CHARACTERISTIC PARAMETERS FOR PROPULSION SYSTEMS COOPERATING WIH SHAFT GENERATOR ON FEEDER CONTAINER SHIPS

Cezary BEHRENDT[1]

[1]*Institute of Marine Propulsion Plants Operations, Maritime University of Szczecin, Poland*

Abstract
The paper presents the obtained parameters of specific propulsion systems cooperating with shaft generators, used at feeder container ships. Based on the collected technical and operational data for container ships of various load capacity, constructed between 2000 and 2015, and by applying different analytical and statistical methods the parameters have been determined. Shaft generators' power has been established in relation to the power of main engines. The ratio of shaft generator power to main engine power has been also determined as well as the speed developed by container ships depending on the propulsion system power and on the relation to the generators' power to the power of main engines. Feeder container ships have been selected as a subject of the analysis taking into consideration the environmental and economic aspects. This type of ships is the most frequently operated in the sea regions where strict rules and provisions on exhaust gas emission apply. They transport container to and from ports serving ships of high bearing capacity. The parameters obtained may be applied to specify the ratio for exhaust gas emission, to compare fuel consumption for various methods of generating electricity and to assess the possibilities to use the waste heat recovery systems along with turbogenerators.

Key words: *feeder container ship, energetic systems, characteristic parameters*

INTRODUCTION

The problem of proper selection of shaft generator power and the electricity generation methods refers in particular to container ships due to a high demand for electricity as a result of a large number of the refrigerated containers being transported thereby.
Generating electricity using shaft generators driven by the main engine is one of the alternative methods to reduce fuel consumption and the cost of electricity generation.
The efficiency of that solution results from the generally known advantages such as:

- the reduction of fuel cost and cost of lubricating oils used in the process of electricity generation due to higher efficiency of the main engine when compared with auxiliary diesel engines for power generator units;
- improvement of the environment by the reduction of exhaust gas emission and remaining petroleum waste.

These effects however include certain defects. The main ones are:

- the requirement to stabilize the frequency of current generated by the generator in every operational condition of the propulsion system (variable rotational speed of the generator driven by the main engine);
- using a shaft generator to reduce the ship speed as a part of the main engine power is transferred to the generator as opposed to the propeller. The speed decrease depends on the shaft generator power and is within the range from 5% to 10% of the operational speed (*Balcerski* 1998, *Behrendt* 1997).

The power of shaft generators installed on ships depends on the type and purpose of the ship.
The rule is that a shaft generator should fully cover the demand for electricity for cargo ships while sea voyage.
The power of shaft generators equals to from 115% to 120% (*James M., Wolfe P.E., Morgan M. & Fanberg P.E.* 2014, *MAN Diesel & Turbo* 2013) of the design power resulting from the electric balance. Such a power surplus is assumed due to the fact that:

- the sum of powers of working electrical equipment and machines is a random variable;
- the generator is loaded with starting current of electric motors;

- along with time the generator efficiency decreases as well as electric motors supplied by it.

Increasingly common on ships are used waste heat recovery systems in order to maximize the amount of steam generated in waste heat boilers. The steam is used to cover the demand for heat on a ship and to drive turbogenerators (*Behrendt* 2016, *Hagesteijn G.P.J.J., Hooijmans P.M, v.d. Meij K.H., Greening D. & Yu L.* 2014, *MAN Diesel & Turbo* 2012, *Mitsubishi Energy Recovery System for Container Vessels* 2015). The power of a turbogenerator depends mainly on the main engine power and its power load. Due to high speeds developed by container ships and hence the main engine power, this type of ships is in particular suitable to install the waste heat recovery systems.
A traditional method for determining a demand for electricity, applied by naval design offices, consists of preparing an electric balance in which electric motors' powers are summed up. Based on this, marine generators' power is specified.
The paper aim is to present the characteristic parameters for propulsion systems of feeder container ships which would specify the relations of shaft generators' powers to the main engine power, ship speed, deadweight capacity, the number of crewmembers, the number of transported containers. For that purpose, technical and operational data of the ships has been gathered. The data refers to the feeder container ships of various dimensions, constructed between 2000 and 2015. The data has been processed.
Similar methods of determining characteristic parameters for propulsion systems have been applied for other ships' types (*Balcerski A., Bocheński D.* 1998, *Matuszak Z., Nicewicz G.* 2013).

