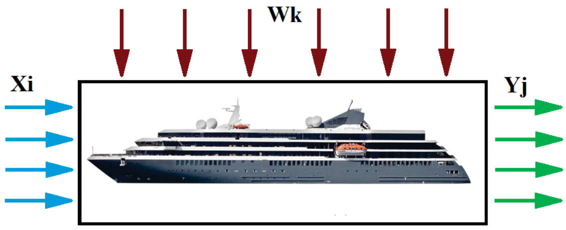

Fig. 1. *The object of research*

In this paper, the research model is a Class 1B cruise ship (Fig. 1), which is a modern polar cruise ship making voyages in different parts of the world and in different weather conditions. The route on which the research is carried out is a one-month period, consisting of 4-day cruises from 01.06.2023 to 30.06.2023, and is characterized by the following characteristics:

- A change in water temperature from 17ºC (La Coruña, Spain) to 10ºC (Bergen, Norway), allowing to establish dependencies in relation to the change of the physical environment.

- Constant loads of the electrical equipment in different operating modes of the ship for the studied period.

- Maintaining a different route in the west - north direction at an approximately constant average speed - v -15 ÷ 12 [n.m./h];

- About the same crossing in nautical miles for the day.

The ship can carry 200 passengers with a crew of around 110. The ship has a modern propulsion scheme that allows better specific fuel consumption at different speeds and ship loads. The vessel parameters are, Deadweight Tonnage (DWT): 1166 t and for cruise ships they are a function of Gross Tonnage (GT): 9934 is designed to sail around the world in extreme weather conditions and has a top speed of 13.5 knots. Auxiliary engine data are: Engine Make: Rolls Royce/Bergen Engines, Model: C25:33L6, Maximum Continuous Power (MCR) 2000 kW RPM (at MCR) 1000 RPM. Heat output at 100% 2 x 521 kW (main engines) + 1x442 kW (additional engine.An illustration of power system separation is given in Fig. 2.

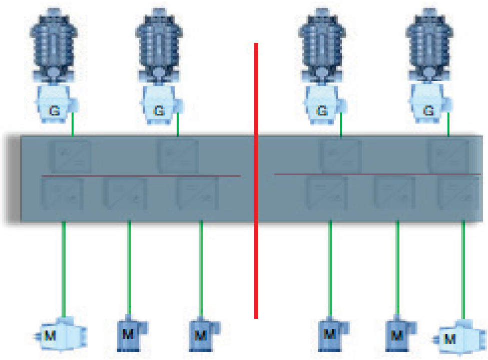

***Fig. 2** - Illustration of Power System segregation*

To simplify the data processing of the experiment, values of the factors are entered, which for quantitative factors are determined according to formula 1:

$$\dot{X}_i = \frac{X_i - X_{i0}}{I_i} \tag{1}$$

where: - coded value of the ith factor; X_i – natural value of the i-th factor; X_{i0} – natural value of the main level of the i-th factor; I_i – variation interval of the i-th factor. Factor values are plotted in a table called an experiment planning matrix. The planning matrix is constructed using the so-called character rotation rule. Table 1 presents a planning matrix for an experiment with three factors varying at two levels.

Table 1. Three-factor, two-level experiment planning matrix

Experiment №	X_1	X_2	X_3	Y
1	1	1	1	Y_1
2	-1	1	1	Y_2
3	1	-1	1	Y_3
4	-1	-1	1	Y_4
5	1	1	-1	Y_5
6	-1	1	-1	Y_6
7	1	-1	-1	Y_7
8	-1	-1	-1	Y_8

The research had to examine large databases (Table 3), in particular the reports from the weekly reports for each cruise, distance travelled, transport work and weather/sea conditions, to separate all the components of energy efficiency and develop more valid indicators of energy efficiency in ship operations. The normality of the matrix means that the sum of the squares of the elements of a ladder vector for each factor is equal to the number of trials and can be determined by the formula:

$$\sum_{j=1}^{N} \dot{X}_{ij}^2 = N \tag{2}$$

Experiment planning theory was used in the study, which made it possible to obtain mathematical models describing the interrelationships between various factors (speed, cooling water temperature, air temperature, excitation, etc.) and to optimize power losses and level of the operational indicators for reporting the energy efficiency of the ships. For each day, the average EEOI index was calculated according to Formula 3, taking into account a value for CF=3.206 corresponding to HFO, which is the only fuel used in sailing. The data are shown in Table 2.

