

Mean long-term service parameters of transport ship propulsion system

Part II Propulsion engine service parameters of transport ship sailing on a given shipping route

Tadeusz Szelangiewicz
Katarzyna Żelazny
Szczecin University of Technology

ABSTRACT

During ship sailing on a given shipping route in real weather conditions all propulsion system performance parameters of the ship change along with changes of instantaneous total resistance and speed of the ship. In this paper results of calculations are presented of distribution function and mean statistical values of screw propeller thrust, rotational speed and efficiency as well as propulsion engine power output and specific fuel oil consumption occurring on selected shipping routes. On this basis new guidelines for ship propulsion system design procedure are formulated.

Keywords: thrust, efficiency and rotational speed of screw propeller, long-term prediction, shipping route, design working point of screw propeller

SERVICE PARAMETERS OF PROPULSION ENGINE OPERATION

The service parameters of propulsion engine operation, calculated below for a ship sailing on a given shipping route, are as follows:

- ☆ engine power output N
- ☆ engine speed (number of engine revolutions per time unit) n
- ☆ specific fuel oil consumption (SFOC), g , or hourly fuel oil consumption G .

The first two parameters (N , n) determine engine working point (if engine directly drives propeller without any reduction gear then $n = n_p$). During ship's sailing on a given shipping route in changeable weather conditions the engine working point changes its location. By controlling fuel charge (consequently also number of revolutions) a new engine working point is searched with the use of the criterion assumed below, so as to get it placed within engine layout area. Change of location of the engine working point makes fuel oil consumption changing: both the specific, g , and hourly one G .

ENGINE PERFORMANCE CHARACTERISTICS AND LOAD DIAGRAM

The propulsion engine load diagram consists of a few areas limited by appropriate characteristic lines. Working point of propulsion engine can be located in the areas but in some of them – only for a determined time of operation. The example

load diagram of a Sulzer propulsion engine is shown together with depicted SFOC characteristics in Fig. 7.

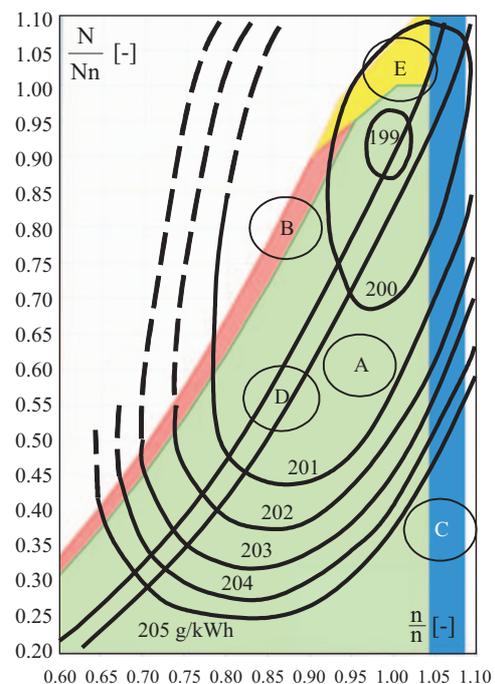


Fig. 7. Load diagram of a Sulzer propulsion engine [8].
 M_n – rated torque, **A** – continuous rating area (green); **B** – engine overload area (red); **C** – sea trial rating area (blue); **D** – still-water optimum rating area (...); **E** – instantaneous rating area (yellow)

The particular areas are limited by engine performance characteristics of the following form:

$$N = k_m \cdot n^m \quad (13)$$

where:

- N – engine power output
- k_m – coefficient for a given characteristic line
- n – engine speed
- m – exponent depending on an engine type and producer; for SULZER RTA 52, RTA 62, RT 72, RTA 84 slow-speed diesel engines:
 - $m = 0$ – for nominal continuous rating or maximum continuous rating,
 - $m = 1$ – for constant torque characteristics,
 - $m = 2.45$ – for overload characteristics.

Particular characteristics and range of engine speed are determined depending on an engine type (producer).

