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The effect of hull biofouling on parameters characterising ship propulsion system efficiency

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ABSTRACT

One of most important issues concerning technical objects is the increase of their operating performance. For a ship this performance mainly depends on the efficiency of its main pro-pulsion system and the resistance generated during its motion on water. The overall ship re-sistance, in turn, mainly depends on the hull friction resistance, closely related with the pres-ence of different types of roughness on the hull surface, including underwater part biofouling. The article analyses the effect of hull biofouling on selected parameters characterising the efficiency of the ship propulsion system with adjustable propeller. For this purpose a two-year research experiment was performed on a sailing vessel during its motor navigation phases. Based on the obtained results, three groups of characteristics were worked out for different combinations of engine rotational speed and adjustable propeller pitch settings. The obtained results have revealed that the phenomenon of underwater hull biofouling affects remarkably the parameters characterising propulsion system efficiency. In particular, the development of the biofouling layer leads to significant reduction of the speed of navigation.

Keywords: Ship, hull, biofouling, propulsion system, efficiency

INTRODUCTION

One of most important issues concerning any technical object is the increase of its operating performance. In most common formulation, performance is the result of the undertaken ac-tions which are described by the relation of the obtained results to the incurred expenditures. It depends on many factors, one of which is efficiency. This issue also concerns mobile float-ing objects, for which the incurred expenses mainly depend on the consumption of resources needed for undertaking a given action. The consumption of those resources, in turn, depends on factors affecting the efficiency of the propulsion system, among other agents. For a ship as the watercraft unit, consumption of resources mainly depends on:

- operating efficiency of the main propulsion system,
- motion resistance.

A major part of ship motion resistance is generated by hull friction, which depends on many factors connected with the presence of different types of unevenness on the ship hull surface. One of more important factors acting towards the increase of the resistance during ship operation is biofouling of its underwater part. This phenomenon consists in the formation of a bio-film as a result of action of microorganisms which produce extracellular polymeric substances, with further colonisation of this biofilm by marine flora and fauna. A general origin lays in biological and physical processes taking place in seawater, which depend on the climate zone and the type of applied coatings, among other factors. The above process is becoming more intensive with the increasing age of the ship and the time elapse from hull cleaning and paint-ing during the last ship docking. As a result of the process of the biofouling layer develop-ment, an uneven structure is formed on the ship hull surface. This structure increases the weight and friction resistance of the ship, thus affecting its hydrodynamic characteristics, op-erating speed and manoeuvrability.

The article discusses the effect of ship's hull biofouling on selected parameters characterising the efficiency of the ship propulsion system. For this purpose an experiment was planned to perform a relatively long-term examination of biofouling of the underwater hull part between successive ship dockings. An applicative goal of this research was to create a basis for decision making by a ship owner about economic justification of ship operation with relatively long time intervals between successive dockings.

Evaluating the effect of hull biofouling on parameters characterising ship propulsion efficiency requires excluding the ship, for some time, from normal operation in order to collect data for different meteorological conditions, (the force and direction of wind, for instance), nautical conditions, (the speed and direction of sea current, for instance), and operating conditions, (such as the loading level, for instance), and their correlation with different positions of main propulsion engine settings. That is why a decision was made to carry out these investigations on the sailing ship STS Pogoria. This prototype ship, launched in 1980, is equipped with a barquentine rig. Its gross tonnage is 290 GT, overall length 47.29 m, width 8 m, and draught 3.5 m (data from [5] and ship documentation required by the marine administration). The following characteristic features concerning its navigation can be named:

- low main engine power in relation to the size of the ship,
- certain proportion of motoring (about 50% of navigation during a one-week voyage),
- voyages over very different water regions (Baltic Sea, North Sea, Mediterranean Sea, and Atlantic Ocean with different characteristics of:
  - meteorological, nautical, and operating conditions,
  - biological and physical processes taking place in seawater,
- short voyages (1 to 3 weeks) with short passages between harbours (1 to 4 days),
- relatively long times between successive dockings.