Table 2. Cruise data for the current period

Fuel total [mt]	393.43
Distance pier to pier [nm]	5589.3
Time total [h]	723,8
Fuel stopped (mt)	48,08
Time Stopped [h]	252,3
Passenger [pax]	254
Speed Sailing [knots]	13,1
EEOI [gCO2/pax.nm]	914

Assumed m_{cargo}= 9934 [MT] corresponding to tonnage at nominal load.

$$EEOI_{AVG} = \frac{\sum_i \sum_j FC_{i,j} C_{Fj}}{\sum_i m_{c\arg oi} \cdot D} \tag{3}$$

where: j – type of fuel; i – course number; FCi,j – consumed fuel [t], CF,j – environmental impact factor of the jth type of fuel [tCO2/tFuel]; mcargo – mass of transported cargo [t] or number of passengers [no.]; D – distance traveled in nautical miles to perform the specified work [n.m.] [1]. Ship speed has a non-linear relationship with fuel consumption. A ship that sails slower will emit less greenhouse gases than a ship that sails faster. Cruise ships sail in different hydrometeorological conditions and itineraries, which is why it is necessary to make a separate analysis depending on the mode of operation of the main and auxiliary engines.

For each object (ship), different types and complexity of models can be compiled, examining different magnitudes of factors that influence different parameters. When taking into account their actions, at certain fixed levels of the essential factors, the output parameters will have a random character.Then it is necessary to take into account the dependence between the conditional mathematical expectation of the considered parameter ad the set of essential factors (formula 4) [5].

$$m\lfloor Y_j / X_1, X_2, ..., X_m \rfloor = f(X_1, X_2, ..., X_m) \tag{4}$$

The quantities Yj(j=1, 2,...,l) characterize the research objective and are called optimization parameters (OP) or output parameters (IP). All controllable factors Xi (i=1,2,...,m) through which the researcher affects the "black box" are called essential factors (SF). The Xi factors are non-random and independent of each other so that the experimenter can control the given process. Under independent should be understood those that do not have a direct unambiguous functional dependence. The set of factors Wk (k=1,2,…,q) that are uncontrollable but influence Yj are called disturbing factors. Correlation analysis is used to assess the interrelationship between the changes in the studied factors and, in particular, an assessment of the correlation coefficient according to the Persson-Brave definition shown in Formula 5[4].

$$R_{XY} = \frac{\sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{n \cdot \sigma_X \cdot \sigma_Y} = \\ = \frac{\sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{\sum_{i=1}^{n} \sqrt{(X_i - \bar{X})(Y_i - \bar{Y})}} \tag{5}$$

where: Xi, Yi – the investigated random variables (it can be the actual speed of the ship or the various factors, that affect speed, such as engine power, sea conditions and sea water temperature, etc.); i – number of the studied quantity; n – total number of measurements in the studied sample.

The studied period is from 01.06.2023 to 01.07.2023. The period is characterized by a significant stay in the Mediterranean Sea -

Atlantic Ocean under approximately constant weather conditions. During data collection, the focus was specifically on energy efficiency measures.

The results we obtain using the theory of experiment suggest that the operation of the ship under the influence of various factors on its operation can give a good prediction for the reduction of its carbon emissions.The calculated value of EEOI [gCO2/pax.nm] referred to the primary source of electricity - marine fuel is 913.1, with an expected value of 1110 [gCO2/pax.nm].