In Fig. 7, on the engine load diagram the SFOC characteristics, g , are shown. They are provided by engine producer and valid for a given engine and determined conditions (a given air temperature etc). There are also more general characteristics published by engine producers in the form of relevant nomograms, e.g. [8], which make it possible to calculate the SFOC depending on an engine type (producers), its nominal parameters (power and speed), instantaneous engine load as well as ambient conditions (temperature of air and cooling water). The way of making use of the nomograms to calculate the SFOC of engines is given in [5]. Fuel consumption can be also determined on the basis of measurements carried out with the use of special instruments (flow meters, calibrated tanks) during propulsion engine operation [1].

SHIP PROPULSION CHARACTERISTICS – PROPULSION SYSTEM’S PERFORMANCE IN CHANGEABLE WEATHER CONDITIONS

The ship propulsion characteristics are the following : curves of propulsion power, thrust, efficiency and torque at propeller’s cone, fuel consumption and ship speed available for a given ship resistance characteristic. The characteristics are usually presented on the propulsion engine load diagram in function of propeller (engine) speed or ship speed (then characteristic of constant number of revolutions is attached). The propulsion characteristics published in the subject-matter literature are usually elaborated on the basis of:

- ⇒ model test results of free propellers or behind-the-hull ones
- ⇒ results of measurements carried out on ship board [2, 7]
- ⇒ results of measurements carried out on ship board with simultaneous use of free-propeller characteristics derived from model tests or numerically determined [3, 4, 5, 6].

For purposes of this work a numerical method for predicting the ship propulsion characteristics was elaborated (for a designed ship appropriate model tests are not to be performed), in the following form:

- $T(V, n)$ - propeller thrust
- $Q(V, n)$ - propeller torque
- $\eta_0(V, n)$ - propeller efficiency
- $P_D(V, n)$ - power output at propeller’s cone
- $V(P_D, n)$ - ship speed characteristic

where:

- V – ship speed
- n – engine speed (if the engine is of a slow speed then $n = n_p$, where n_p - propeller speed).

The ship propulsion characteristics for K1 ship (its parameters given in [9]), presented in Fig. 8, 9, 10, were calculated for the assumed additional resistance increments ΔR , resulting from the assumed constant values of the wind velocity V_A . As the power, thrust and torque were calculated at propeller’s cone the engine power output was recalculated for the same point.

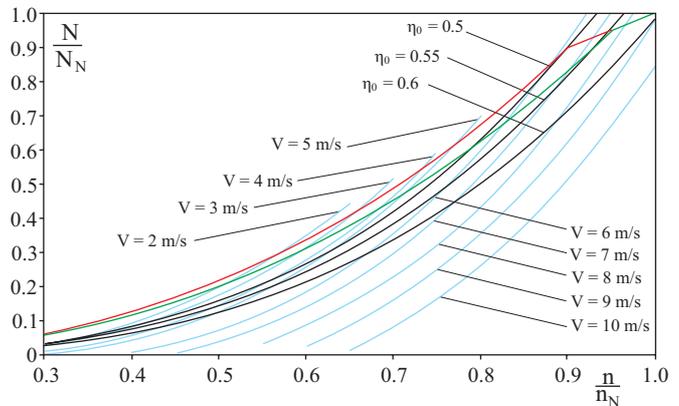


Fig. 8. Constant ship speed and constant propeller efficiency characteristics of K1 ship

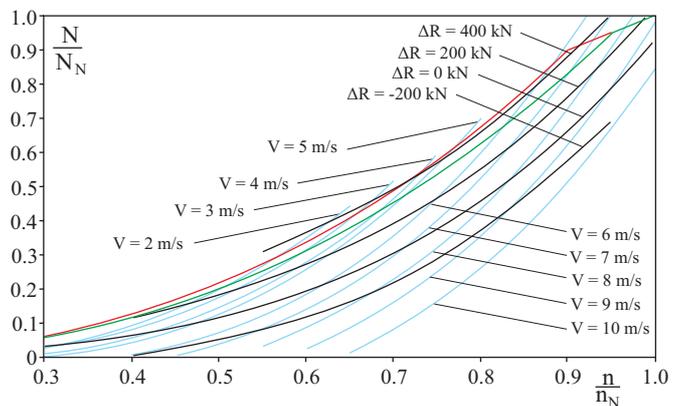


Fig. 9. Constant ship speed and constant additional ship resistance characteristics of K1 ship