The ship has three navigation modes:

- pure sailing,
- pure motoring,
- hybrid navigation (engine assisted by sails).

As a rule, in all these modes the phenomenon of underwater hull part biofouling affects the hull resistance to the same extent. The reported research was performed only for the second mode of navigation: pure motoring.

SHIP HULL BIOFOULING AND FACTORS AFFECTING THIS PHENOMENON

The "father" of the method to evaluate the ship resistance is believed to be William Froude, a British engineer, who was the first to formulate the laws governing the resistance experienced by ships sailing on water. In 1868, he performed a detailed examination of ship resistance, the results of which were published in [4]. Froude proposed to divide the overall ship resistance into two components: the skin friction resistance and the residuary resistance. In fact, the re-sistance with which water counteracts to the motion of the ship immersed in it is a composi-tion of a number of partial resistances. A detailed description of particular partial resistances can be found in [3], among other sources.

In a general case, the friction resistance is affected by a number of factors resulting from the unevenness of the ship hull surface. These factors can be analysed both in micro- and macro scale. (Fig. 1).

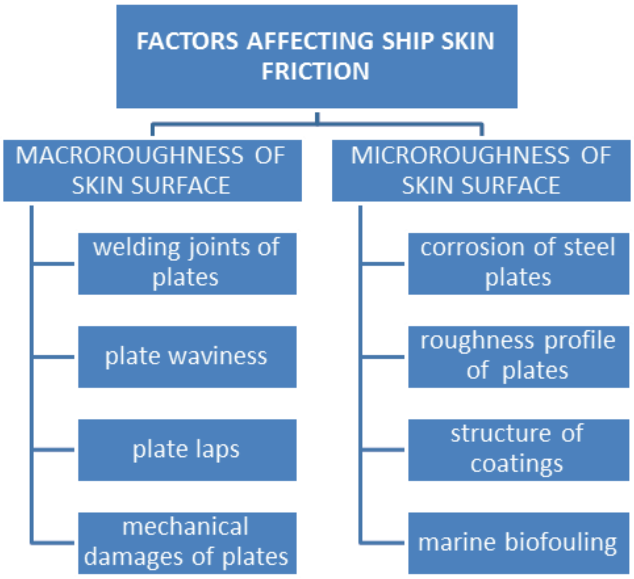

Fig. 1. Classification of factors affecting the hull friction resistance

An essential factor affecting the ship's hull resistance is the phenomenon of biological bio-fouling of its underwater part. Extremely severe hull biofouling can increase hull resistance by as much as 40%, at the same time reducing its speed by 2 knots. The corresponding increase of fuel consumption amounts to 20% [14].

In the literature, hull resistance changes are presented with respect to the last docking (last cleaning of the submersed hull part) used as the reference, or as the process of biofilm for-mation observed in laboratory conditions.

The report [7] of the United States Naval Institute includes diagrams which illustrate, among other issues, the effect of hull biofouling on the increase of its resistance. In particular, the following relations are presented:

- shaft power vs. sailing speed for successive months from last docking,
- shaft power (in percents) vs. months from last docking for different sailing speeds,
- sailing speeds vs. months from last docking fro constant shaft power.

Ref. [9] presents diagrams of the increase of the residuary hull resistance vs. times after dif-ferent types of preservation methods applied to the submerged hull part (skin, screw propel-ler). The data for the diagrams was obtained via measuring power and revolutions of the main engine and making use of the created mathematical model of ship propulsion efficiency. The measurements were performed in similar meteorological conditions and for similar ship loads. Similar diagrams were also presented in [8,10], among other sources.

On the other hand, Ref. [12] reports the research of biological biofouling performed in labora-tory conditions. Sheets of steel used for shipbuilding were covered with anti-biofouling coat-ing materials and immersed in seawater for 12 months. After each month one sheet was lifted from water, cleaned, and covered with anti-biofouling coating again. The research aimed at evaluating the resistance of the examined surface to biofouling. One of the measured parameters was the surface related weight increase of dry biofilm vs. time of sheet staying in sea wa-ter. It was concluded that this relation is not proportional.

