

ALTERNATIVE DIAGNOSTIC METHOD APPLIED ON MARINE DIESEL ENGINES HAVING LIMITED MONITORING SUSCEPTIBILITY

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Nomenclature

Parameters:	V – volume
a – sound velocity	α – rotation angle
c – exhaust flow velocity	χ – isentropic exponent
c_p – specific heat at constant pressure	ρ – density
D – diagnostic measure	τ – time
f – frequency	Abbreviations and indexes:
\dot{H}^* – exhaust enthalpy flux	BL, BP – left and high cylinder block
i – number of cylinder feeding channel	CH – cooler
L – distance	OWK – crankshaft revolutions
m – number of strokes on one working cycle	R – Root’s compressor
\dot{m} – mass rate of flow	S – compressor
M_a – Mach number	T – turbine
n – crankshaft rotational speed	f – wave
p – pressure	imp – impulse
R – individual gas constant	k1, k2, k3, k4 – specific control sections
T – temperature	sp – exhaust
v_f – velocity of a peak pressure amplitude	

Abstract

The paper presents a method of technical state evaluation of working spaces of a marine diesel engine at the limited control susceptibility. The method foresees making diagnosis of the engine’s working spaces on the basis of measurements of the exhaust gas pressure in the channels connecting engine cylinders with turbocharger’s turbine. Diagnostic measurements are carried out at representative (comparative) steady loads depending on floating conditions.

In the beginning of the article the research objects are characterized i.e. ZWIEZDA marine main engine M401 type and DETROIT DIESEL marine auxiliary engine DDA149TI type. Then, a diagnostic measure used to identify the condition of the considered engines are defined. Moreover, selected results of diagnostic tests carried out on the engines being in current operation on warships in the Polish Navy are demonstrated. The tested diagnostic classifiers confirmed that the elaborated method could be successfully applied for the engine which are not equipped with indicator valves.

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? Nowadays, this is one of the research priorities in the Polish Navy. It will allow users to apply the operation strategies according to the engine technical state. These types of engines, characterized with limited control susceptibility are widely used in the Polish Navy warships. So far they have been operated according to the utility potential 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 diagnostic research issue of workspaces of marine diesel engines on the basis of the pressure waveforms analysis in the channels of exhaust gases as a function of time could be viewed as the innovative one. For the time being, the studies within the gas-dynamic processes of combustion engines flow channels have been mainly conducted for design development purposes. The results of these works were widely presented in publications of scientific teams directed by: W. Mitianiec and A. Jaroszewski (Mitianiec, 1993) T. Rychter and A. Teodorczyk (Rychter, 1990) and M. Sobieszcański (Sobieszcański, 2000).

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 local and foreign centers** 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 of the processes inside the marine diesel engines cylinders, 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 introducing warships equipped with such engines into service by the Polish Navy. On the basis of conducted simulation studies it has been proved that the changes in the technical state of the engine's working spaces cause deformations of the exhaust pressure waveform in a channel that powers a turbocharger's turbine determining the exhaust energy stream in front of the turbine, and at the same time - the turbine's power, supercharging compressor's **delivery and, finally, the engine's performance and efficiency**. As a result of the experimental studies carried out on real objects it has been confirmed that it is possible to extract the adequate diagnostic parameters that uniquely identify these changes from the set of thermodynamic parameters characterizing pulsating flow of exhaust gases leaving the engine's cylinders (Korczewski 2010). In the case of considered engines the following parameters have been distinguished:

- velocity of a peak pressure amplitude,
- **dispose enthalpy flux of the exhaust in the outlet channel control sections,**
- 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 ZWIEZDA marine diesel engines M401 type - main propulsion engines. The second engine group consisted of 8 DETROIT DIESEL marine diesel engines DDA149TI type - auxiliary engines.



As the result, 23 engines have been tested. They are currently used in the Polish Navy warships, i.e. 46 cylinder blocks, which give a total number of 308 examined cylinders – Fig. 1.

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 M401 type is shown in Figure 2.

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).

The auxiliary DETROIT DIESEL engine 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 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 DDA149TI type is shown in Figure 4.

Similarly to the M401 engines DDA149TI type engines' exhaust channels are cooled by means of 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 components 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. It was assumed that the diagnostic parameters were measured and analysed during the engine steady work (steady

load). The analysis of the measurement possibility and usefulness of the exhaust pressure and temperature in flow channels has been covered 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.

During the measurements of pressure in control cross-sections of the exhaust outlet channel, each of the signals was registered simultaneously by two sensors at 20 kHz frequency. In order to eliminate an occurrence of the aliasing phenomenon, a low-pass filter was applied. The filter restricts a sampled signal to the frequency below Nequist's frequency, which in the carried out investigations equaled 10 kHz. In the performed measurements, the low-pass filter was eliminating frequencies above 8 kHz (2 kHz margin was applied to cover a transitory interval of the filter's profile) (Zacharewicz, 2009).

The pressure's measuring error resulting from a resolution of the applied transducer (12 bit) equals ± 171 Pa. It yields 0.024 % at the measuring range $0 \div 0.7$ MPa. It should be also pointed out, that measuring lines as well as applied amplifiers introduce error about 2%. Overall, a total measurement error oscillates within 2% of the measuring range.

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 **peak pressure amplitude** 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 velocity of a peak pressure amplitude 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 SULZER AL type engines, where its diagnostic informativeness was confirmed (Dornseifer, 1981, Korczewski, 2009). But there was 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, but still it was possible to fix one pressure sensor in the exhaust outlet channel. It was enough to evaluate their technical state by means of two other diagnostic parameters remaining i.e. dispose enthalpy flux of

the exhaust in control sections of the outlet channel as well as 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.