MATERIALS AND METHODS

On the grounds of an analysis of science studies (*Schiff & Hafen 2000-2015*, *Pohl K.* 2009) the author was enabled to prepare Table 1. The table includes technical and operational data of the container ships constructed in shipyards located around the world between 2000 and 2015. Due to a limited size of the paper, Table 1 includes data regarding chosen the ships constructed in 2000 only. The full table consists of data referring to 87 container ships.

Tab1. Technical and operational parameters of selected feeder container ships

Ship name/ Year of built/ Country of built	Dead weight	Container no/ Refrigerated Container no	Vessel Speed	ME* Type / Power	Propeller Type	SG* Power	No and BT* Power	No and DG* Power
	D	n/n_1	v	N_{SG}	FPP*/CPP*	N_{PZ}	N_S	N_{SZP}
	[dwt]	[-]	[kn]	[kW]	[-]	[kW]	[kW]	[kW]
Geuldiep/ 2000/ Spain	4.100	240/100	13	MaK 6M32/ 2.880	CPP	240	1x290	2x160
Marcape/ 2000/ China	5.100	550/40	16	MaK 9M32/ 3.960	CPP	780	1x450	3x300
Annegret/ 2000/ Germany	9.631	813/50	20	MAN 9L48/60/ 9.450	CPP	1000	1x750	3x300
Apollon/ 2000/ Korea	11.950	901/176	17	Wartsila 8L46B/ 7.800	CPP	900	1x700	2x600
Isolde/ 2000/ Germany	34.026	2442/400	21	MAN L70MC/ 19.180	CPP	1400	1x1100	3x780
* ME- Main Engine, FPP-Fixed Pitch Propeller, CPP-Controllable Pitch Propeller, SG-Shaft Generator, BT-Bow Thruster, DG-Diesel Generator								

When analyzing the data in Table 1 and the remaining data, it may be stated as follows:

- deadweight capacity of feeder container ships is of highly variable. The smallest ships' deadweight capacity is 4,000 DWT, while the largest ones, given the service possibilities of destination ports, have the deadweight capacity of 40,000 DWT;
- the maximum number of transported containers varied from 200 to 3,000 items. Each ship could transport refrigerated containers the number of which equaled to from 40 to 500 items;
- operational speeds of the ships were within the range of 13-24 kn and were lower than the speeds developed by container ships transporting a cargo to large cargo ports; their maximum operational speed may equal to 28 kn;
- the power of the main engines varied within the range of 2.000 and 25.000 kW; the power is mainly dependable on the developed speed ships' capacity;
- every propulsion systems of the analyzed container ships were equipped with shaft generators the powers of which were sufficient to cover the demand for electricity of the ships and the transported refrigerated containers during a sea voyage;
- every container ship was equipped with a bow thruster/bow thrusters which enhanced maneuverability, especially in small harbors;
- the most ships were furnished with the CPP (Controllable Pitch Propeller); this stabilizes the frequency of current generated by the shaft generator in variable operational conditions. This technical solution is characteristic for feeder container ships.

Collected technical and operational data of feeder container ships allowed, using statistical analysis, to determine various characteristic parameters.

RESULTS AND DISCUSSION

The data in Tab. 1 allowed to determine numerous characteristic parameters. Certain, selected ones are presented and discussed in this section.
Figure 1 presents a function showing a relation of shaft generator power to the power of the main engine.

