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ENHANCED DIAGNOSTIC TECHNIQUES FOR MARINE DIESEL ENGINES: ACHIEVING IMO DECARBONIZATION COMPLIANCE

This paper discusses hardware-based methods for monitoring the operational parameters of marine diesel engines and online mathematical modeling techniques (digital twins) for calculating the emissions of CO_2, NOx, soot, and other harmful pollutants. It is demonstrated that measuring and analyzing the engine's vibrational diagrams in parallel with gas pressure diagrams in the cylinders allows the evaluation of the actual fuel injection and gas distribution timings. The obtained data is used to refine the mathematical model of the engine's working process, which determines the engine's indicator parameters and power, as well as the emission of harmful substances that need to be monitored in compliance with current IMO requirements. The authors have accumulated experience in using the discussed hardware-based methods for diagnosing marine engines during operation. The hardware and software methods discussed have been implemented into a real-time system for in-service diagnostics of marine engines. The system is designed based on a modern dual-core controller with high performance and low power consumption, incorporating a high-speed ADC with sufficient capability to monitor the working process with a 0.1-degree crankshaft rotation resolution for all types of marine main and auxiliary engines. The system also utilizes wireless data transmission technology. A contemporary Android/iOS smartphone or tablet serves as the computational and graphical component of the system. This real-time system enables the utilization of all the advantages of parallel pressure and vibroacoustic analysis, including real-time determination of key operating parameters, identification of top dead center position, and evaluation of fuel delivery and gas distribution phases. Additionally, it harnesses the benefits of employing a digital twin—an online mathematical model of the engine cylinder's working process. These solutions will enhance diagnostic quality and, ultimately, improve the operational efficiency of marine engines by reducing operational costs and extending the period of reliable, trouble-free operation.

Key words: *diagnostics; two-stroke engine; vibration sensor; fuel injector; exhaust valve; engine indicator parameters.*

Introduction

The International Maritime Organization (IMO) has adopted a series of measures and strategies aimed at reducing greenhouse gas emissions and decarbonizing the maritime industry. The essence of the latest IMO requirements for decarbonizing marine engines is to reduce emissions of carbon dioxide (CO_2) and other greenhouse gases.

In April 2018, the IMO adopted an initial strategy [1] to reduce greenhouse gas emissions from ships, which includes the following main objectives:

– reducing the amount of CO_2 emissions by at least 40% by 2030 and striving for 70% by 2050 compared to 2008 levels;

– reducing the total volume of greenhouse gas emissions from international shipping by at least 50% by 2050 compared to 2008 levels;

– aiming full decarbonization of maritime transport in this century [2].

To achieve these goals, the IMO proposes the use of various technological and operational measures, such as improving the energy efficiency of engines, using alternative energy sources such as liquefied natural gas (LNG) or hydrogen, and encouraging innovation in new technologies that enhance the efficiency of marine engines [1, 2].

Performance analysis and diagnostics of marine engines are essential for improving operational efficiency and decarbonization of marine engines. During performance analysis, key parameters such as MIP, IPower, Pmax, Pcomp, etc., are determined, analyzed, compared with sea trial data, and adjusted according to the chosen operational strategy.

Various diagnostic systems from different manufacturers are used for conducting performance analysis, such as Premet® XL by LEHMANN & MICHELS GmbH, Doctor Analysis by Icon Research Ltd., EPM-XPplus by IMES GmbH, MarPrime by Maridis GmbH, and D4.0H by Depas Lab. (ONMU) [3]. However, it should be noted that even the most advanced systems only determine a small portion of the parameters required for accurate and quality diagnosis of the critical components of the engine.

To expand the volume of analyzed information, a digital twin of the engine, such as Blitz-PRO [4], can be used. The digital twin is an advanced online model that is precisely tuned to the engine using data obtained from diagnostic systems. The digital twin allows for analyzing a wide range of parameters, thus enabling qualitative and reliable diagnosis of the technical condition of the engine components and monitoring emissions in accordance with the current requirements of the International Maritime Organization (IMO) [1, 2].

Main content

The safe operation of a vessel and its compliance with the latest International Maritime Organization (IMO) standards for decarbonization depend on the continuous and reliable operation of main and auxiliary engines. Such conditions can be ensured through periodic performance analysis and diagnostics of the engine's key components responsible for the quality of the working process. Performance analysis allows for optimizing the operation of cylinders, evenly distributing the load between them, and timely identifying dangerous trends in the engine's technical condition. Parameter analysis also helps reduce the overall vibration levels of the engines, achieve fuel consumption close to the rated values, and improve the overall energy efficiency of the vessel in accordance with IMO requirements.