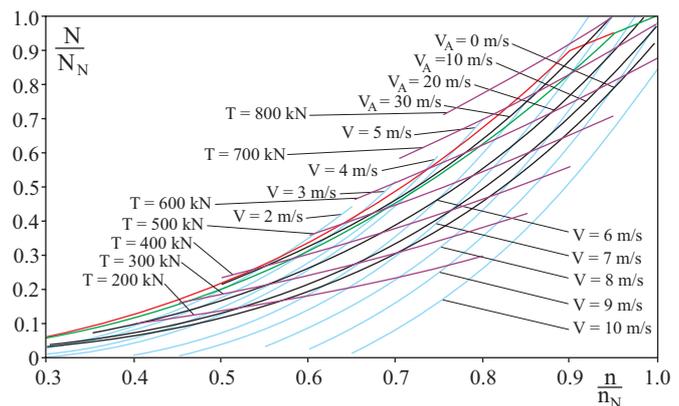
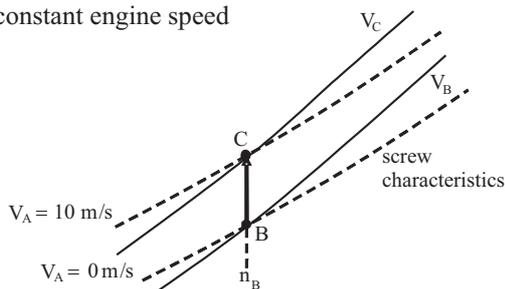


Fig. 10. Constant ship speed and constant propeller thrust characteristics of K1 ship, and constant wind velocity characteristic

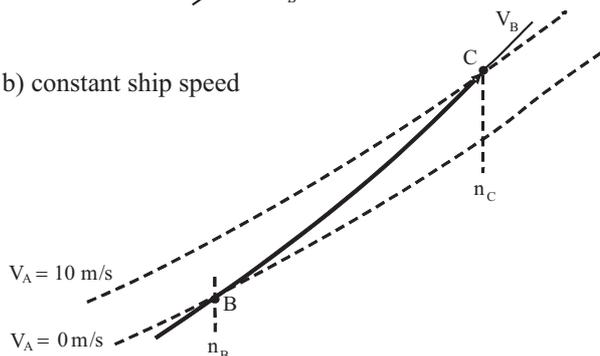
In Fig. 10 are given the characteristics of constant velocity of wind blowing from a determined direction with respect to direction of ship motion (in the considered case the ship sails upwind –but such characteristics can be made for arbitrary wind and/or wave directions). They make it possible to correctly select a propulsion system’s working point for changeable weather conditions or to predict, e.g., maximum ship’s speed in the case of sea state worsening.

Possible change of propulsion system working point (for fixed pitch propeller) due to an additional resistance increase resulting from wind in the case in question (upwind motion of ship), is presented in Fig. 11.

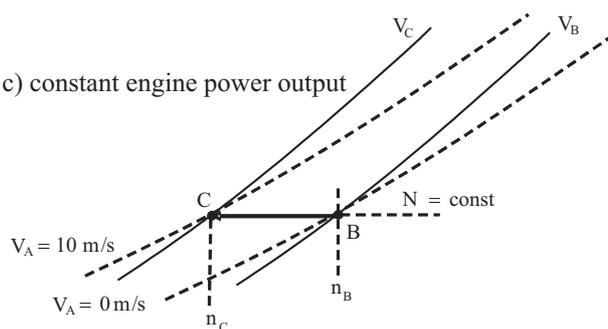
a) constant engine speed



b) constant ship speed



c) constant engine power output



d) constant specific fuel oil consumption (SFOC)

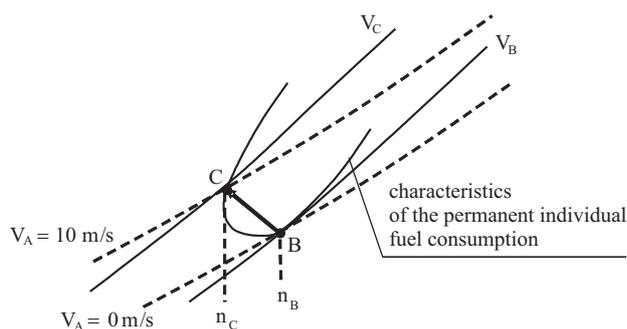


Fig. 11. Examples of change of propulsion system working point, resulting from an increase of additional resistance due to changeable weather conditions

