



## EVALUATION OF WORKING SPACES' TECHNICAL CONDITION OF MARINE DIESEL ENGINE ON THE BASIS OF OPERATION RESEARCH

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### Nomenclature

Parameters	Abbreviations and indexes
D – diagnostic measure	BL, BP – left and high cylinder block
$\dot{H}^*$ - exhaust enthalpy flux	CH – cooler
n – crankshaft speed	k1, k2, k3, k4 – specific control sections
p – pressure	R – Roots' compressor
V - volume	OWK – crankshaft revolutions
$\alpha$ – rotation angle	S – compressor
$\tau$ – time	T – turbine

### Abstract

*The paper presents the method of evaluation of the technical state of working spaces of a marine diesel engine at the reduced control susceptibility. The method foresees making diagnosis on the basis of the measurements of exhaust gas pressure in the channels connecting engine cylinders with turbocharger's turbine. In the beginning of the article the research objects are characterized i.e. ZWIEZDA main engine of M401 type and the auxiliary engine DETROIT DIESEL of DDA149TI type. Then, there has been defined a diagnostic measure used to identify the condition of the considered engines. Moreover, there have been presented the selected results of diagnostic tests carried out on the engines being in current operation on warships in the Polish Navy*

*Keywords: marine diesel engines, working spaces, operation, diagnostics*

## 1. Introduction

How to develop methods for assessing a technical condition of the working spaces of marine diesel engines which are not equipped with indicator valves by the manufacturer this is one of the research priorities of the Mechanic-Electric Faculty of the Polish Naval Academy. It will allow users to apply the operation strategies according to the engine technical state. These types of engines, characterized with reduced control susceptibility are widely used in Polish Navy ships. So far they have been operated according to the utility potential utility expressed by the fixed working hours adjusted by the producer, so called the engine's service life (engine's installation time).

The essence of the research was to find diagnostic relations between the technical state of working spaces of the marine engine (cylinders, air and exhaust flow channels and inter-blades' spaces of a turbine and compressor of the turbocharger unit) and the waveforms of pressure alterations in the channels connecting engine's cylinder with a turbine of the turbocharger unit.

The issue of diagnostic research of workspaces of marine diesel engines on the basis of an analysis of thy pressure waveforms in the channels of exhaust gases as a function of time is innovative. To this date, the studies within the gas-dynamic processes of flow channels of combustion engines have been mainly conducted for design development purposes. The results of these works were presented in publications of scientific teams directed by: W. Mitianiec and A. Jaroszewski [3] T. Rychter and A. Teodorczyk [4] and M. Sobieszczanski [5].

## 2. Research problem formulation

The following research problem has been formulated on the basis of an analysis of available specialist literature, results of the article authors' own research and results of diagnostic tests conducted by the leading centers in the country and abroad, dealing with broadly understood diagnostics of piston engines:

*How to conduct diagnostic tests aimed to assess a technical condition of the working spaces of marine diesel engines which are not fitted with indicator valves in standard, during current operation?*

Because a direct quantitative and qualitative evaluation processes inside the cylinders of marine diesel engines which are not equipped with indicator valves is not possible, the problem of diagnostic tests of their workspaces has become a significant operational problem. It results from the introducing warships into service in the Polish Navy equipped with such engines. As the result of conducted simulation studies there has been demonstrated that changes in the technical state of the engine's working spaces cause deformation of the exhaust pressure waveform in the channel powering turbocharger's turbine, thus determining the stream of energy from the turbine's exhaust, and thus the turbine's power, delivery of the charged compressor and thus the engine's performance and efficiency. As the result of experimental studies carried out on real objects there has been confirmed that it is possible to extract the adequate diagnostic parameters that uniquely identify these changes from the set of gasdynamic parameters characterizing pulsating flow of exhaust gases leaving the engine's cylinders. In the case of considered engines the following parameters have been distinguished:

- speed of a movement of the peak amplitude of the pressure wave,
- dispose enthalpy flux of the exhaust in control sections of the outlet channel,
- ratio of harmonic amplitudes of the pressure pulsation in the exhaust duct: the primary amplitude to the amplitude relating to the number of cylinders powering the examined supply channel.

### 3. Characteristics of the research objects

During carrying out the experimental research on the Polish Navy vessels the article authors focused on two the most popular types of marine diesel engines at the reduced control susceptibility. The first engine group consisted of 15 ZVIEZDA marine diesel engine of M401 type - main propulsion engines. The second engine group consisted of 8 DETROIT DIESEL marine diesel engine of DDA149TI type - auxiliary engines.