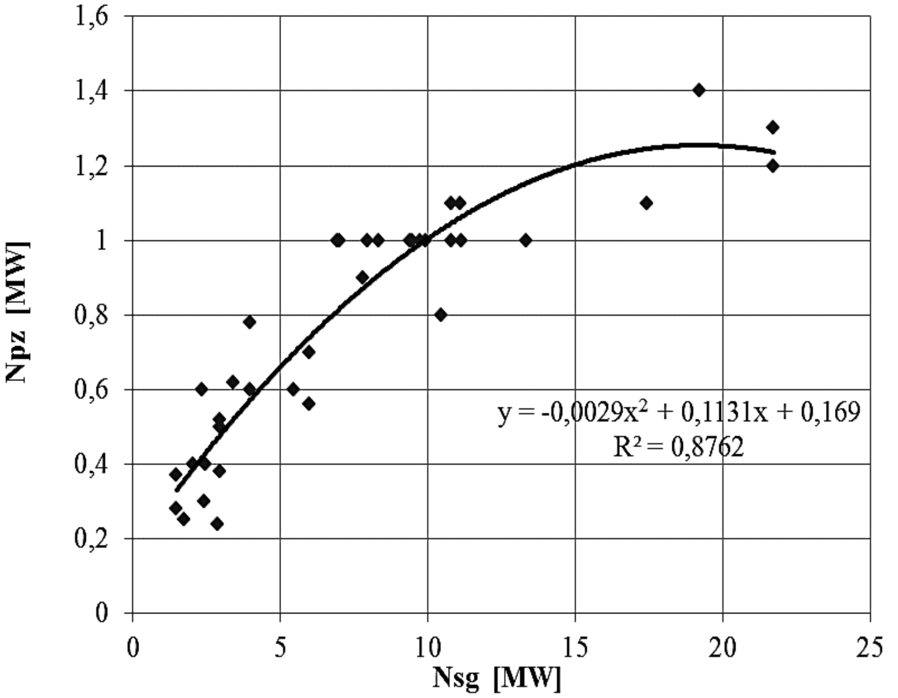

Fig.1 Relation of shaft generator power to the power of the main engine on feeder container ships

As the analyses have not shown any significant differences in the powers of the generators installed on the containers ships within the analyzed period, the graph does not differentiate the points so that they correspond to the individual shipbuilding years.
The obtained formula 1 enables to calculate the power of a shaft generator N_{pz} as a function of main engine power N_{sg}:

$$N_{pz} = -0{,}0029N_{sg}^2 + 0{,}1131N_{sg} + 0{,}169 \qquad [\text{MW}] \qquad (1)$$

Where: N_{sg} [MW] - main engine power

A mathematical relation (formula 2) has been also determined to compute the ratio of the power of a shaft generator N_{pz} to the main engine power depending on the main engine power N_{sg}:

$$\frac{N_{pz}}{N_{sg}} = 24{,}773N_{sg}^{-0{,}45} \qquad [\%] \qquad (2)$$

Formula (1) and (2) are applicable for :

2 MW ≤ N_{sg} ≤ 25 MW

Due to modern software and applications, it is possible to draw a dependency chart in a 3D coordinate system. As independent variables, main engine power N_{SG} and the relation of shaft generator power N_{pz} to main engine power has been selected. The dependent variable is ship speed v.

The relation $v = f\left(N_{sg}, \frac{N_{pz}}{N_{sg}}\right)$ is presented in Figure 2.