It is well known, that the temporary values of impulses' energy oscillate around the average constant value for the steady load's range, according to the complex periodical function, with frequency of the first harmonic described with a formula, as follows (Rychter, 1990, Mitianiec, 1993):

$$f_1 = 2 \frac{i \cdot \omega}{m} \quad (1)$$

The averaged, within one engine's working cycle, value of an enthalpy of the exhaust pressure impulse in characteristic control sections of the flow channel feeding the engine's turbocompressor marks an expression:

$$\bar{H}_{imp} = \int_0^{\tau} \dot{m}_{sp} \cdot c_{sp}(T_{sp}) \cdot T_{sp} d\tau \quad (2)$$

The alterations of enthalpy flux distribution settled for the steady representative engine's loads, related to standard values registered in the initial period of its usage are able to represent a very valuable source of diagnostic information about a technical state of the turbocompressor's turbine, and also about a technical state of the load exchange system.

The most often applied method for the evaluation of energetistic profiles of the channel feeding the engine's pulsatory supercharging system consists in determination of temporary values of the exhaust stream thermodynamic parameters in the separated control volume of the channel. This method bases on measurements of the spreading's velocity of exhaust pressure waves which is formed after the outlet valve's opening.

The wave moves with sound velocity through a cumulative connecting channel in direction to the turbine's nozzle. This sound velocity depends mainly on the exhaust temperature. The velocity of spreading the peak amplitude of the pressure wave v_f stands for the sum of temporary values of the sound velocity a and the exhaust flow velocity in the channel c :

$$v_f = a + c \quad (3)$$

Because the sound velocity in the exhaust expresses a formula:

$$a = \sqrt{\chi \cdot R \cdot T_{sp}} \quad (4)$$

and the exhaust flow velocity in the channel represents the function of Mach number M_a :

$$c = a \cdot M_a \quad (5)$$

thus:

$$v_f = \sqrt{\chi \cdot R \cdot T_{sp}} \cdot (M_a + 1) \quad (6)$$

This way the expression described a temporary value of exhaust temperature was finally received:

$$T_{sp} = \frac{v_f^2}{\chi \cdot R \cdot (M_a + 1)^2} \quad (7)$$

The velocity of spreading the peak amplitude of the pressure wave v_f as well as the Mach M_a number occurring in formula (7) are defined on the basis of measurements of temporary values of total pressure p_1^* and temporary values of static pressure, p_1, p_2 registered in two control sections 1 and 2 of the exhaust channel being located one from another by known distance L - Fig. 5a.

The velocity of spreading the peak amplitude of the pressure wave v_f is calculated as follows:

$$v_f = \frac{L}{\tau_f} \quad (8)$$

where: τ_f – the time of spreading the peak amplitude of the pressure wave from control section 1 to control section 2 of the considered flow channel.

The Mach number M_a defines a formula binding the static pressure p_1 and total pressure p_1^* as well as quotations of the isentropic process realized conventionally during accumulation of exhaust stream in control section 1 of the flow channel:

$$\frac{p_1^*}{p_1} = \left(1 + \frac{\chi - 1}{2} \cdot M_a^2\right)^{\frac{\chi}{\chi - 1}} \quad (9)$$

thus:

$$M_a = \sqrt{\frac{2 \cdot \left[\left(\frac{p_1^*}{p_1} \right)^{\frac{\chi-1}{\chi}} - 1 \right]}{\chi - 1}} \quad (10)$$

The introduced method makes it possible to determine temporary values of the exhaust temperature, which is the averaged value in time τ for the channel capacity being limited by control sections 1 and 2. In this regard a distance between control sections should be the smallest under the condition of assuring the required measurement precision of the time of spreading the peak pressure amplitude in the separated control volume.

In a similar way, by using measurements of the velocity of spreading the pressure impulses, a temporary value of the mass rate of exhaust flow in a separated volume of the flow channel is defined:

$$\dot{m}_{sp} = A \cdot c \cdot \rho_{sp} \quad (11)$$

where a temporary value of exhaust velocity defines a formula:

$$c = M_a \cdot \frac{L}{\tau \cdot (M_a + 1)} \quad (12)$$

and a temporary value of exhaust density – a formula:

$$\rho_{sp} = \frac{p_1}{R_{sp} \cdot T_{sp}} \quad (13)$$

An amplitude of the exhaust pressure's impulse in the individual control sections of the channel that feeds a turbocompressor, and so the exhaust energy and turbine's power are changed in the result of flow resistances within the way between an outlet valve and the turbine's nozzle, as well as in the result of interference and reflection of the pressure waves generated by the other cylinders, that co-operate with the considered channel.

The presented computational algorithm enables carrying out an analysis of changeability of a disposed enthalpy flux of exhaust feeding the engine's turbocompressor, treated as the averaged value in the separated volume of the connecting channel limited by control sections 1 and 2.

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.

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:

$$\dot{H}_{(OWK)}^* = \int_0^{720^\circ} (V \cdot p) d\alpha \quad (14)$$

- whereas for two-stroke engines:

$$\dot{H}_{(OWK)}^* = \int_0^{360^\circ} (V \cdot p) d\alpha \quad (15)$$

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 (Korczewski 2009), therefore, the value of the integral described by equation 14 and 15 is dependent on the course alterations of pressure values.

In order 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:

$$\dot{H}^* = \frac{n}{60 \cdot 360} \cdot \dot{H}_{(OWK)}^* \quad (16)$$

In addition, the integration limits could be determined in such a way to evaluate 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 17).

$$D = \frac{A_1}{A_n} \quad (17)$$

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

5. Representative research results

The ZVIEZDA engines M401 type and DETROIT DIESEL engines 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.

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).

By integrating exhaust pressure courses (recorded in the characteristic control cross-sections of the exhaust outlet channel as a function of an angle of the crankshaft revolution) the disposed enthalpy flux flowing from the individual engine cylinders can be calculated. 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.

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.

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 cyl-

inder 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).

The injectors' checking on the test bed was the next step of diagnostic investigation. It 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 failure, the tests on a proper performance of the injection pump were carried out as 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.