In the described example the ship which starts from the point B, sails in still water with the speed V_B and propeller speed n_B , at the wind velocity $V_A = 0$ m/s. Then an additional resistance appears due to the head wind of the velocity $V_A = 10$ m/s. The following paths from the current propulsion system working point (B) to the new one (C) are possible (Fig. 11) :

a) at constant engine speed, n_B , fuel charge is increased (consequently also engine's power output) until the point C

- on the characteristic of V_A is reached, as a result the ship's speed drops to the value of V_C
- at constant ship's speed V_B fuel charge is increased (consequently power output of the engine as well as its speed grow up to the value of n_C) until the point C is reached (the ship's speed can be kept constant up to the engine's limit curve)
 - at constant engine's power output the point C is reached, the ship's speed drops to the value of V_C as well as the engine's speed – to the value of n_C
 - at the SFOC kept constant the ship's speed and engine's speed is reduced until the point C is reached.

The four possible ways of reaching a new working point of propulsion system at resistance increasing – in this case due to wind velocity increasing – can be applied for different assumed criteria, e.g. : constant ship speed, maximum available ship speed, minimum fuel consumption, constant or maximum propeller efficiency.

For the determination of mean long-term service speed of ship at increasing resistance due to weather conditions the variant „b” will be used first, i.e. the initial ship's speed kept constant until the limiting characteristic is obtained (Fig.7).

When the additional resistance is further increasing the working point of the propulsion system will be searched on the limiting characteristic, i.e. the maximum available speed of the ship. The algorithm for searching the mean, long-term service speed of ship was so elaborated as to make it possible to apply also other variants (criteria) of selecting a new working point, presented in Fig. 11.

MEAN, STATISTICAL SERVICE PARAMETERS OF PROPULSION ENGINE OF SHIP SAILING ON A GIVEN SHIPPING ROUTE

Prediction of the mean, statistical service parameters of propulsion engine is performed in the same way as for screw propeller [10]. At first the instantaneous parameters which result from an instantaneous increase of ship resistance due to wind, waves, sea surface current and possible lay of rudder blade, are calculated and then probability of occurrence of relevant values of propulsion engine's output and speed and the SFOC is calculated.

The total probability of occurrence of given values of propulsion engine output and speed, P_{Tn} is expressed as follows:

$$P_{Tn} = \sum_{A=1}^{n_A} \sum_{S=1}^{n_S} \sum_{\mu=1}^{n_{\mu}} \sum_{H,T=1}^{n_{HT}} \sum_{V=1}^{n_V} \sum_{\psi=1}^{n_{\psi}} p_{n_i} [n_i (\Delta R_i)] \quad (14)$$

$$P_{TN} = \sum_{A=1}^{n_A} \sum_{S=1}^{n_S} \sum_{\mu=1}^{n_{\mu}} \sum_{H,T=1}^{n_{HT}} \sum_{V=1}^{n_V} \sum_{\psi=1}^{n_{\psi}} p_{N_i} [N_i (\Delta R_i)] \quad (15)$$

where:

- P_{Tn} – total probability of occurrence of a given value of the engine speed n_i (if the engine directly drives the propeller the occurrence probabilities of a given value of the engine and propeller speeds are the same: $P_{Tn} = P_{Tnp}$)
- P_{TN} – total probability of occurrence of a given value of the engine power output N_i
- n_i, N_i – instantaneous values of engine speed and output depending on an instantaneous value of the additional resistance ΔR_i

p_{ni}, P_{Ni} – instantaneous occurrence probabilities of given values of the engine's speed n_i and output N_i for an instantaneous situation resulting from ship sailing on a given shipping route, calculated according to (10), [10]

$n_A, n_S, n_u, n_{HT}, n_v, n_w$ – number of zones crossed by a ship, seasons of the year, values of wave direction, wave parameters, ship speed and course angle, respectively.

By applying the same technique as in the case of propeller, the mean statistical values of engine speed and output on a given shipping route can be expressed as follows :

$$\bar{n} = \frac{\sum_{i=1}^{n_n} P_{T_n} \cdot n_i (\Delta R_i = \text{const})}{\sum_{i=1}^{n_n} P_{T_n}} \quad (16)$$

$$\bar{N} = \frac{\sum_{i=1}^{n_n} P_{T_n} \cdot N_i (\Delta R_i = \text{const})}{\sum_{i=1}^{n_n} P_{T_n}} \quad (17)$$

where:

n_n, n_N – number of the intervals containing similar instantaneous values of engine speed and output, respectively.