Being an undesirable phenomenon, biofouling of submerged surfaces of oceanic objects con-sists in building-up of colonies of microorganisms, plants, algae, and mammals on wet and humid structures. The formation of the biofouling layer is a multi-stage process and consists of four basic phases [2]:

- initiation, i.e. creating favourable conditions for the formation of the biofouling layer,
- attachment of microorganisms,
- colonisation of microorganisms,
- growth of organisms.

This process was visually presented in numerous publications, [2, 6] among other sources, while the mechanism of this process was described in [1]. The process of underwater ship hull part biofouling is exposed to a combined action of various factors of physical, chemical, and biological nature (Fig. 2).

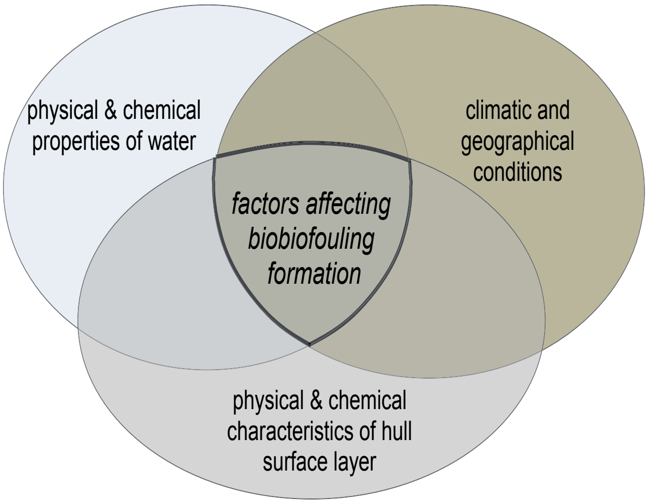

Fig. 2. Combined action of factors affecting the process of formation of a biological layer on the ship hull.

Basic factors affecting the process of formation of the biological layer on the underwater part of the ship hull include:

- temperature of the water in which the ship hull is immersed,
- sunlight illumination of the outer layer of the submerged part of the hull,
- quality of water,
- relative motion of water,
- 'susceptibility' of the outer layer of the ship hull to biofouling, which depends on the roughness of the surface, the applied anti-biofouling coating, and hydrophobicity (ability of chemical particles to repel water particles).

EXAMINING THE EFFECT OF HULL BIOFOULING ON SELECTED PARAMETERS CHARACTERISING SHIP PROPULSION EFFICIENCY

As already mentioned, the most representative watercraft unit for assessing the effect of hull biofouling on selected parameters characterising ship propulsion efficiency seems to be a sail-ing ship which navigates on different water regions with changing meteorological, nautical, and operating conditions. These criteria are met by the sailing ship "Pogoria", equipped with an auxiliary propulsion engine VOLVO-PENTA of nominal power of 228 kW to drive a two-blade adjustable propeller via the reduction gear with gearbox ratio equal to 1:4,5. The nomi-nal rotational speed of the propeller is 356 rpm. During the tests performed for 4 different ship courses, the average speed of the ship was 8,9 knots at the engine rotational speed setting equal to 1600 rpm, and the adjustable propeller pitch setting equal to 17 marks on the steering lever scale. According to the technical data of the propulsion engine [13], the standardised fuel consumption is 212 g/kWh for the rotational speed of 1800 rpm.

Obviously, parameters which characterise the propulsion system efficiency of a ship, including sailing ships, are subject to changes provoked by changes of meteorological, nautical, and operating conditions. In the performed examination, the nautical and meteorological condi-tions, such as the ship course, the force and direction of wind, the speed and direction of sea current, the sea state (height and direction of waves), were considered temporarily constant during the time of measurements, which never exceeded 15 min.