6. Conclusions

A diagnostic method, presented in the paper, enables condition monitoring of working spaces of marine diesel engines which are not equipped with indicator valves in standard (direct cylinder pressure measurements are not possible). The condition assessment is based on thermodynamic and spectral analysis of waveform time courses of the exhaust gas pressure registered in delivery channels of a turbocharger's turbine. Three diagnostic parameters extracted from the courses have been successfully applied to identify technical state alterations of the marine engine working spaces: velocity of a peak pressure amplitude and dispose enthalpy flux of the exhaust in control sections of the channels that connect engine cylinders with a turbocharger's turbine as well as a ratio of harmonic amplitudes of the pressure pulsation in the exhaust ducts.

The elaborated method is especially designed for the engines with pulsatory exhaust-driven superchargers. Its implementation to that kind of marine engines operated in the Polish Navy warships enables their users to carry out more durable, more reliable and lower cost, so called Condition Based Maintenance operation strategy combined with Planned Maintenance strategy.

A practical usefulness of the proposed method for assessing the engine's technical condition was confirmed during examinations of the objects covered with the research project. It is worth mentioning that the systematically conducted measurements resulted in early detection of the failure of the engine's injection pump, which had not generated the observable alterations of other diagnostic symptoms.

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Figure captions

Fig. 1: Division of engines into sub-sets as testing objects M4010 and DDA149TI type.

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

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

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

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

a) measurement test bed and measurement technology, b) diagnostic parameter evaluation.

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.

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 min^{-1}

a) in a state of the full-service fitness, b) in the partial operation suitability - No.1 cylinder leaks.

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.

Fig. 9: Waveforms of the gas pressure in the selected control cross-sections of the exhaust outlet channel as a function of an angle of the crankshaft rotation

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

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,
b) 1, 2 and 3 cylinder of the left block, d) 4, 5 and 6 cylinder of the left block.

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"

a) 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 cylinder of the left block.

Fig.12: Injectors removed from the right engine block of M401 engine

a) injector of cylinder No. 4, b) injector of cylinder No. 5.

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

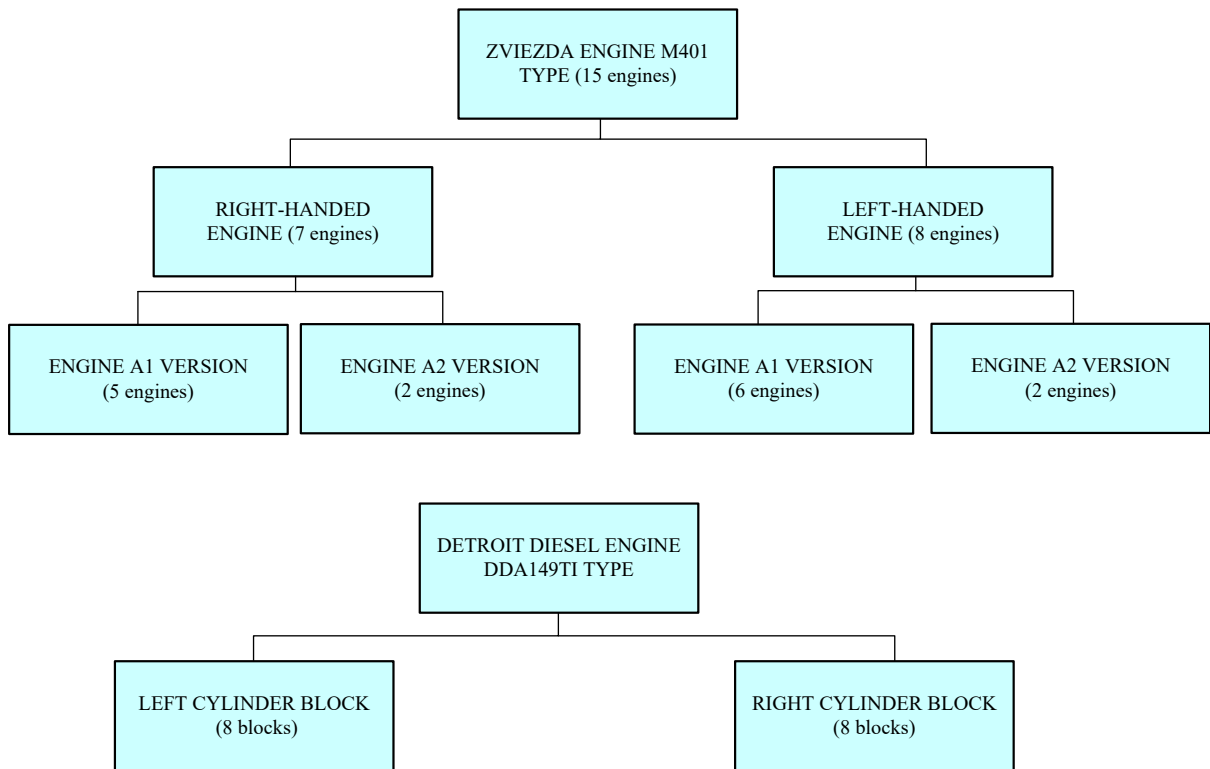


Fig. 1: Division of engines into sub-sets as testing objects M401 and DDA149TI type