During ship sailing on a shipping route in changeable weather conditions all the ship's service parameters result from its engine's working point which is to be located within the area of the engine's load diagram (Fig. 7) characterized by engine speed and power output.

Having the occurrence probabilities of given values of engine speed and output one is able to determine the occurrence probability of a given working point, i.e. of the pairs of values : engine speed – engine output (in the same way as for those of propeller speed – ship speed, Fig. 5 in [10]).

The calculated distribution function of engine speed – engine output makes it possible to calculate the distribution function of SFOC as a determined value of fuel consumption corresponds with each of engine's working point, Fig. 7. Having the distribution function one can calculate the mean long-term value of specific fuel oil consumption for a given shipping route, in a similar way as for engine speed and output.

RESULTS OF CALCULATIONS

Results of the calculations for the selected ship and shipping route (engine and shipping route parameters were specified in [9]), are presented in the form of :

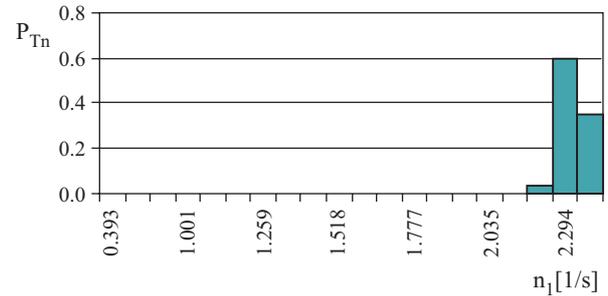
- engine speed histogram and mean statistical value
- engine power output histogram and mean statistical value
- specific fuel oil consumption (SFOC) distribution function and mean statistical value
- probability distribution function of long-term occurrence of given values of engine speed and output (histogram of engine's working point)
- mean, long-term working point of propulsion engine.

In the figures the calculation results are presented - under the assumption that engine's output reaches at most $0.9 N_n$ - for K1 containership [9] and the two very different shipping routes : 5b - "easy" one and 2b - „difficult" one - in the sense of occurrence of long-term weather parameters.

Ship: K1 - assumed service speed = 8.44 [m/s]
- probability of maintaining a given speed, P_{VE}

Engine speed histograms

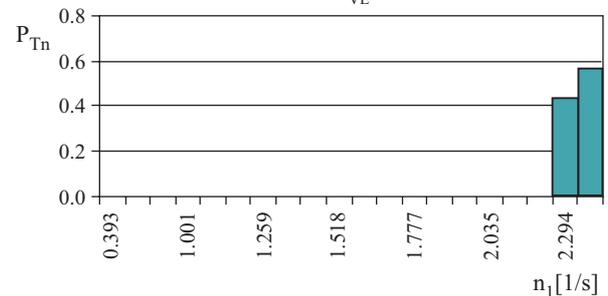
Route no. 2b - $P_{VE} = 0.50$



Nominal engine speed $n_n = 2.330$ [1/s]

Mean engine speed $\bar{n} = 2.335$ [1/s]

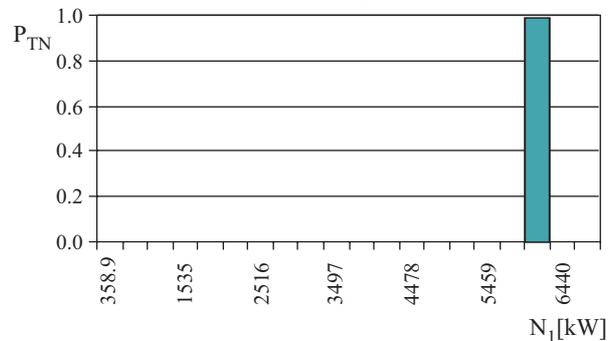
Route no. 5b - $P_{VE} = 0.83$



Mean engine speed $\bar{n} = 2.335$ [1/s]