Some defects can be identified through the analysis of indicator diagrams P(°CA) and the main parameters of the working process calculated from them, such as P_{max}, P_{comp}, MIP, ignition angles, and fuel ignition delay periods. Examples of such defects can include deviations in MIP, P_{max}, or end compression pressure, as well as increased ignition delay periods, and others.

The analysis of one of the most typical defects in cylinder operation - reduction in end compression pressure (P_{comp}) - is associated with ambiguities. The reduction in P_{comp} can be caused by several diverse reasons, such as wear of cylinder liners, wear, breakage, and/or sticking of piston rings, valve leakage, or malfunctioning valves timing. All these causes will result in the same consequence - a decrease in the parameter P_{comp}, followed by P_{max} and MIP [3]. Thus, the true cause of the defect may remain uncertain.

Similarly, to the defect of decreased Pcomp, some other defects that manifest on the P(°CA) diagrams can be caused by various reasons. A typical example is malfunctions in the high-pressure fuel equipment operation. These defects often occur during continuous engine operation. For example, late combustion process, which is determined by the phases of fuel ignition points on the P(°CA) diagram, can be a result of late fuel injection and/or wear of precision components in the high-pressure fuel equipment, leading to a decrease in fuel pressure before the injectors at the moment of injection. Therefore, determining operational defects based solely on the analysis of P(°CA) diagrams may not be accurate.

Measurements and analysis of diagrams in the high-pressure fuel system before the injectors could provide comprehensive diagnostic information. However, such measurements do not comply with the strategy of non-destructive testing and cannot be carried out on marine engines in operational conditions due to the risk of fuel leaks when installing high-pressure sensors. Such measurements using non-standard devices are prohibited by most marine certification societies [5, 6].

An alternative to direct measurements is the use of vibration sensors on a magnetic platform. Such sensors can be quickly installed in a chosen location, reducing the overall measurement time and allowing for quasi-stationary engine operation conditions. Vibration diagrams and P(°CA) diagrams should be recorded in parallel and analyzed together. The proposed method is suitable for analyzing defects in the high-pressure fuel equipment and the gas distribution mechanism. The use of magnetic vibration sensors fully complies with the modern strategy of non-destructive testing of marine engines.

The P(°CA) diagrams and vibration diagrams, initially recorded as functions of time, are transformed into functions of crankshaft angle using an analytical algorithm for determining TDC: P(t, ms) -> P(°CA) [3, 7].

The D4.0HT diagnostic system

The D4.0HT diagnostic system is a portable system for diagnosing two-stroke and four-stroke engines. The system is designed in ONMU to determine the parameters of marine and stationary diesel and gas engines running on heavy fuel without any restrictions, Table 1.

Table 1. Specifications of D4.0HT diagnostic system

<table>
<tr><td></td><td>Pressure sensor PS-20m
Measuring range: 0-250 bar;
Capacitive type, non-cooled;
Permissible surface temperature: up to 350°C;
Max. error: <= 1.5%;
Weight: 0.5 kg;
Installed on a standard indicator cock, W27x1/10.</td></tr>
<tr><td colspan="2">Vibration sensor VS-20
Frequency range: 0.1 to 18 kHz;
Filter passband: 1.0 kHz;
Max. Operating temperature: 90°C;
Sensor has a magnetic base.</td></tr>
<tr><td colspan="2">Real-time module D4.0HT
Based on RCM2000 processor, 25 MHz;
ADC: 125 kHz, 12-bit;
USB / RS-232 interface;
Automatic determination of engine cycle;
Contrast display; One-button control;
Approximately 12 hours of autonomous operation;
130 x 80 x 40 mm; 0.5 kg; 6VDC (4 x A1)</td></tr>
</table>

The D4.0HT system has the following features [3]:

– a vibroacoustic sensor works in parallel with the gas pressure sensor in the cylinder;

– a high-precision algorithm based on a compression model is used to determine TDC (top dead center), without the need for a hardware TDC sensor.

The system is controlled by a single multifunctional button and has a durable aluminum housing. The real-time module of the D4.0HT system is designed for direct recording of working process data and preliminary calculation of 3 key parameters:

– *Pz* (P_{max}) - the maximum combustion pressure in the cylinder (average, minimum, and maximum values over several working cycles).

– *RPM* - the rotational frequency of the diesel engine's crankshaft.