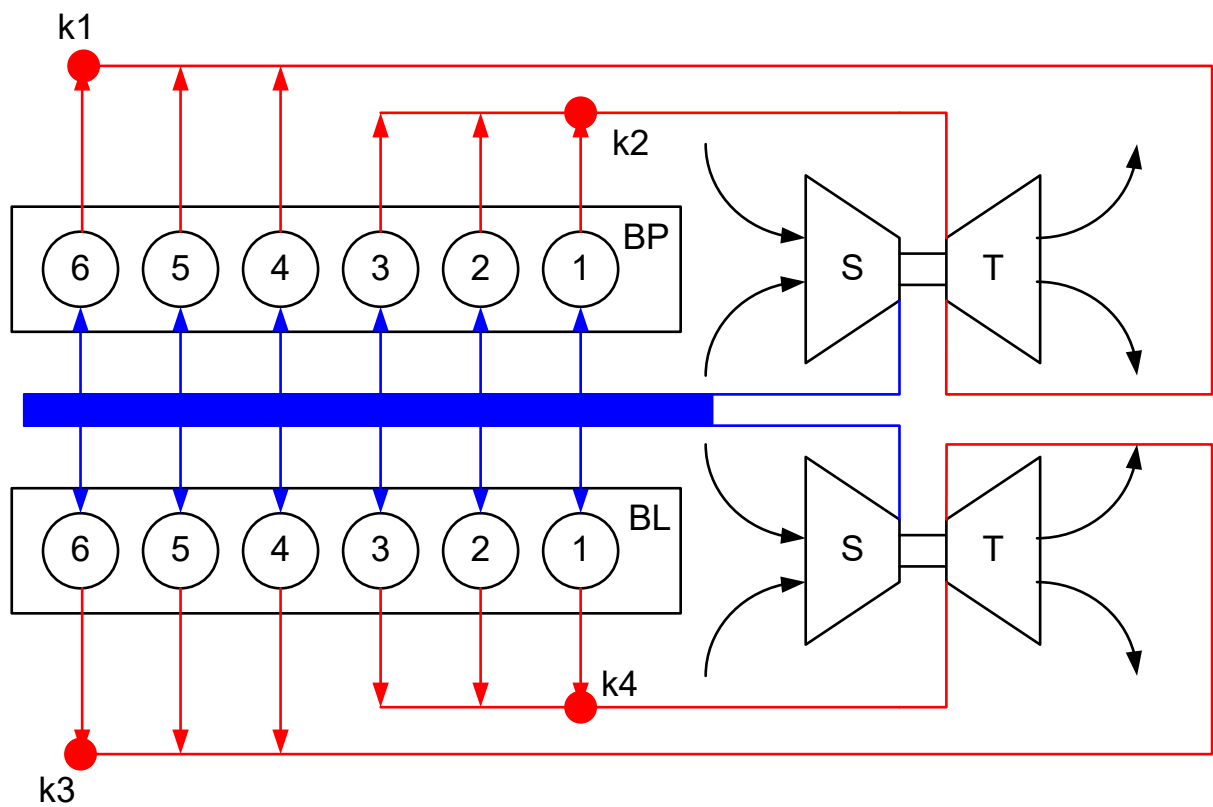


Fig. 2: Schematic diagram of the fluid-flow system of the ZVIEZDA engine M401 type

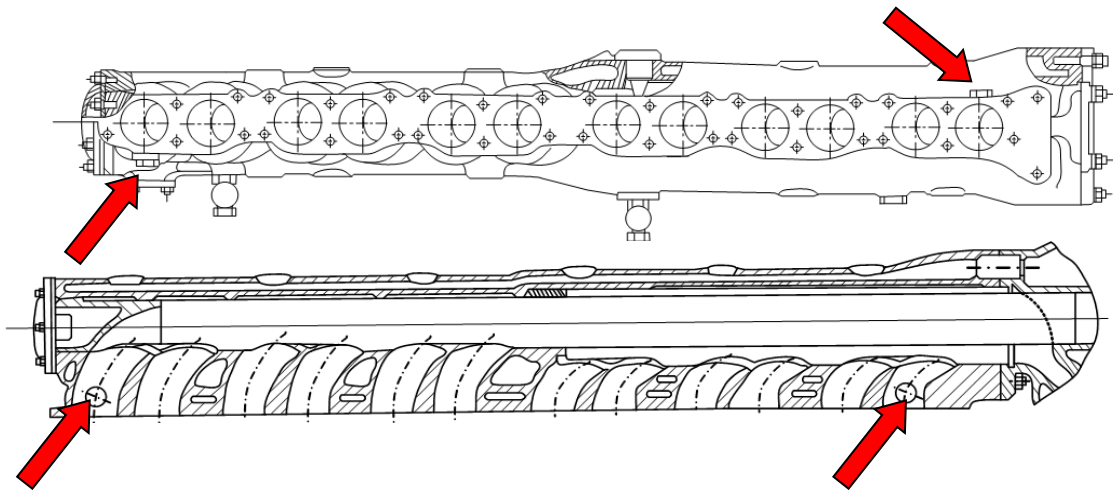


Fig. 3. Exhaust channel of M401 engine with marked places of mounting the pressure transducers

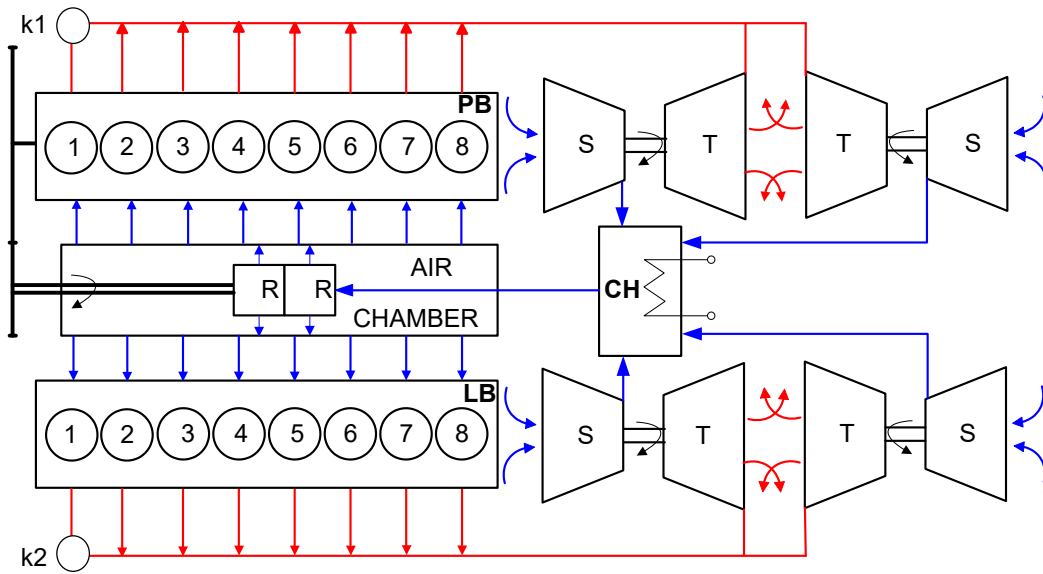


Fig. 4: Schematic diagram of the fluid-flow system of the DETROIT DIESEL engine of DDA149T1 type