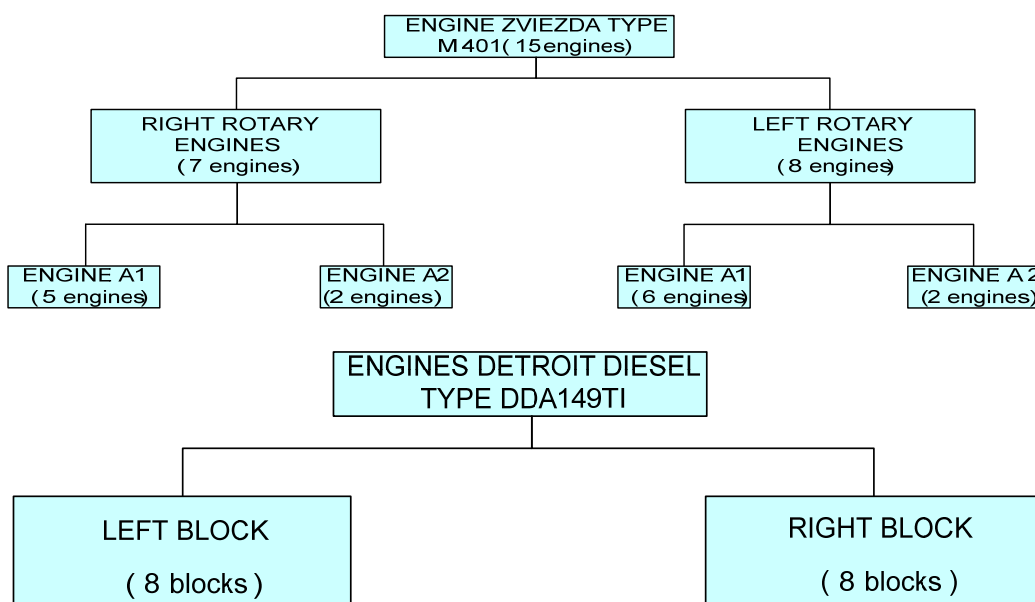


Fig.1. Division of engines into sub-sets as testing objects M4010 type, b) DDA149TI type

As the result, 23 engines have been tested. They are in the current use on the Polish Navy warships, i.e. 46 cylinder blocks, which give a total number of 308 examined cylinders.

The ZVIEZDA engine of M401 type is a four-stroke, V-type, twelve-cylinder engine applied to power small boats (minesweepers of 207 type). The engine is turbocharged by two turbochargers in the pulsation system. A general view of the fluid-flow system of the ZVIEZDA engine of M401 type is shown in figure 2.

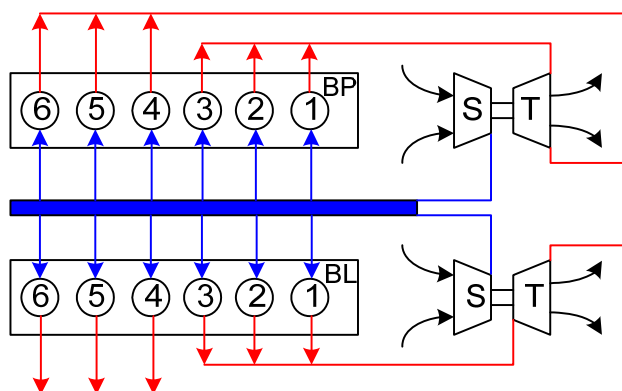


Fig. 2. Schematic diagram of the fluid-flow system of the ZVIEZDA engine of M401 type

The exhaust outlet channels in this engine (powering turbocharger's turbine) are made in the form of two coaxial tubes. The internal one is fed with exhaust from cylinders 4, 5 and 6, while the external one - with cylinders 1, 2 and 3. In addition, the gas flow channel is cooled by means of the external (sea) water by the so-called "water jacket". Such a design of the channel makes difficult the access to the gas space. Technology openings provided by the engine's manufacturer represent only one place where it is possible to install a pressure transducer (fig. 3).