– *Pt* - the average pressure in the cylinder during the working cycle.

The indication data from individual cylinders is transmitted from the D4.0HT module to a computer via a serial USB/RS-232 interface.

The engine cycle is automatically determined or can be manually set. Automatic engine cycle detection allows for monitoring without prior setup for engine type (engine data can be entered after measurements during the full calculation of parameters). In many cases, this option is useful and saves time in indicating measurements when used in marine conditions.

The software provides calculation of following parameters:

The software provides calculation of following parameters:

– mean indicated pressure $P_i \backslash\backslash\backslash MIP$;

– cylinder gross indicated power $N_i \backslash\backslash P_i$;

– crankshaft speed RPM;

– maximum combustion pressure:

$P_{\max}, P_{\max}^{\min}, P_{\max}^{\max}, \varphi P_{\max}$;

– maximum compression pressure P_{comp};

– pressure at the specific points of indicated diagram (36° after TDC) $P_{\exp}$;

– maximum pressure increase rate $(dp/d\varphi)_{\max}$;

– pressure increase ratio $\lambda = \dfrac{P_{\max}}{P_{\text{comp}}}$;

– firing pressure $P'_c\,(\varphi P'_c)$;

– actual and geometrical fuel injection timing:

$\alpha, \alpha^G, \Phi_{INJ}, \Phi_{INJ}^G$;

– ignition delay τ_D, Φ_{τ_D};

– gas distribution valves and ports timing

$\varphi_{in}^{op}, \varphi_{in}^{cls}, \varphi_{exh}^{cls}, \varphi_{exh}^{op}$;

– valve train mechanism and fuel injection equipment technical state estimation;

– pressure at any point of diagram p_x;

– numerical filtration and FFT spectral analysis.

Unlike the MarPrime system by Maridis GmbH, the D4.0HT system uses a vibroacoustic sensor with a different frequency range, which allows for high-precision determination of the needle valve displacement in fuel injectors, gas distribution valves, and plunger in the plunger pair of the fuel injection pump. Fuel injection phases are determined with high precision based on the moments of needle valve lift and seating. Gas distribution phases are determined based on the moments of valve seating. The sensor allows for determination of the moments of plunger window closing and fuel cutoff. As a result, the vibroacoustic sensor enables determination of fuel injection and gas distribution phases, as well as diagnosis of the technical condition of corresponded units. In recent versions, options for gas turbine compressor vibrodiagnostics and electronic lubrication system for cylinder oil injectors have been added to the system [5].

In the D4.0HT system, the automatic determination of TDC (Top Dead Center) is carried out using a proprietary algorithm based on solving the equation P'=0 during the compression stroke prior to the start of combustion. Data preprocessing is performed using a digital filter [5, 6]. This automatic TDC determination allows for a maximum error of no more than 0.1°CA in TDC determination, and the final calculation of indicated cylinder power is performed with error of no more than 2.5%.

In the Premet® XL system by LEHMANN & MICHELS GmbH, automatic determination of TDC is also provided. However, in the Doctor Analysis system by Icon Research Ltd, automatic TDC determination is not available. Instead, the system offers a procedure for manual TDC correction, or the option to have this procedure performed by Icon Research specialists.

However, it is also possible to perform TDC correction independently using pressure diagram analysis, with a correction step and accuracy of TDC setting of 0.1°CA.

TDC detection from the *P′* = 0 equation

The proposed approach relies on the principle that when there is no combustion occurring within the cylinder, the rate of change of pressure at the top dead center (TDC) piston position is equal to zero, with the exception of the TDC thermal loss angle, which corresponds to the dissipation of heat to the cylinder walls.

$$P'_{f\text{-}\delta f_T} = P'_{\Theta} = 0\,, \tag{1}$$

Taking into account the angle of TDC thermal loss at the apex of the piston, we obtain:

$$\Theta = f - \delta f_T\,, \tag{2}$$

If we utilize equation (3) to determine the rate of pressure change within the compression region and solve the aforementioned equations, the Top Dead Center (TDC) coordinate can be calculated (refer to Figure 1).