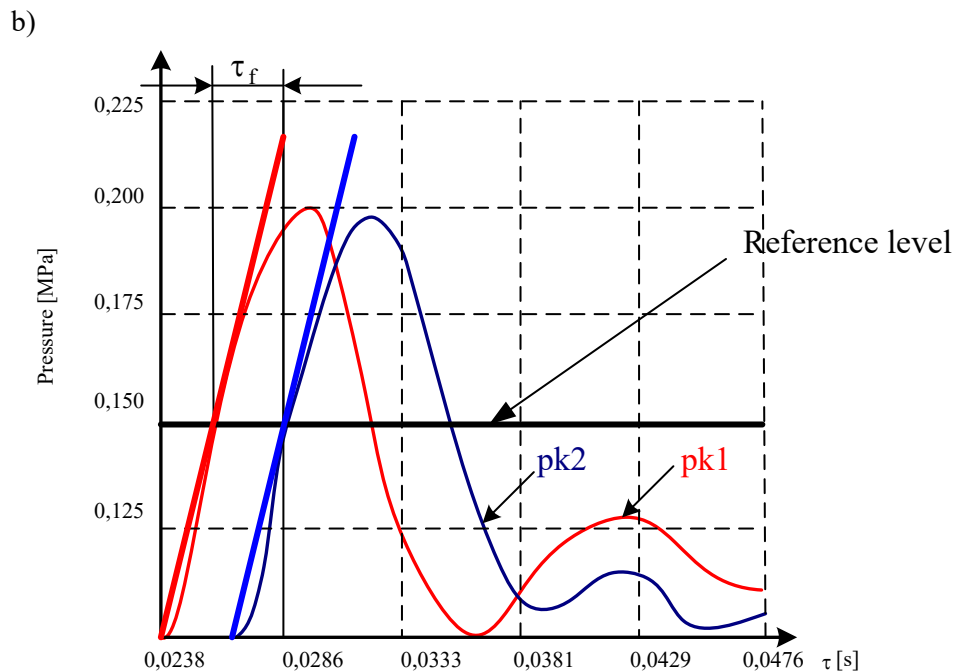
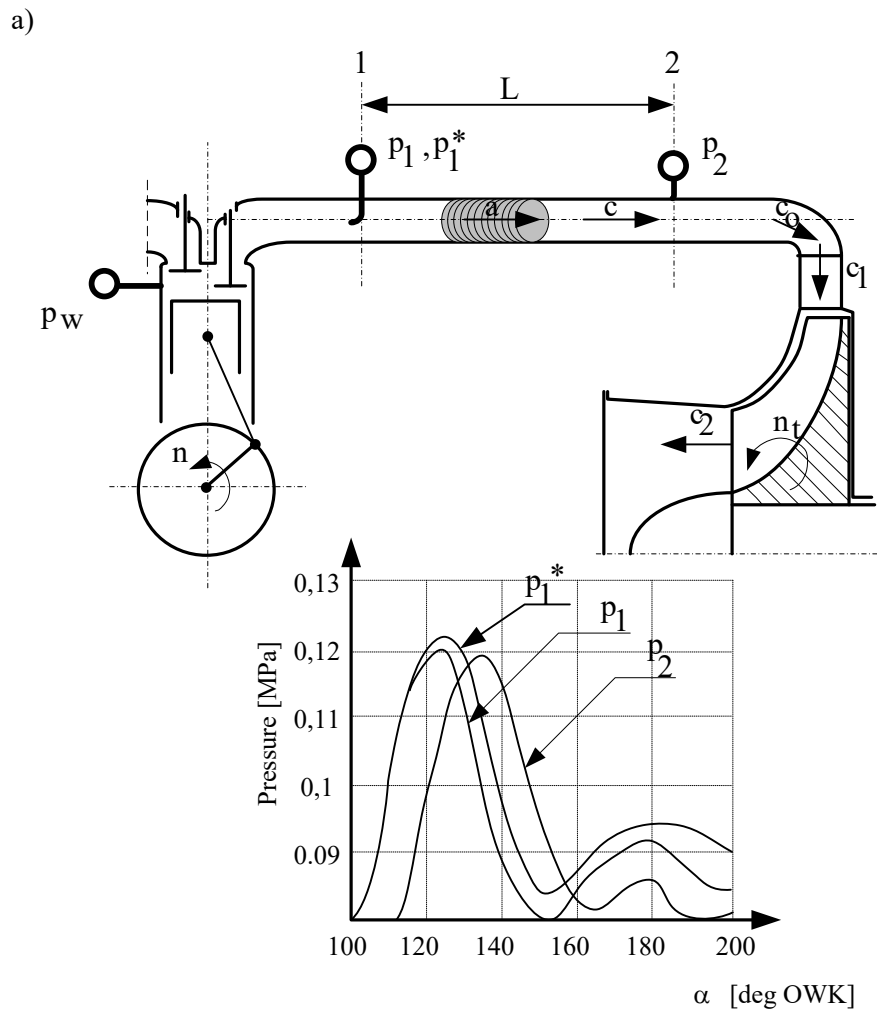


Fig. 5: The principle of determining the peak velocity amplitude of the wave pressure in the exhaust outlet duct