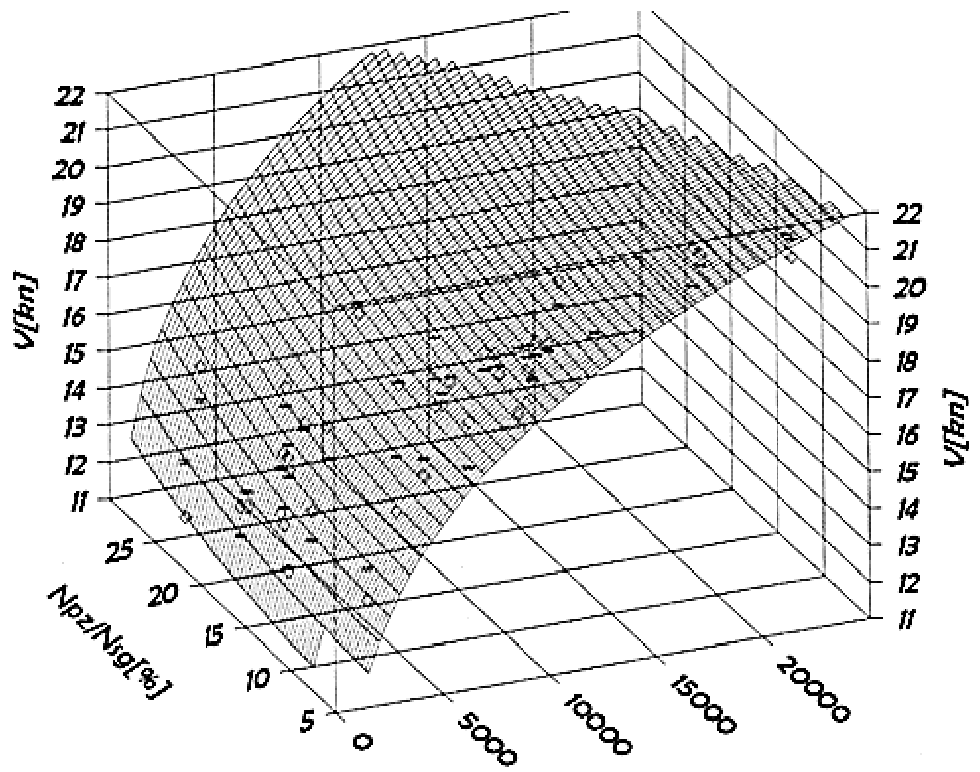

Fig. 2 Speed of container ships in connection to the power of main engine and the relation of shaft generators

The plane presented in Figure 2 may be calculated using formula 3:

$$v = 0{,}8735 + 0{,}2195 \ln N_{sg} + 2{,}8034 e^{-5} \left(\frac{N_{pz}}{N_{sg}}\right)^{2{,}5} \quad [\text{kn}] \qquad (3)$$

The formula 3 is applicable for:

$5\% \le \frac{N_{pz}}{N_{sg}} \le 25\%, \qquad 2000 \le N_{sg} \le 25000$ kW

The formulas specifying selected parameters for feeder container ships, characterize with large values of the squared correlation coefficient (formula 1, R^2=0,8762, formula 2, R^2=0,8804 and formula 3, R^2=0,9053).

Statistical method presented in the paper was first time used to determine various characteristic parameters of feeder container ships. Similar methods of determining characteristic parameters for propulsion systems and energetic systems have been applied for other ships' types (*Balcerski A., Bocheński D.* for technological and energetic systems of fishing vessels and dredgers, *James M., Wolfe P.E., Morgan M. & Fanberg P.E.* for ships' electrical power plants, *Matuszak Z., Nicewicz G.* for marine electric power plants of container ships and drilling platforms, *Behrendt C.* for ships' propulsion system cooperating with shaft generator).

According the research analysis method presented in the paper allowed to determine numerous characteristic parameters chosen and dedicated to ships' types. Achieved formulas characterize with large values of the squared correlation coefficient.

Characteristic parameters are used on preliminary stage of ships' design and energetic analysis.