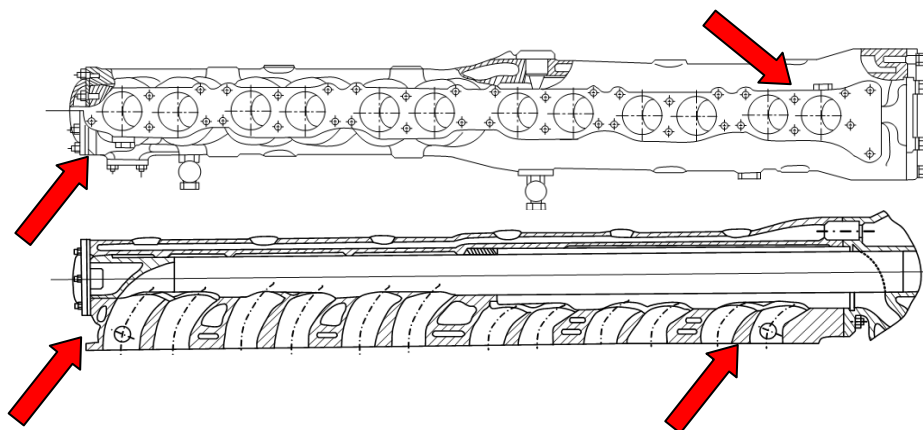


Fig. 3. Exhaust channel of M401 engine with marked places of mounting the pressure transducers

The auxiliary DETROIT DIESEL engine of DDA149TI type, operated on frigates the Oliver Hazard Perry class represents another object of the conducted research. This is a two-stroke, V-type, sixteen-cylinder engine, supercharged in two stages. The first stage of supercharging system consists of four turbochargers - two ones for each cylinder block. The second stage of supercharging system consists of two Roots' supercharging compressors driven directly from the engine's crankshaft. A general view of the fluid-flow system of the DETROIT DIESEL engine of DDA149TI type is shown in figure 4.

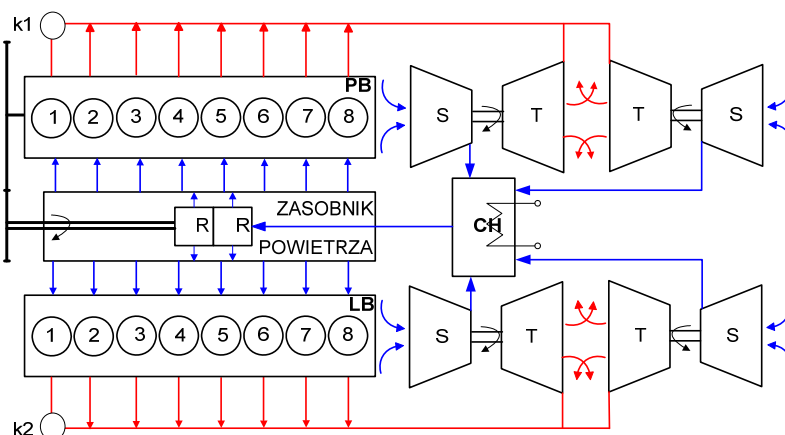


Fig. 4. Schematic diagram of the fluid-flow system of the DETROIT DIESEL engine of DDA149TI type

Similarly to the M401 engines DDA149TI type engines' exhaust channels are cooled through the so called "water jacket". Such a solution makes it difficult to install pressure sensors in any sections of the exhaust channel connecting the engine's cylinders to the turbocharger's turbine. The channel's ends closed with the special sealing covers represent the only one structural component of the channel, which are not cooled with "water jacket", where the sensors measuring the exhaust pressure could be mounted (k1 and k2 in figure 4).

#### 4. Diagnostic measures

Investigations of marine diesel engines necessitate the need to define the diagnostic measurements enabling the univocal identification and location of the occurring engine's technical unfitness states. The analysis of the measurement and usage possibility of the exhaust pressure and temperature in flow channels has been within the conducted research. At the preliminary stage of analysis it was decided to reject the exhaust temperature as a parameter being difficult to measure with an assumed sampling frequency (20kHz), due to the thermal inertia of available thermocouples. Within the further studies, three diagnostic measures were applied, which are based on the pressure measurement in selected specific sections of the exhaust outlet channels.

The velocity of the peak amplitude of the pressure wave in the exhaust outlet channel represents the first one defined diagnostic measure. A value determination of this diagnostic measure requires two pressure sensors placed in the exhaust outlet channel, distanced each other by at least 50 cm. The measure equals the relation of the road (understood as the distance between the sensors) to the time of running the peak amplitude of the exhaust pressure wave between the sensors. The principle of determining the speed of movement of the peak amplitude of the pressure wave is shown in figure 5. A real application possibility of the so-defined diagnostic parameter to assess the engine working spaces' technical state have been tested on the AL type SULZER engines, where its diagnostic informativeness was confirmed [1,2]. But, there is no possibility to install simultaneously two pressure sensors in the exhaust outlet channel of the considered ZVEZDA and DETROIT DIESEL engines. Hence, it was not possible to apply this diagnostic measure for these engines.