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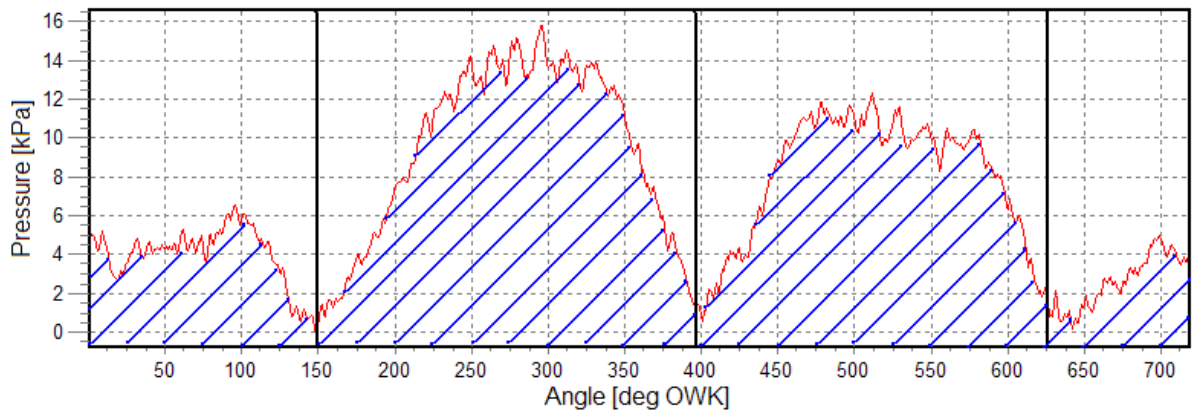


Fig. 6: Waveform course of exhaust pressure in the outlet channel of ZVIEZDA M401 marine diesel engine as a function of an angle of the crankshaft revolution

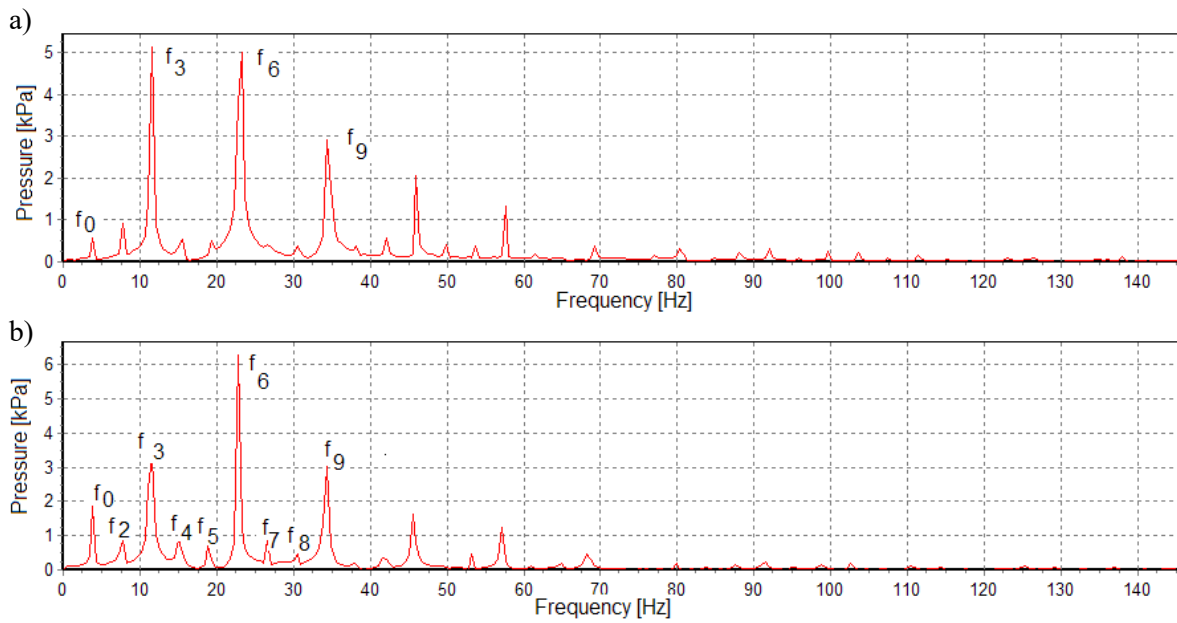


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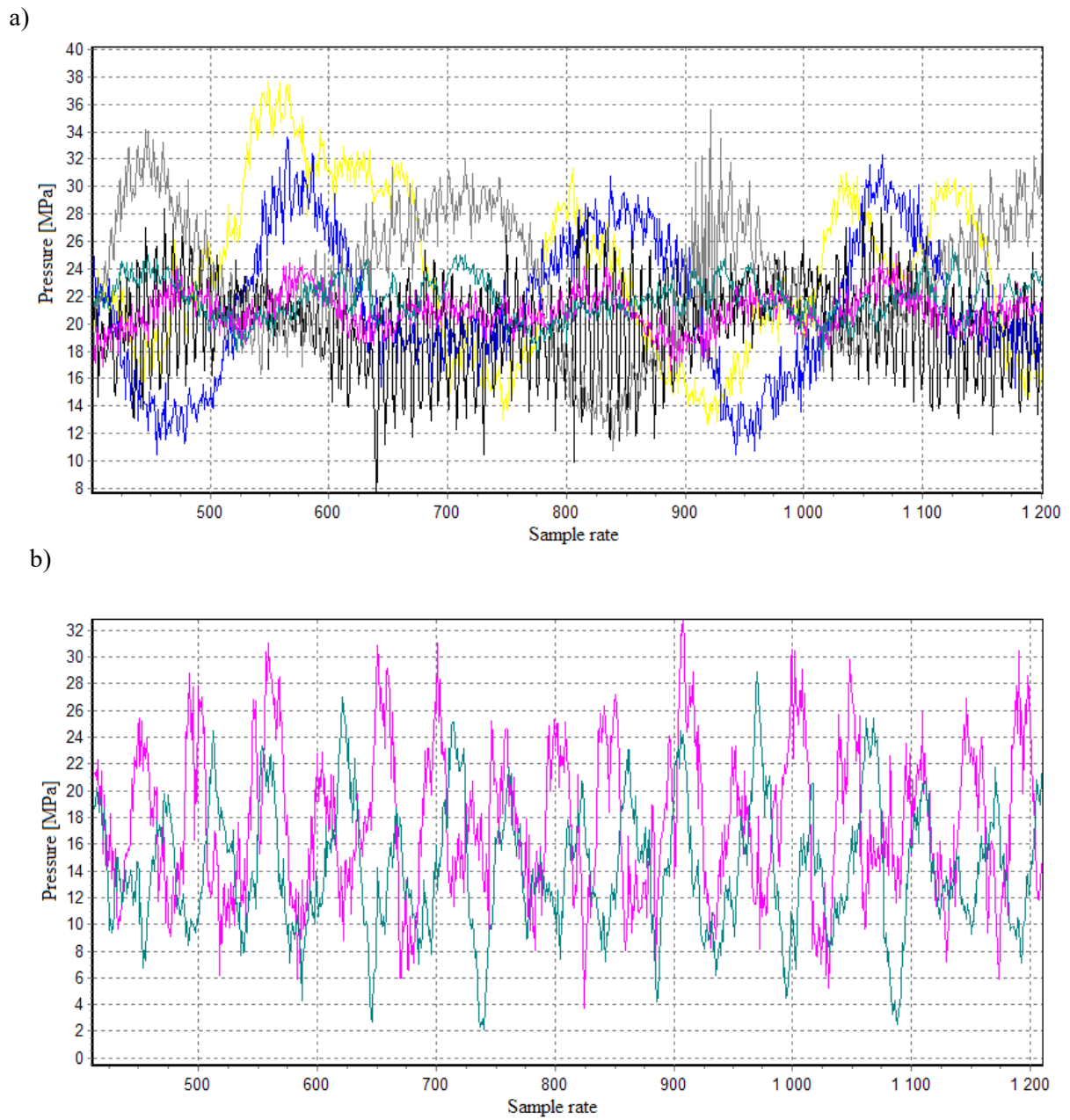