Power output histograms

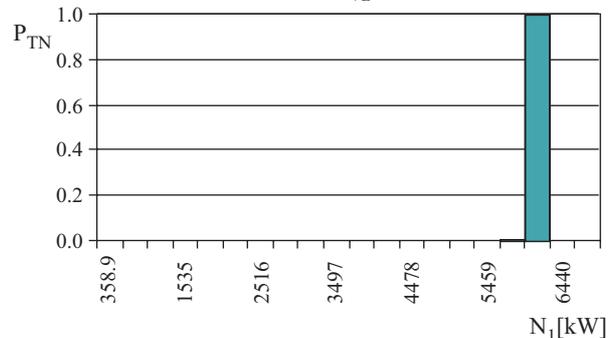
Route no. 2b - $P_{VE} = 0.50$



Nominal power output $N_n = 6930$ [kW]

Mean power output $\bar{N} = 6164$ [kW]

Route no. 5b - $P_{VE} = 0.50$



Mean power output $\bar{N} = 6156$ [kW]

Fig. 12. Histograms and mean statistical values of speed and output of propulsion engine of K1 ship sailing on shipping routes : 2b and 5b

Ship: K1 - assumed service speed = 8.44 [m/s] - mean specific fuel oil consumption (SFOC) in still water, $g = 199.00$ g/kWh

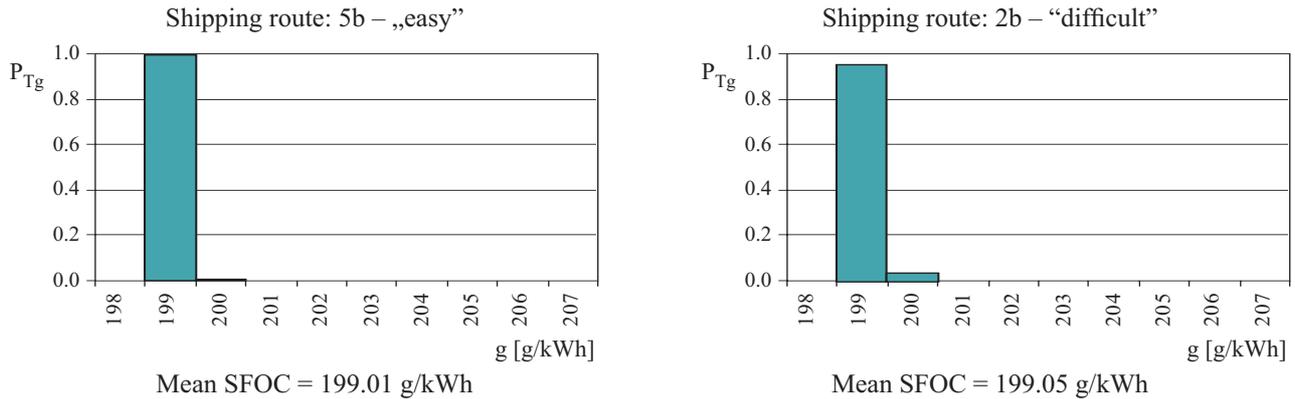


Fig. 13. Histograms and mean statistical values of specific fuel oil consumption (SFOC) for K1 ship sailing on shipping routes : 2b and 5b