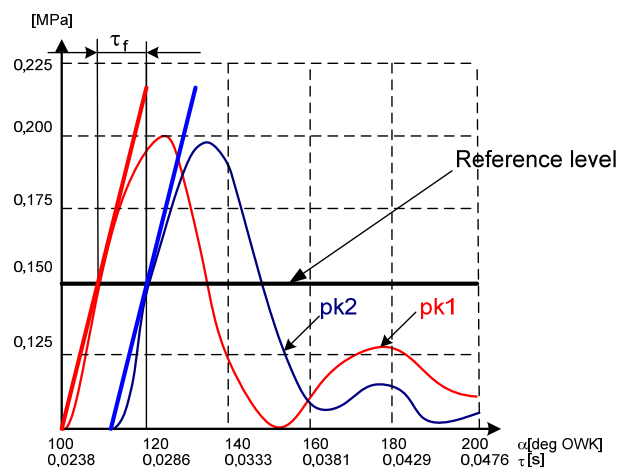


Fig. 5. The principle of determining the peak velocity amplitude of the wave pressure in the exhaust outlet duct

A disposed enthalpy flux of exhaust stream in characteristic test cross-sections of the outlet channel stands for another diagnostic measure used in experimental research. It is defined as an integral of the pressure waveform's course in terms of an angle of the engine's crankshaft revolution with reference to the time (relation 1, 2 and 3). An exemplifying course of the exhaust pressure waveform in the control section of the outlet channel, recorded during the experimental tests of the engine M401 is shown in figure 6.



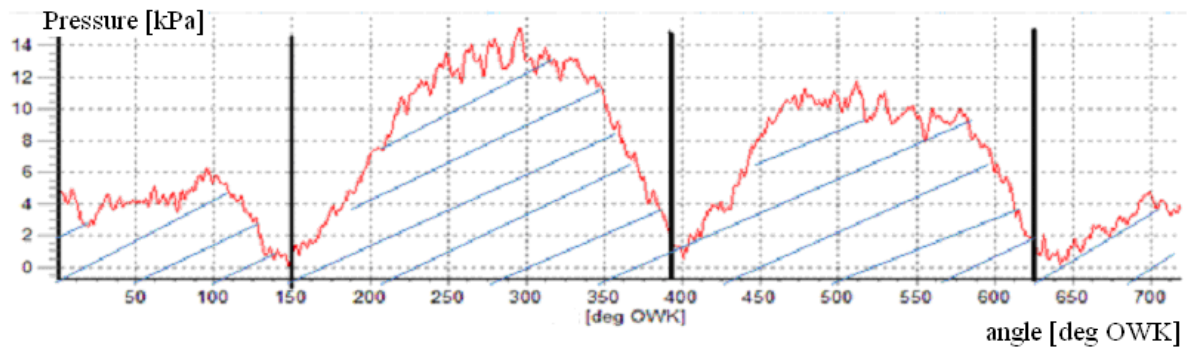


Fig. 6. Waveform course of exhaust pressure in the outlet channel of ZVIEZDA M401 marine diesel engine as a function of an angle of the crankshaft revolution

The course of exhaust pressure as a function of an angle of the crankshaft revolution was integrated within the value's limits of an angle of the crankshaft revolution corresponding to the engine's cycle:

- for four-stroke engines the following relation was used:

$$\dot{H}_{(OWK)}^* = \int_0^{720^\circ} (V \cdot p) d\alpha \quad (1)$$

- whereas for two-stroke engines:

$$\dot{H}_{(OWK)}^* = \int_0^{360^\circ} (V \cdot p) d\alpha \quad (2)$$

There could be proved for the considered engines that the mean volume of all the cylinders feeding the cumulative channel is constant over the time [1], therefore, the value of the integral described by equation 2 and 3 is dependent on the course alterations of pressure values.

In to determine disposed enthalpy flux the value obtained from integration must be multiplied by a coefficient which converts angle degrees of the engine's crankshaft revolution to the corresponding time expressed in seconds. The appropriate calculation formula can be written as follows:

$$\dot{H}^* = \frac{n}{60 \cdot 360} \cdot \dot{H}_{(OWK)}^* \quad (3)$$

In addition, the limits of integration could be determined in such a way to determine the enthalpy flux of the exhaust streams generated by individual engine's cylinders by analyzing the pressure waveform shown in figure 6 and the working sequence of the engine's individual cylinder sections. It restricts the area of searching the unfitness state to the concrete cylinder section.