Consequently, the following assumptions were adopted before examination:

- examination is to be performed in still water conditions (the sea state up to 2^0 in Douglas scale) and at the absence of wind or at very light wind (the wind force up to 2^0 in Beaufort scale), to provide opportunities for determining the pure effect of engine rotational speed and adjustable propeller pitch settings on the measured parameters,
- the ship speed in successive months from docking will be measured for the same engine rotational speed and adjustable propeller pitch settings.

Moreover, the list of the assumed temporarily constant parameters also included such operat-ing conditions as:

- draught depending of ship loading and seawater salinity,
- shape of the underwater part of the hull (no deformation resulting from bumping into oth-er objects),
- quality of sail rolling and the deck arrangement of additional objects which can affect air whirling over the deck, etc.

The adopted assumptions and the past experience gained during voyages on sailing ships have enabled to make a preliminary selection of parameters which will be used for evaluating the effect of hull biofouling of STS POGORIA on the selected parameters characterising the pro-pulsion system efficiency (Table 1).

Table 1. Measuring parameters

Parameter	Symbol	Unit
speed over the ground	v	knot
fuel consumption	B_h	l/h
angular momentum of the shaft propeller	M_s	%M_N
engine rotational speed	n_s	rpm
pitch of controllable pitch propeller	H	indicating scale

Values of the parameter 'ship speed over the ground' were read from the GPS receiver.

Values of the parameter 'fuel consumption' were measured using a specially constructed measuring instrument, the operating idea of which consisted in connecting a scaled tank to the main engine fuel installation. A scheme of this installation is shown in Fig. 3.

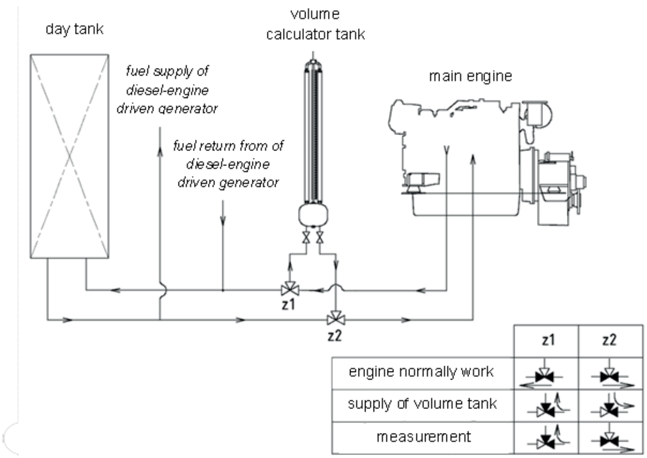

Fig. 3. Scheme of installation for fuel consumption measurements

The three-way L-type valves, marked z1 and z2, enable cutting off the measuring tank once the measurements are completed and return to the normal situation in which the main engine is supplied from the day fuel tank.

Values of the parameter 'propeller shaft torque' were measured using a wireless tensometric torque meter specially installed on the propeller shaft. The torque meter transmits the signal making use of the phenomenon of magnetic induction. The principle of operation of this torque meter is schematically shown in Fig. 4. The torque was read using a deflection gauge (micro ammeter) as percent of the calculated nominal torque.

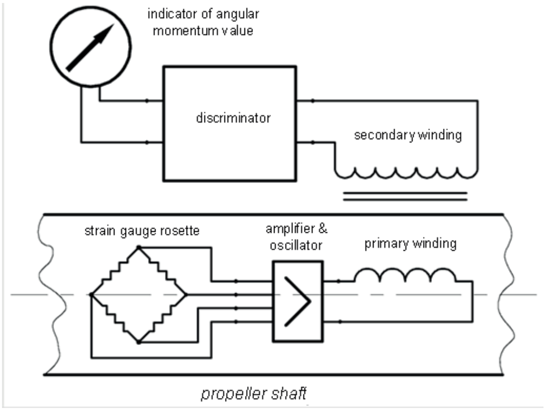

Fig. 4. Principle of operation of torque meter

Settings for the rotational speed of the engine, (and, consequently, of the adjustable propeller) and for the adjustable propeller pitch were selected using two steering levers situated on the navigating bridge.