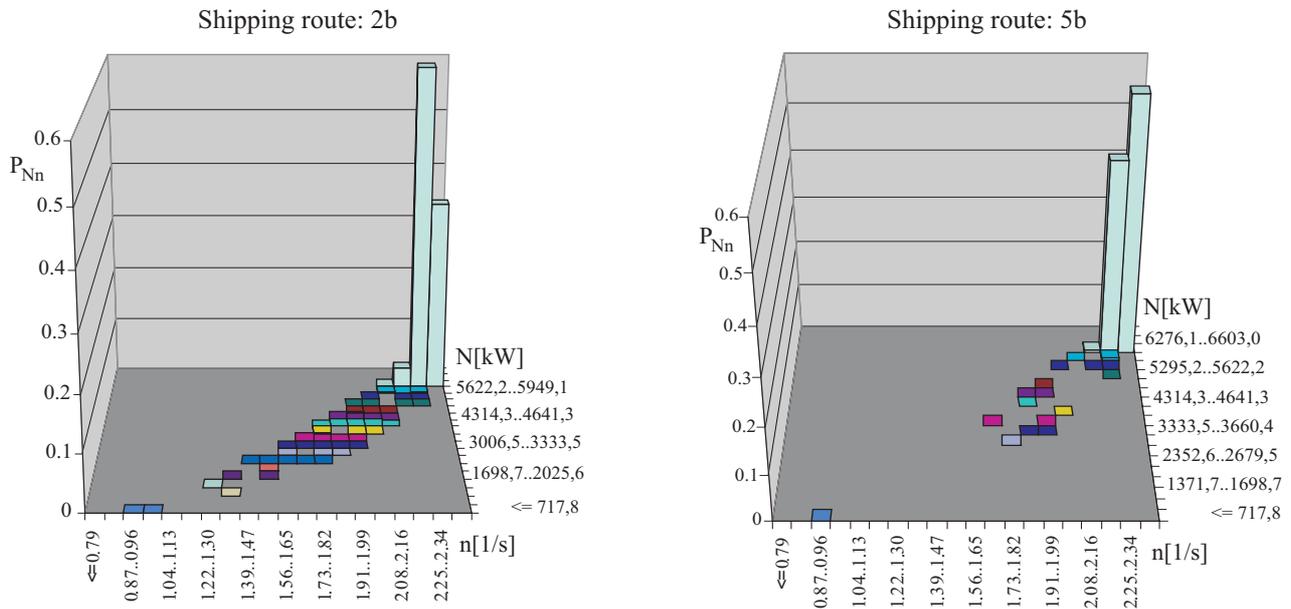


Fig. 14. Probability of occurrence of the propulsion engine's working point (engine speed-output), P_{Nm} for K1 ship sailing on shipping routes : 2b and 5b

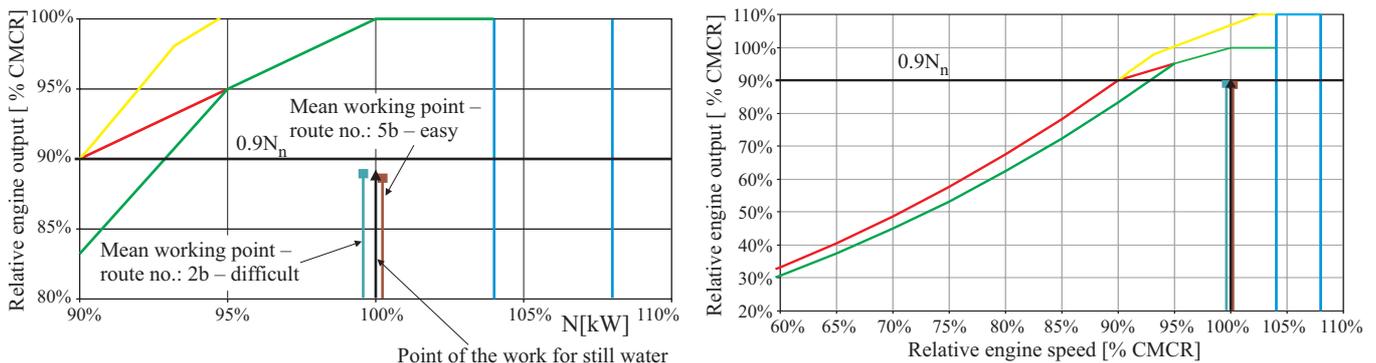


Fig. 15. Mean, long-term working point of propulsion engine of K1 ship sailing on shipping routes : 2b and 5b

FINAL CONCLUSIONS

○ Conclusions resulting from the calculations of mean statistical service parameters of screw propeller were presented in [10]. Results of the calculations of the mean statistical parameters of propulsion engine operation (engine speed, output and specific fuel oil consumption - SFOC) in the form of histograms are very similar to those of screw propeller as the engine in question directly drives

the propeller and the calculated power output is used only for propelling the ship (as no other power consumers were taken into consideration, e.g. shaft generators).

○ The calculations of SFOC were performed for approximate characteristics under the assumption that the engine is new, air and cooling water parameters are standard and ship's hull and screw propeller are clean (un fouled). Therefore the calculation results should be assessed rather qualitatively but not quantitatively.