The ratio of harmonics' amplitudes  $D$  of the registered exhaust pressure represents the last measure used in operation investigations of marine diesel engines, defined as: the basic harmonic to the harmonic corresponding to the number of cylinders powering the examined flow channel (expression 4).

$$D = \frac{A_1}{A_n} \quad (4)$$

The examples of frequency characteristics for two different states of technical fitness are shown in figure 7



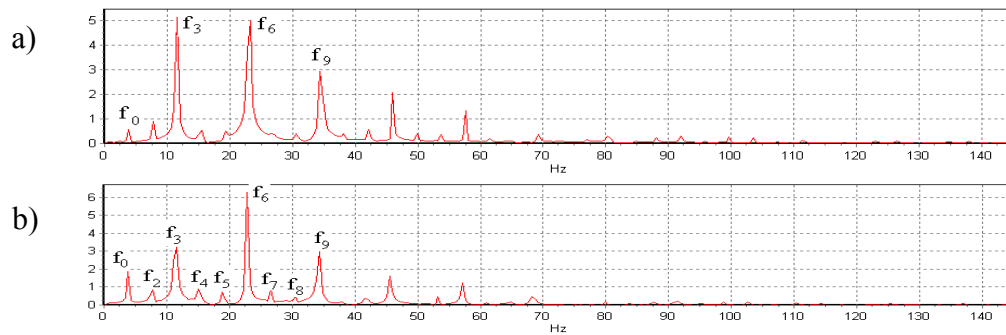


Fig. 7. An amplitude spectrum of the pressure pulsation in the exhaust channel of SULZER 6AL20/24 type engine for the crankshaft rotational speed equals  $492 \text{ min}^{-1}$   
 a) in a state of the full-service fitness, b) in the partial operation suitability - No.1 cylinder leaks.

## 5. Representative research results

The engines ZVIEZDA M401 type and DETROIT DIESEL DDA149TI type have been covered by a passive experiment. Pressure waveforms for characteristic control cross sections of the exhaust outlet channel as a function of the sample's number were recorded as the result of the worked out studies. By knowing the sampling frequency these waveforms can be treated as a function of time. An exemplifying course of the exhaust pressure for the test engine is shown in figure 8.

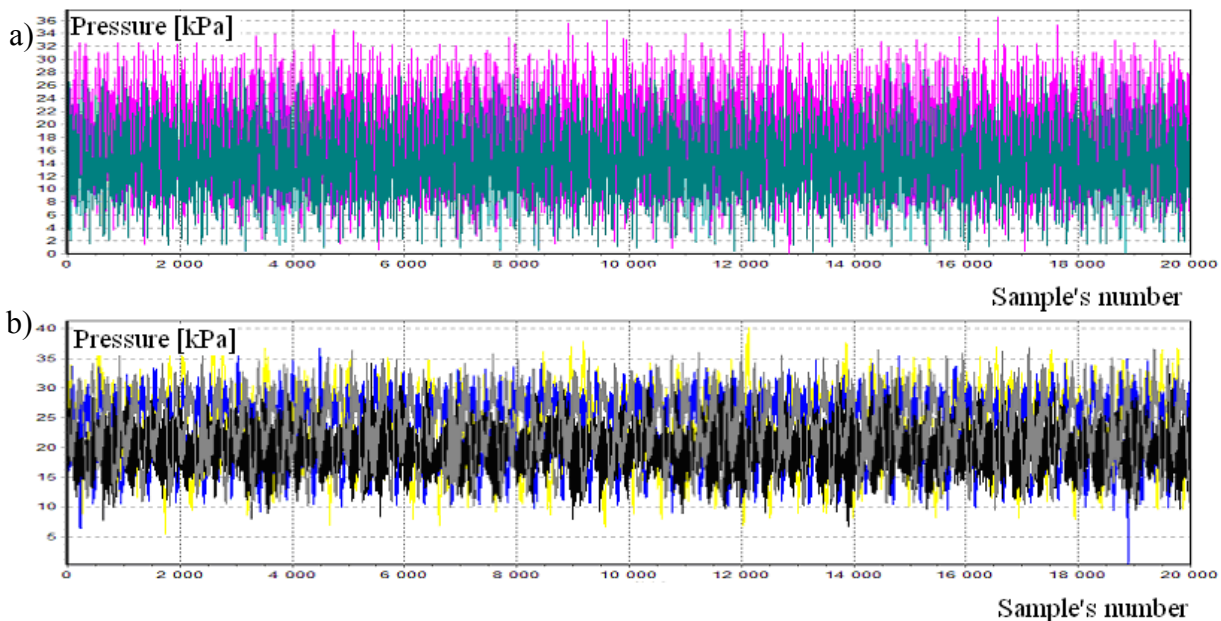


Fig. 8. Pressure waveforms in the selected control cross-sections of the exhaust channel as a function of the sample's number

a) ZVIEZDA engine M401 type, b) DETROIT DIESEL engine DDA149TI type.