Values of the propulsion system setting 'engine rotational speed' were read as indications of the speed indicator (with 50 rpm accuracy) being part of standard equipment of the propulsion engine system. The minimal rotational idling speed of the propulsion engine is approximately equal to 530 rpm, while the maximal rotational speed is 2000 rpm. However, there is no direct relation between the position of the steering lever and the engine rotational speed, as setting of the same required rotational speed may correspond to different positions of the common rail (steering lever on the navigating bridge) depending on the current load.

Values of the propulsion system setting 'adjustable propeller pitch' were read as successive positions of the steering mechanism remote control lever. In the given case the propeller pitch was read as the lever position with respect to the disc scaled from -25 to +25 marks (negative values mean sailing backward).

In practice, the available ranges of settings for engine rotational speed and adjustable propeller pitch are limited by meteorological, nautical, and operating conditions, and range between 1100 and 19000 rpm for the engine rotational speed and up to 18 marks in case of the adjustable propeller pitch. Exceeding these limits provokes unacceptably high temperatures of the propulsion system gearbox.

To collect all data needed for evaluation of selected parameters characterising the ship propul-sion system efficiency, 195 observations were performed during 20 months, starting from the time when the ship was docked and the underwater part of the ship's hull was covered with new anti-biofouling coating, which was the controlled depletion polymer CDP INTERSPEED 340. The results of the above observations have been collected and published as the engineer-ing diploma thesis [11].

It was assumed that only those quantities will be used which can be easily determined during the ship voyage by an operator (captain or navigating officer) based on standard navigating and measuring instruments installed on sailing ships. The examination was performed:

- in the assumed weather conditions,
- in different water regions in which the effect of the sea current was negligibly small (at sufficiently large distances from coasts, mainly on the Mediterranean Sea and the Baltic Sea),
- for different combinations of settings for engine rotational speed and adjustable pro-peller pitch.

In total, 10 quantities were recorded, and the results were entered to a special measurement sheet.

The effect of hull biofouling on the parameters characterising ship propulsion system effi-ciency was assessed based on relations between ship speed, propeller shaft torque, and instan-taneous fuel consumption on the one hand, and the hull biofouling related friction resistance component on the other hand.

Other components of the ship resistance were assumed constant, taking into account the fol-lowing circumstances:

- the residuary resistance and the air resistance can be considered negligibly small, as ac-cording to the adopted assumptions – test were carried out during comparable meteorolog-ical and nautical conditions,
- friction resistance components (excluding the component resulting from hull biofouling) have not changed much during the time interval of ship operation examination.

In mechanics, friction resistance is expressed in units of force. Obviously, the friction re-sistance force, including the component resulting from hull biofouling, cannot be measured directly in marine conditions during watercraft unit operation, and indirect methods are to be used. In the reported case an assumption was adopted that the friction resistance component resulting from ship hull biofouling is in relation to the time of biofouling layer formation, i.e. to the time of hull staying in water. Consequently, the time elapse from hull cleaning and painting during the last ship docking was assumed as the parameter characterising the increase of the friction resistance generated by the biofouling phenomenon.

The obtained results of examination have made the basis for preparing three groups of charac-teristics for different combinations of engine rotational speed and adjustable propeller pitch settings, which presented:

- ship speed vs. time elapse from last docking,
- fuel consumption vs. time elapse from last docking,
- propeller shaft torque vs. time elapse from last docking.

Since in month 4, 8, 13 and 17 meteorological conditions made performing tests in the as-sumed conditions impossible, results referring to these months are missed in the diagrams.

The measurements of particular parameters in a given month have revealed that their values differ between each other, although within a small range. Possible reasons for these differ-ences included:

- unavoidable slight differences of meteorological, nautical and operating conditions be-tween consecutive measurements,
- unavoidable errors in measurements of particular parameters: ship speed over the ground, engine revolutions, fuel consumption, and propeller setting with respect to the position of the steering lever which controls its pitch, (the propeller setting lever on the control panel is connected with the steering mechanism of the adjustable propeller via mechanical ten-sion members).