- The obtained histograms and mean statistical parameters depend not only on weather conditions on a given shipping route but also on an assumed criterion of propulsion control; the presented calculations were performed for the criterion of maintaining the ship speed constant (Variant “b”, Fig. 11) and if it is not possible – for a maximum available speed at the engine power output of $0.9 N_n$ at the most. The assumed criteria of ship propulsion (engine) control highly influence service parameters of propulsion system. This can be observed in the case of the SFOC distribution as well as occurrence probability of a given working point of engine on a given shipping route.
- The condition of maintaining the assumed ship speed may result in a somewhat greater SFOC value on a shipping route where statistically more favourable weather conditions occur than on those of more harsh weather conditions. Hence not only weather conditions occurring on a shipping route are decisive of fuel consumption level. Therefore to obtain a possibly low SFOC level the propulsion control should be optimized by using various criteria (Fig. 11) depending on a given situation. In real conditions also ship course can be changed that consequently is equivalent to shipping route optimization.
- The elaborated computer software makes it possible to choose different control criteria of ship propulsion and optimize both its service parameters and entire shipping route.
- Calculations of probability of occurrence of propulsion engine working point (Fig. 14 and 15) may be also used for assessing the wear level of engine or its elements as well as for scheduling overhauls.

NOMENCLATURE

- g – specific fuel oil combustion (SFOC)
- G – hourly fuel oil combustion
- k_{ep} – coefficient of engine performance characteristic
- N – engine power output
- N_n – nominal engine power output
- \bar{N}_n – mean long-term engine power output
- n – engine speed (number of revolutions per time unit)
- n_n – nominal engine speed
- n_p – propeller speed
- \bar{n} – mean long-term engine speed
- $n_A, n_S, n_{\mu}, n_{HT}, n_V, n_W$ – number of : sea areas crossed by a ship, seasons, values of wave directions, wave parameters, ship speed and course, respectively
- P_D – power delivered to propeller cone
- P_{Nn} – probability of occurrence of a given working point of propulsion engine of the power output N and speed n

- P_{VE} – probability of maintaining a given speed
- P_{TN} – probability of occurrence of a given value of engine power output
- P_{Tn} – probability of occurrence of a given value of engine speed
- p_w – probability of ship being in a given situation
- Q – propeller torque
- ΔR – additional ship resistance due to weather conditions
- T – propeller thrust
- V – ship speed
- V_A – mean wind velocity
- V_E – ship service speed
- η_0 – free-propeller efficiency.

BIBLIOGRAPHY

1. Balcerski A.: *Probabilistic models in the theory of design and operation of ship diesel engine power plants* (in Polish), Publ. by Foundation for Promotion of Shipbuilding Industry & Maritime Economy, Gdańsk 2007
2. Beukelman W., Buitenhek M.: *Full scale measurements and predicted sea-keeping performance of the containership “Atlantic Crown”*, International Shipbuilding Progress, Vol. 21, No. 243, 1974
3. Chachulski K.: *Power problems of operation of ship propulsion systems* (in Polish), Maritime Publishers (Wydawnictwo Morskie), Gdańsk 1991
4. Chachulski K.: *Control of loading state of propulsion engine and its fuel combustion in any service conditions* (in Polish). 14th International Symposium of Ship Power Plants, Szczecin, 1992
5. Chachulski K.: *Methods and algorithms for solving the operation problems of ship propulsion systems* (in Polish). Szczecin Maritime University, Szczecin, 1992
6. Chachulski K.: *Fundamental problems of ship propulsion systems* (in Polish), Maritime Publishers (Wydawnictwo Morskie), Gdańsk 1988
7. Ferdinande V., De Lembre R.: *Service - performance and sea-keeping trials on a car-ferry*, International Shipbuilding Progress, Vol. 17, No. 196, 1970,
8. SULZER : *General Technical Data for Marine Diesel Engines*, 1986
9. Szelangiewicz T., Żelazny K.: *Calculation of the mean long-term service speed of transport ship, Part III: Influence of shipping route and ship parameters on its service speed*, Polish Maritime Research, No 2/2007

CONTACT WITH THE AUTHORS

Prof. Tadeusz Szelangiewicz
 Katarzyna Żelazny, D.Sc., Eng.
 Faculty of Marine Technology,
 Szczecin University of Technology
 Al. Piastów 41
 71-065 Szczecin, POLAND
 e-mail : tadeusz.szelangiewicz@ps.pl