A transformation to the pressure courses as a function of an angle of the crankshaft rotation has been worked out on the basis of the recorded pressure courses, as a function of the sample's number (fig. 9)

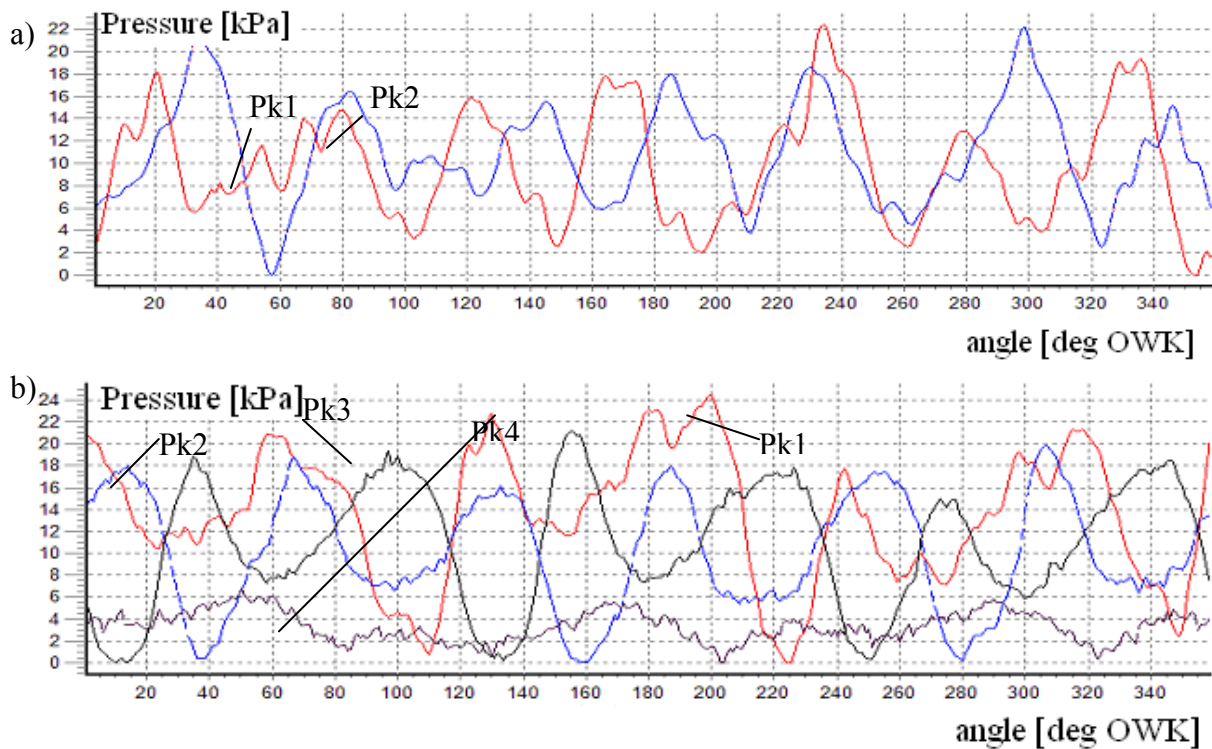


Fig. 9. Waveform of the gas pressure in the monitoring cross channel exhaust gases as a function of the angle of rotation of the crankshaft: a) engine type M401 ZVIEZDA, b) DETROIT DIESEL engine type DDA149TI.

As the result of integrating the exhaust pressure courses recorded in the characteristic control cross-sections of the exhaust outlet channel as a function of the rotation angle a disposed enthalpy flux flowing from the individual engine cylinders were obtained. A bar graph presenting the computed values of this diagnostic parameter for each of the cylinder sections of ZVEZDA engine M401 type is shown in figure 10