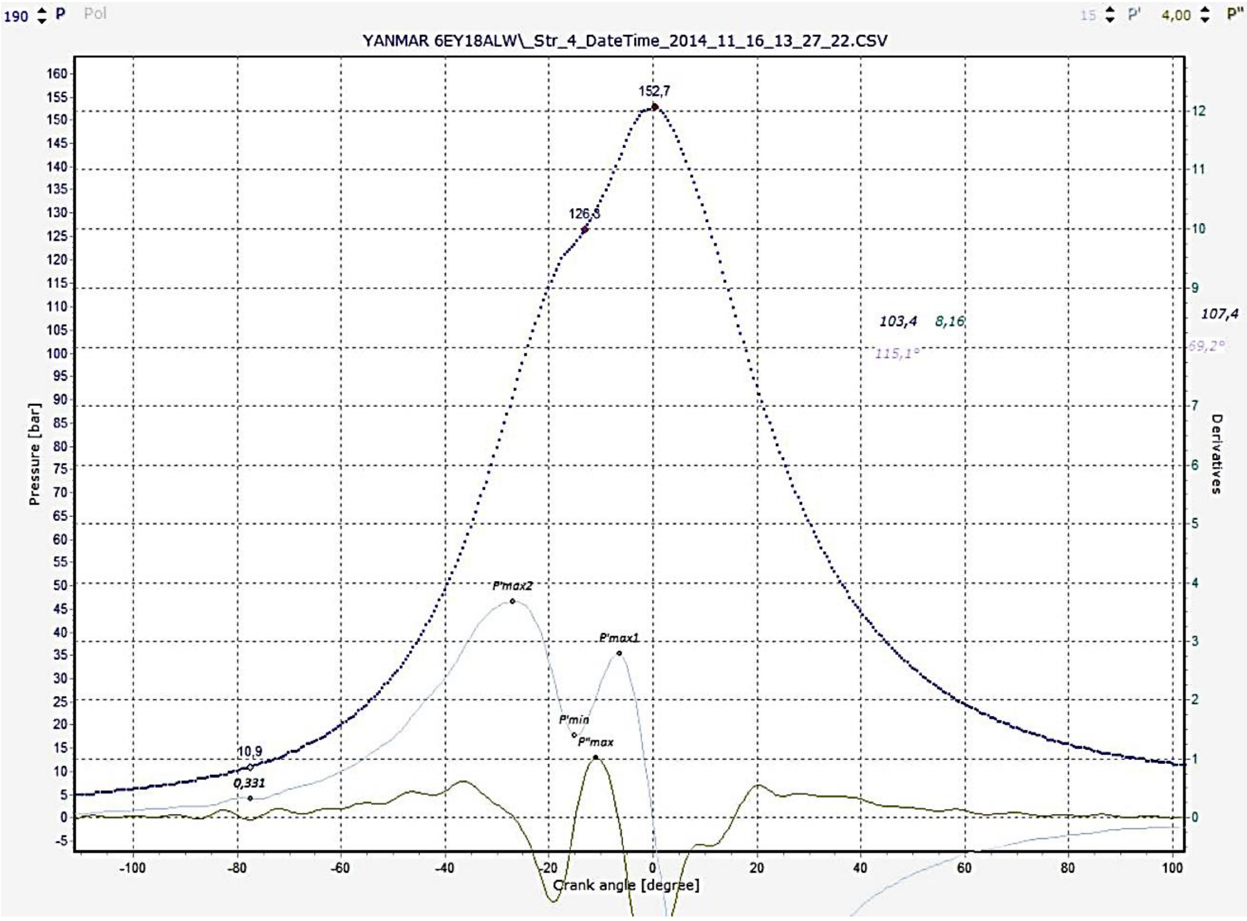

Fig. 1. TDC determination task

The rate of pressure change within the compression region expressed as follows:

$$\frac{dP_{comp}}{d\Theta} = -P_a V_a^{n_1} n_1 \frac{1}{V_{\Theta}^{n_1+1}} \times \frac{dV_{\Theta}}{d\Theta}, \quad (3)$$

where P_a – pressure at the start of compression;

$V_{\Theta} = V_f - \delta f_T$ – cylinder volume, where:

$$V_f = V_C + 0.5 V_S \left[1 + \frac{1}{\lambda_Ш} - \cos f - \frac{1}{\lambda_Ш} \sqrt{1 - \left(\lambda_Ш \sin f\right)^2} \right]$$

V_C – compression chamber volume;

$V_S = V_C \left(\varepsilon - 1\right)$ – the volume described by the piston;

ε – compression ratio in cylinder;

$\lambda_Ш = R_{KP} / L_Ш = S / 2L_Ш$ – the ratio between the crank radius and the length of the connecting rod.