CONCLUSIONS

- The practical applications of the obtained formulas can be as follows:
  - determining energy efficiency indicators for all devices and machinery in the engine room according to the guidelines and requirements of the International Maritime Agency *(Lloyds Register);*
  - forecasting exhaust gas emission for various methods of generating electricity and in various operational conditions;
  - determining feeder container ship speed at recommended operation together with slow stimming;
  - determining cooperation conditions for propulsion systems and shaft generator at the design stage;
  - comparing actual demand for electricity with possible to have it generated using a turbogenerator;
  - determining configuration of waste heat recovery systems to achieve maximum steam capacity;
  - determining electric energy demand in function of refrigerated container quantity and ships' speed;
  - determining influence ratio of the power of a shaft generator to the main engine power depending on the main engine power and their influence on the ships' speed.
- Applied presented method of determining characteristic parameters for propulsion systems for other ships' types.

ACKNOWLEDGMENTS

This research outcome has been achieved under the research project no. 2/S/IESO/2014 financed from a subsidy of the Polish Ministry of Science and Higher Educations for statutory activities of Maritime University of Szczecin.

REFERENCES

1. Balcerski A., Bocheński D. (1998). *Układy technologiczne i energetyczne jednostek oceanotechniczych / Technological and energetic systems of ocean vessels*. Gdańsk : Gdańsk University of Technology.
2. Behrendt C. (1997). Service Investigations of a Ship Propulsion System Cooperating with Suspended Electric Generator, *Polish Maritime Research, No 2 (12)*, 29-31.
3. Behrendt C. (2016). An Analysis of Monitoring Requirements for Waste Heat Resource in Marine Power Systems, In *57-th International Conference of Machine Design Departments ICMD2016*, (pp.189-194), Book of Proceedings.
4. Hagesteijn G.P.J.J., Hooijmans P.M, v.d. Meij K.H., Greening D. & Yu L. (2014). Traditions Broken in Modern Container Ship Design. In *Conference Design & Operation of Container Ships* (pp. 36-46), Book of Proceedings.
5. Implementing a Ship Energy Efficiency Management Plan (SEEMP), Guidance for shipowners and operators (2012). *Lloyds Register, (version 2.0).*
6. James M., Wolfe P.E., Morgan M. & Fanberg P.E. (2014). Statistical Analysis for Shipboard Electrical Power Plant Design. *The Glosten Associates, Inc.publication*. http://www.sname.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=dad4cc49-da68-4274-a622-916100d514a4 [accesed May 02.2017]
7. MAN Diesel & Turbo (2012). *Quantum 9000. Two-stroke LNG by DNV and MAN Diesel & Turbo*, Publication no. 5510-0108, MAN Diesel & Turbo, Copenhagen, Denmark.
8. MAN Diesel & Turbo (2013). *Propulsion Trends in Container Vessels Two-stroke Engines*. Publication No 5510-0040-02ppr. Copyright©MAN Diesel & Turbo, Copenhagen, Denmark.
9. Matuszak Z., Nicewicz G. (2013). Analysis of marine electric power plants loads. In *ICMD2013 Conference Modern Methods of Construction Design Proceedings.* (pp.273-281), Springer International Publishing Switzerland 2014.
10. Mitsubishi Energy Recovery System for Container Vessels (2015). *Mitsubishi Heavy Industries Ltd, Nagasaki Shipyard & Machinery Works, Marine Machinery Design Department* http://pdf.nauticexpo.com/pdf/mitsubishi-heavy-industries-ship-ocean/energy-recovery-system-container-vessels/32135-20215.html [accesed Apr.14.2017].
11. Produced Ship List (2000-2015). *Schiff & Hafen*. DVV Media Group GmbH.
12. Pohl K. (2009). The Container Ships from Szczecin. Szczecin: Grapus Sp. z o.o.

Corresponding author:

Assoc. Prof. Cezary Behrendt, Ph.D. Eng, Institute of Marine Propulsion Plants Operations, Faculty of Marine Engineering, Maritime University of Szczecin, Wały Chrobrego 1-2, 70-500 Szczecin, Poland, phone: +48 91 4809479, e-mail: c.behrendt@am.szczecin.pl