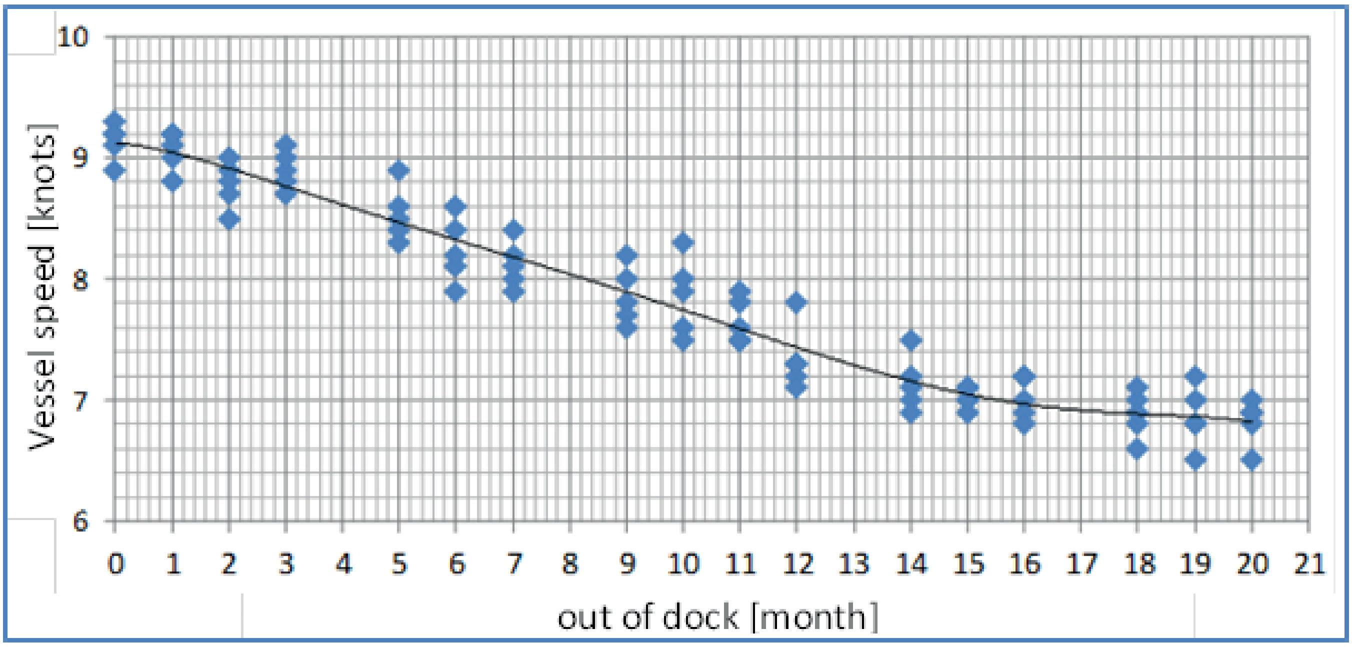

Fig. 5. Ship speed vs. time elapse from last docking

Figure 5 shows the relation between the ship speed and the number of months from the last docking for a combination of the engine rotational speed setting and the adjustable propeller pitch setting equal to, respectively, 1400 [rpm] and 14 [marks], along with the trend curve calculated with the aid of the sixth-order polynomial trend function embedded in Excel.

The performed examination reveals that the ship speed decreases with time, i.e. with the bio-film development on the ship hull. In the examined time interval, i.e. during 20 months of ship operation from last docking, the smallest rate of speed decrease was observed for settings corresponding to low ship speeds, and the highest – for high speeds. This tendency is con-nected with the fact that ship hull biofouling results in the increase of hull friction resistance, and in the resultant speed decrease when the same propulsion system settings are maintained. This decrease is higher for higher propulsion system settings which increase the ship speed. In particular, the speed decrease for the settings shown in Fig. 5 approximately amounted to 25%.