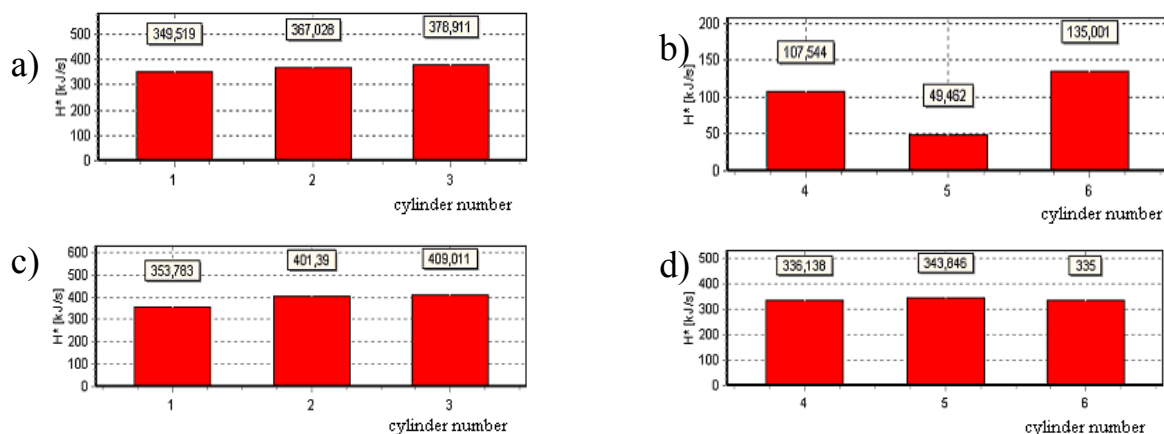


Fig. 10. Disposed enthalpy flux flowing from the individual cylinder sections of ZVEZDA engine M401 type a) 1, 2 and 3 cylinder of the right block, b) 4, 5 and 6 cylinder of the right block, c) 1, 2 and 3 cylinder of the left block, d) 4, 5 and 6 cylinder of the left block.

A received frequency characteristics representing the result of a spectral analysis of the exhaust pressure time courses recorded for the selected control cross-sections are shown in figure 11.



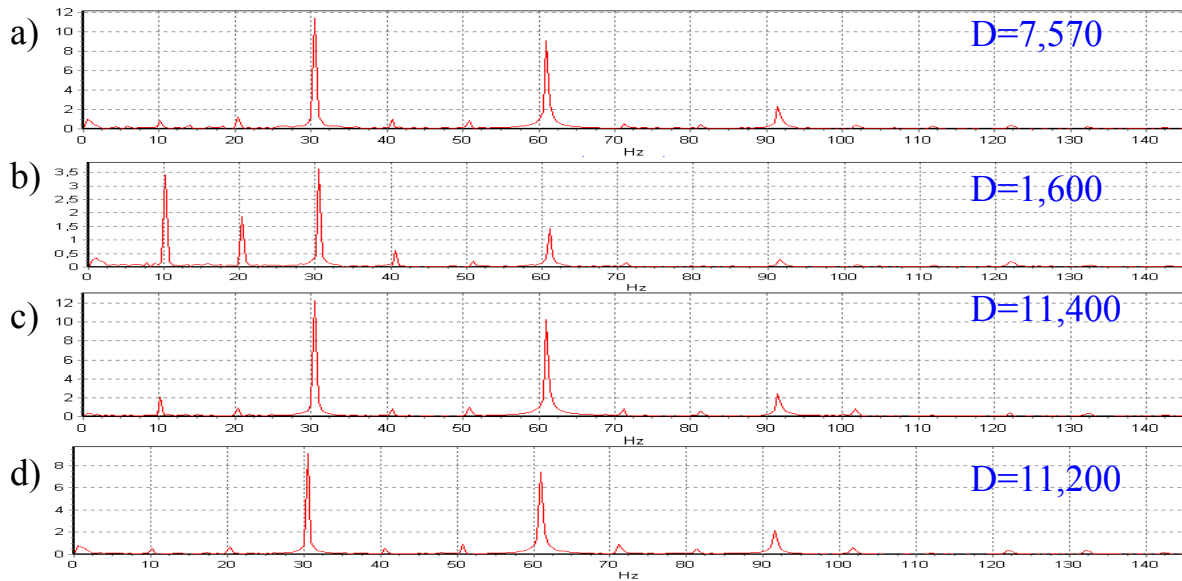


Fig. 11. Frequency characteristics of the time course of the exhaust pressure pulsation in control cross-sections for M401 engine along with the marked values of the diagnostic measure assigned by "D"  
 c) 1, 2 and 3 cylinder of the right block, b) 4, 5 and 6 cylinder of the right block,  
 d) 1, 2 and 3 cylinder of the left block, d) 4, 5 and 6 cylindre of the left block.