Fig. 8: Pressure waveforms in the selected control cross-sections of the exhaust channel as a function of the sample's number
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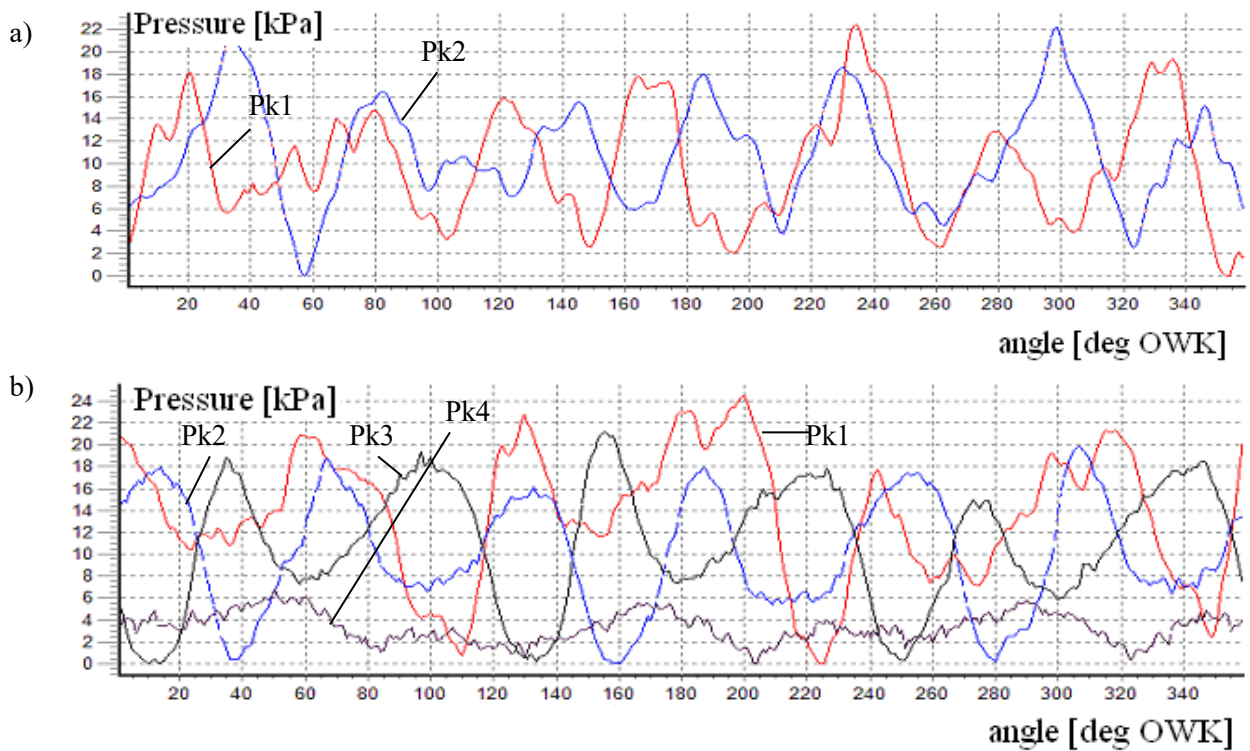


Fig. 9: Waveforms of the gas pressure in the selected control cross-sections of the exhaust outlet channel as a function of an angle of the crankshaft rotation
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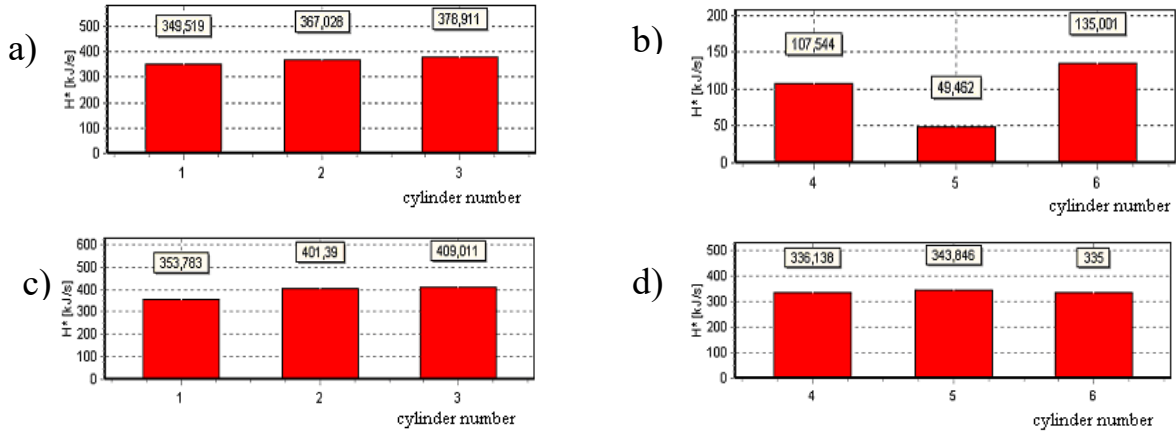