The analysis of the obtained results has proved that particular relations are not linear and reveal characteristic time intervals. Clear increase of the rate of speed decrease can be ob-served between, approximately, month 3 and month 14 from the last docking. A likely reason for this effect is the favourable climate for the development of the biofouling layer (sailing on the Mediterranean Sea), along with short sailing time intervals and frequent calls at harbours. In the time interval starting approximately from month 14 from the last docking, the ship speed decrease is stopped, which is most likely caused by less intensive development of the biofilm layer, or more precisely the final stage of this development. Within one month after the next docking, detailed observations of the underwater hull part were performed at the height of changing draught line of the ship. The dominating structure in the upper part of this line was a green layer shown in Fig. 6. The left-hand side of the picture presents a fragment of the fixed green layer which has been removed using a putty knife.

Fig. 6. Green layer which dominates in the upper part of the changing draught line, and frag-ment of the removed green layer.

The dominating element in the lower part of the changing draught line was a relatively firm and rough layer of crustaceans which composed a uniform and compact structure (Fig. 7).

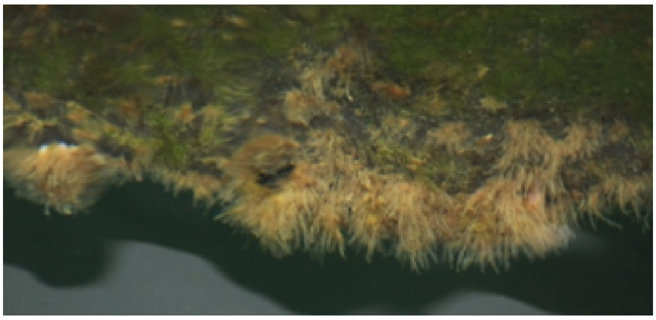

Fig. 7. Layer of crustaceans composing a uniform and compact structure

To analyse the nature of this layer, its fragment was torn off and its photo was taken on the squared background, with the dimensions of squares equal to 5x5 mm (Fig. 8).

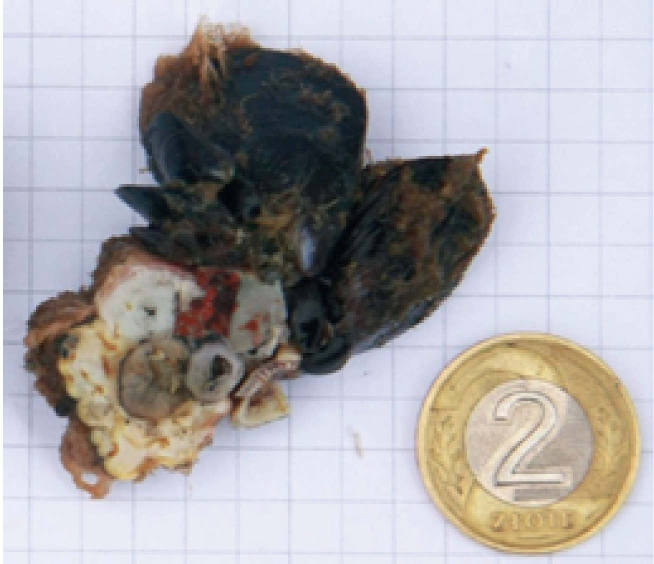

Fig. 8. Torn off fragment of the layer of crustaceans

Organoleptic analysis of the fragment of this layer has revealed that it has the form of com-pact and relatively hard layer of different crustaceans, firmly interconnected with each other. The thickness of the biofilm layer in the vicinity of the changing draught line was approxi-mately equal to 3-4 cm.

Figure 9 shows the propeller shaft torque vs. number of months from the last docking for a combination of the engine rotational speed setting and the adjustable propeller pitch setting equal to, respectively, 1200 [rpm] and 12 [marks], along with the trend curve calculated with the aid of the linear trend function embedded in Excel.