It can be concluded from the data presented in figures 10 and 11 that the combustion process worked out in 4, 5 and 6 cylinders group of the right cylinder block is incorrect. This is proved by the values of the diagnostic measures  $D$  (amplitude relation of the primary harmonic of pressure in the exhaust outlet channel to the third harmonic) and by the values of disposed enthalpy flux  $\dot{H}^*$ . It can be also concluded from the analysis of quantity data shown in figure 11b) that the abnormal combustion process takes place in the cylinder number 5 of the right cylinder block. In order to confirm the formulated diagnosis the injectors of 4, 5 and 6 cylinder of the right cylinder block were dismantled and checked. Well visible corrosion traces have been observed on the injector of cylinder 5. This is evidence that disturbances within the fuel combustion process in this cylinder had been taken place (fig. 12b).

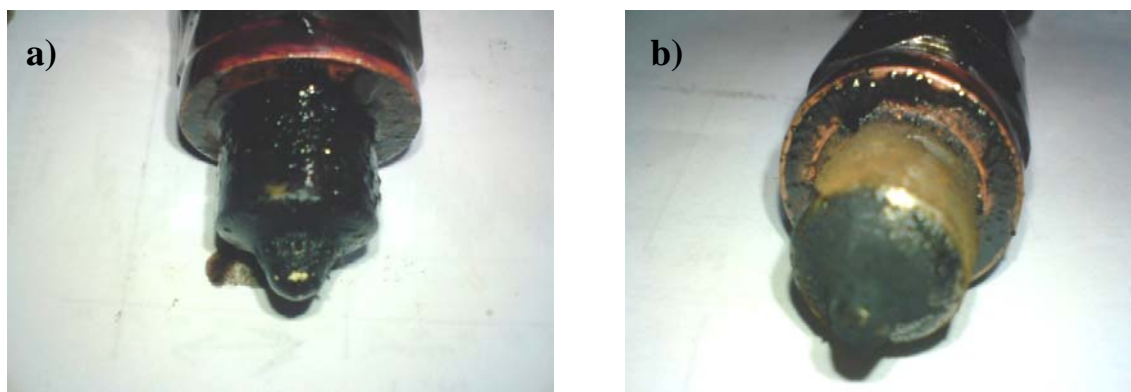
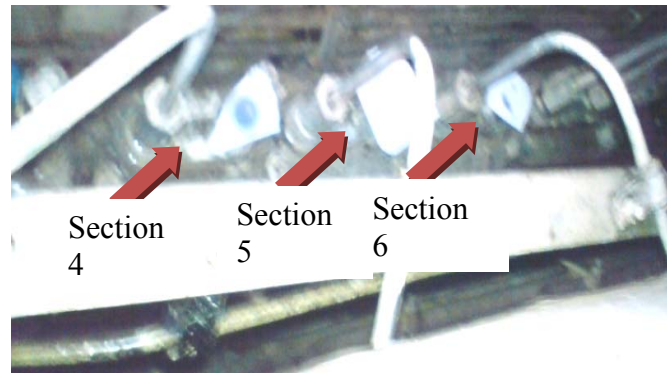


Fig.12. Injectors screwed out from the right engine block of M401 engine  
 a) injector of cylinder No. 4, b) injector of cylinder No. 5.

The injectors' checking on the test bed was the next step of diagnostic investigation. There was confirmed that the injector opening pressure is compatible with the value incorporated in the engine's technical documentation. Moreover, the fuel spray picture did not also deviate from the



norm. After exclusion of the injector's the tests on a proper performance of the injection pump were carried out as failure the next step of diagnostic activities. For this purpose, high pressure pipes of 4, 5 and 6 cylinder of the engine's right cylinder block were dismantled. Paper flakes were laid in places of the dismantled pipes and the engine crankshaft was rotated. The fuel doses were observed on the flakes covering sections 4 and 6 of the injection pump, while the fuel was not observed on the flake covering section 5 (fig. 13). A lack of the fuel dose on the flake covering the connector of section 5 of the fuel pump testifies its damage.



*Fig. 13. A view of the fuel pump during its testing*

## 6. Conclusion

The method, presented in the paper, is foreseen for assessing the technical condition of the working spaces of marine diesel engines which are not equipped with indicator valves. The method represents the main achievement of the worked out research project No 0T00B02129 and Ph.D. dissertation defended by Marcin Zacharewicz in 2010. Its implementation to the marine engines operated in the Polish Navy will permit a passage from the less effective strategy of an operation according to the hourly service life to the operation according to the engine's technical shape.

The practical usefulness of the proposed method for assessing the engine's technical condition was confirmed during the research on real objects. It is worth mentioning that the conducted research resulted in early detection of the unfitness of the engine's injection pump, which before did not generate the observable alteration of other diagnostic symptoms.

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