Table. 3. Cruise data for one month current period

Legs per month										KPI		
ID	Start-End	Start Leg (dd-HH:mm)	Fuel Tota [mt]	Distance pier to pie [nm]	Time Tota [h]	Fuel Stopped (mt)	Time Stopped [h]	Passenger [pax]	Speed Sailing [knots]	EEOI [gCO2/pax.mn]	CII [gCO2/GT.mn]	Fuel per NM Sailing [kg/nm]
1	Horta, Faial, Azores - Praia da Vitoria, Azores	1-07:48	12,04	109,6	47,6	6,28	37,7	255	11,7	1382	35,5	50,7
2	Praia da Vitoria, Azores - Velas, Sao Jorge, Azores	3-07:24	6,99	97,1	24,1	2,45	14,1	256	10,6	901	23,2	44,7
3	Velas, Sao Jorge, Azores - Vila do Porto, Azores	4-07:30	13,2	181,4	24,3	1,69	10	256	13,8	911	23,5	61
4	Vila do Porto, Azores - Funchal, Madeira	5-07:48	30,1	487,6	46,9	1,32	7,5	253	12,6	782	19,9	58,2
5	Funchal, Madeira - Lisbon, Portugal	7-07:42	34,66	531,2	48,5	1,66	10	189	14	1107	21,1	62,1
6	Lisbon, Portugal - La Coruna, Spain	9-08:12	28,21	374,2	31,6	1,28	6,1	220	15,1	1098	24,3	71,8
7	La Coruna, Spain - Port Medoc, France	10-16:48	22,4	363,2	38,1	1,19	6,6	220	11,8	899	19,9	56,6
8	Port Medoc, France - Le Palais, France	12-06:54	10,41	148,9	23,8	2,22	11,5	219	12,6	1024	22,6	53,2
9	Le Palais, France - St. Malo, France	13-06:42	18,79	279,7	27,5	1,46	7,3	219	14,8	983	21,7	60,7
10	St. Malo, France - Honfleur, France	14-10:12	11,35	170,7	23,9	1,59	9,3	217	12,7	982	21,5	54,8
11	Honfleur, France - Ostend, Belgium	15-10:06	13,53	201,4	22,4	1,38	7,6	217	14,8	993	21,7	58,4
12	Ostend, Belgium - Bremerhaven, Germany	16-08:30	18,16	309,3	47,6	1,67	9	216	7,9	871	18,9	50
13	Bremerhaven, Germany - Harlingen, The Netherland	18-08:06	13,36	183,5	23,5	1,76	9,6	289	15,3	808	23,5	64,7
14	Harlingen, The Netherland - Texel, The Netherlands	19-07:36	8,57	130	23,9	2,26	12,2	289	12,2	731	21,3	41,5
15	Texel, The Netherlands - Helgoland, Germany	20-07:30	12,67	187	25,3	2,12	11,4	289	14,5	752	21,9	52,6
16	Helgoland, Germany - Bremerhaven, Germany	21-08:48	7,68	77,9	23,2	1,82	9,1	289	4,2	1093	31,8	69,2
17	Bremerhaven, Germany - Harlingen, The Netherland	22-08:00	12,44	182,4	25,6	2,04	9,7	273	11,9	801	22	54,4
18	Harlingen, The Netherland - Texel, The Netherlands	23-09:36	10,65	132,8	22,2	2,26	10	273	12,8	941	25,9	75,2
19	Texel, The Netherlands - Helgoland, Germany	24-07:48	13,24	188,2	24,8	2,29	10,4	273	14	826	22,7	55,7
20	Helgoland, Germany - Bremerhaven, Germany	25-08:36	7,58	79,6	22,3	1,96	9	273	4,6	1118	30,7	75,6
21	Bremerhaven, Germany - Bergen, Norway	26-06:54	35,94	471,2	48,7	2,32	10,9	277	12,8	883	24,6	70,2
22	Bergen, Norway - Geiranger, Norway	28-07:36	16,1	228,1	26,5	1,73	8,9	279	13,6	811	22,8	58,5
23	Geiranger, Norway - Kristiansund, Norway	29-10:06	7,96	124,1	21,5	1,8	8,6	279	0	737	20,7	NA
24	Kristiansund, Norway - Reine, Norway	30-07:36	27,42	350,2	30	1,54	5,8	279	15,2	900	25,3	72,8

Carbon emission limits are decreasing by 2% year-on-year, as set out in IMO guidelines, resulting in the necessary continuous improvement in ship performance over the years. Changing weather and sea conditions cause significant levels of disruption to ships' operational modes, thus degrading their energy efficiency indices such as EEOI and CLL. Increasing the ship's speed while keeping the engine power constant, or vice versa, is directly related to the energy efficiency of the vessel[3] .

CONCLUSION

The analysis performed with the help of experiment planning theory is a tool that is suitable for use in the analysis of energy processes in ship electrical power systems.

Through it, mathematical models can be obtained describing the relationships between various external factors that influence energy indicators and the energy indices for carbon emissions. A prediction of the total amount of fuel needed to overcome a ship's drag under real weather conditions can lead to a prediction of the speed that ship can achieve with a given amount of power, which is one of the most important factors in energy efficiency.

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