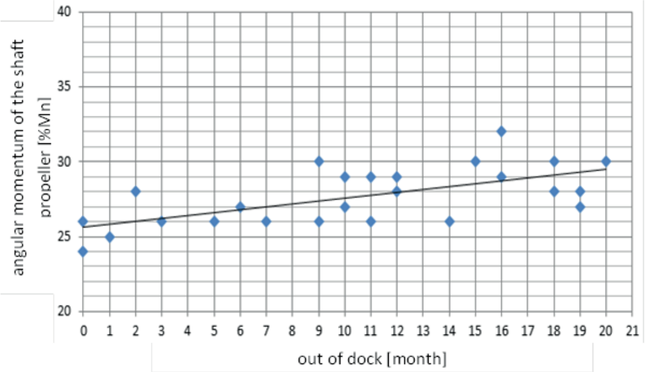

Fig. 9. Propeller shaft torque vs. time elapse from last docking.

The performed examination has revealed that the value of the measured torque increases with the increasing time from the last docking. The increase of the propeller shaft torque in the examined time interval was caused by growing hull biofouling, which decreased the ship speed at the same assumed setting of the adjustable propeller pitch. This, in turn, changed the velocity and structure of the water flow approaching the propeller, thus affecting the propeller characteristics and shifting the point of operation of the entire propulsion system.

Figure 10 shows the fuel consumption vs. time from the last docking for a combination of the engine rotational speed setting and the adjustable propeller pitch setting equal to, respective-ly, 1400 [rpm] and 14 [marks], along with the trend curve calculated with the aid of the loga-rithmic trend function embedded in Excel.

The fuel consumption measurements were started in month 6 after the last docking, which was caused by the fact that at the initial time interval this measurement had been performed using flow meters installed on the fuel inlet to the engine and the return pipe from injector overflows. The fuel consumptions were calculated for successive observations as differences in indications of these flow meters. After some time, it turned out that the results of measure-ments performed using this method were burdened with relatively big errors, due to remarka-ble disturbances having place in the combined return flow from the main engine and two en-gines which drive the electric power generators.

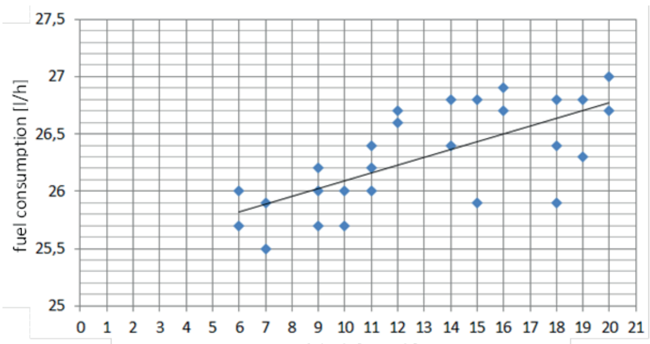

Fig. 10. Fuel consumption vs. time elapse from last docking

The performed examination has revealed that the fuel consumption slightly increases with the increasing time from the last docking. This fuel consumption increase in the examined time interval was mainly caused by the increase of the propeller shaft torque, the reasons of which were given above when discussing the relation between the propeller shaft torque and the time from the last docking. A possible additional cause was the wear of the main engine fuel system elements (injection pump, injectors) being a source of various leaks in this system.

CONCLUSIONS

Based on the results obtained in the reported examination, the following conclusions can be formulated:

- a factor of relatively high importance which increases the ship hull friction resistance is the phenomenon of biofouling of its underwater part,
- the phenomenon of biofouling of the underwater part of the ship hull affect considerably the parameters which characterise the efficiency of its propulsion system, in particular the build-up of the biofilm layer can lead to remarkable decrease of the sailing speed (by about 25%),
- the performed examination can make a basis for a ship owner to make decision about eco-nomic reasonability of operation of a ship with long time intervals between successive dockings.

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