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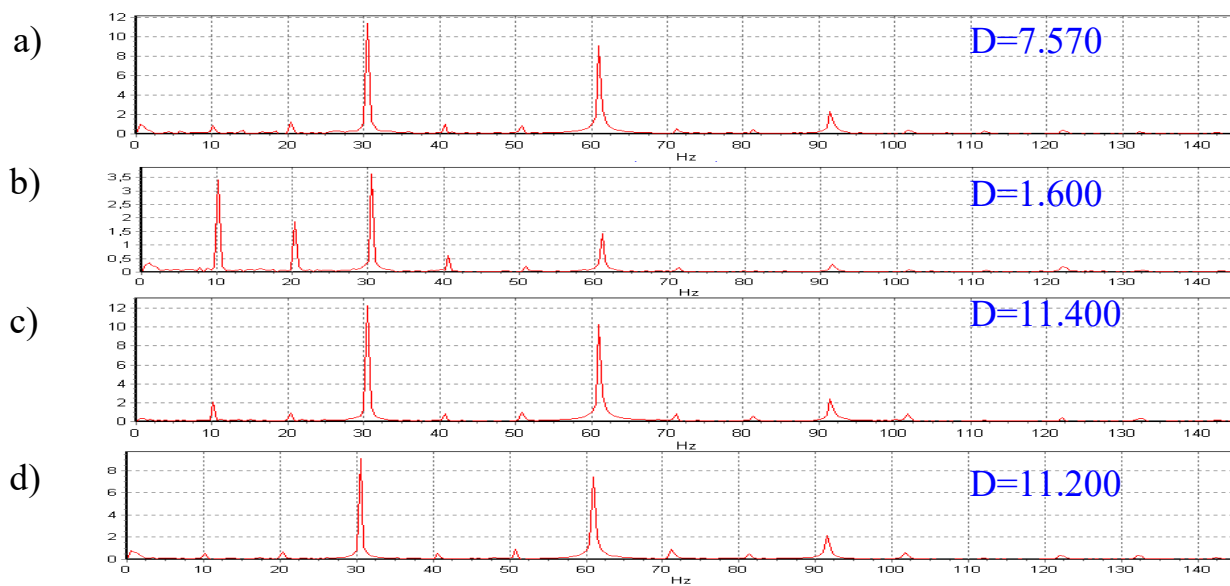


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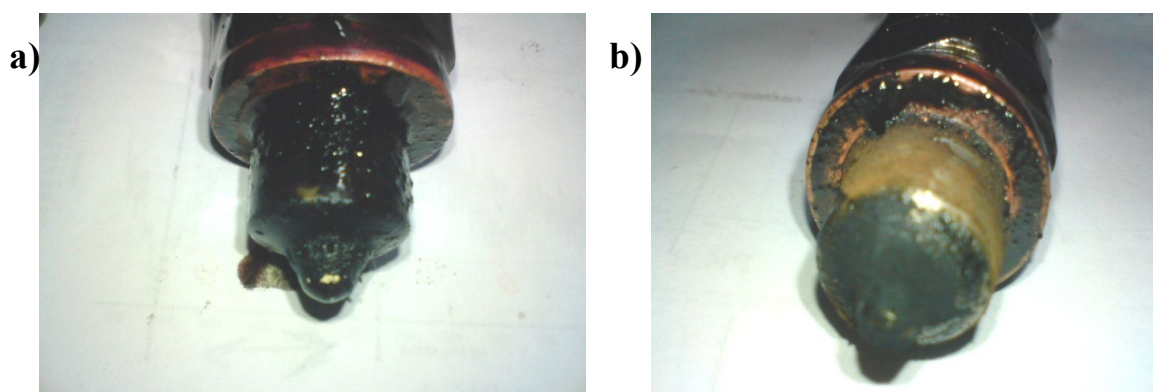


Fig.12: Injectors removed from the right engine block of M401 engine
 a) injector of cylinder No. 4, b) injector of cylinder No. 5.

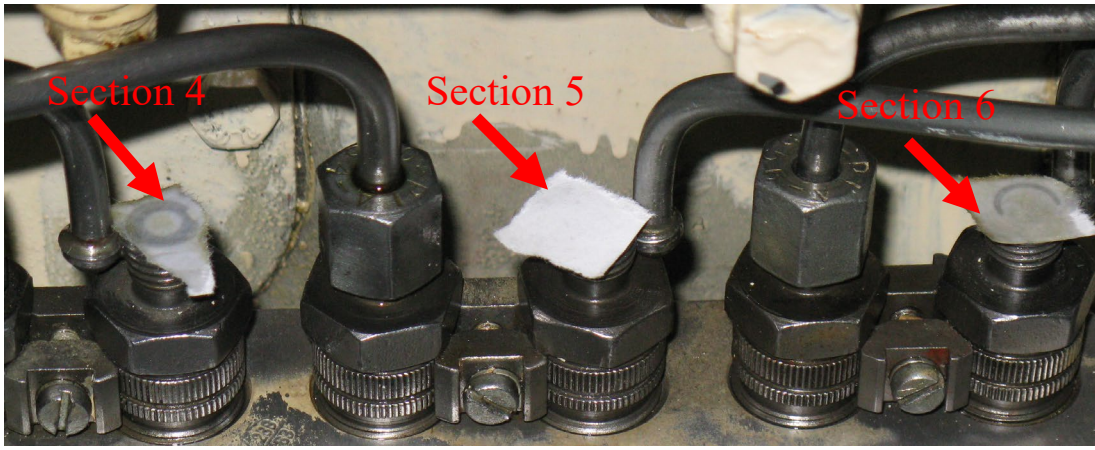


Fig. 13: A view of the fuel pump during its testing