Data filtration

Despite the excellent quality of IMES pressure sensors, characterized by low relative error ($\sigma < 1\%$) and minimal noise levels, the subsequent numerical differentiation of the obtained indicator diagrams poses significant challenges in conducting accurate numeric analysis of the $dP/d\varphi$ curves. As a result, determining the coordinates of the maximum $dP/d\varphi$ values prior to combustion becomes highly uncertain, as depicted in Figure 2. Consequently, it becomes evident that the implementation of an appropriate data filtering procedure is imperative.

Our preference lies in utilizing the Butterworth digital low-pass filter [3] due to its frequency characteristics, which closely resemble those of an ideal integrator and exhibit a monotonic response within the passband.

The frequency characteristics of a j-th order Butterworth digital low-pass filter are as follows:

$$G(f) = \frac{G_0}{\sqrt{1 + \left(f / f_C\right)^{2j}}}, \quad (4)$$

where G_0 – the gain coefficient;

f_C – the cutoff frequency (at which the amplitude is 3dB);

j – the filter order.

Figure 2 illustrates the $P(\varphi)$ and $P'(\varphi)$ diagrams obtained prior to the application of the Butterworth low-pass filter. The presence of analog and digital noise during the recording of $P(\varphi)$ introduces significant uncertainties in determining the coordinates of the maximum $P'(\varphi)$ values. Consequently, analyzing the second derivative, $P''(\varphi)$, is infeasible in this particular scenario.

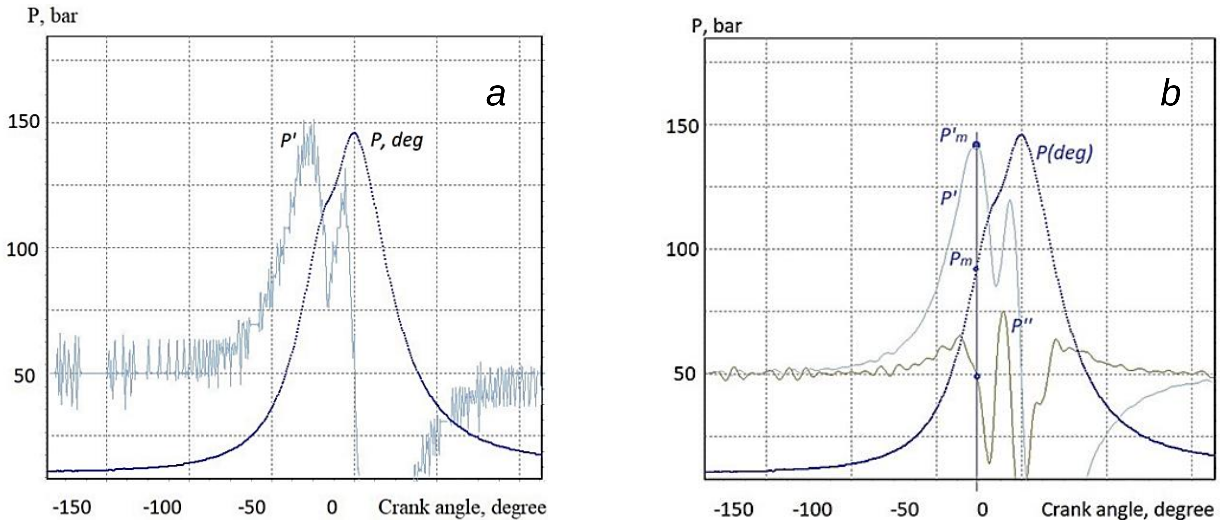

Fig. 2. Diagrams P(φ), P'(φ), P''(φ) before (a) after (b) applying the Butterworth low pass filter

The implementation of the Butterworth low-pass filter enables the numerical analysis of the first derivative, $P'(\varphi)$, and the second derivative, $P''(\varphi)$, as depicted in Figure 2. Moreover, it facilitates the determination of the coordinate representing the maximum compression stroke speed within the working cylinder, denoted as point *P'm*.

During the recording of indicator diagrams utilizing IMES pressure sensors, characterized by a relative error of less than 1% and a sampling step of $\Delta \leq 0.5$ °CA, the choice of a filter order, $j = 5 \div 7$, proves to be effective in suppressing high-frequency noise on the $P'(\varphi)$ and $P''(\varphi)$ curves. This filtering approach not only ensures adequate noise suppression but also allows for subsequent analysis to identify local extrema. These extrema serve as synchronization points for the indicator diagrams, facilitating their transformation from time-based functions into crank angle degree functions.

Figure 3 illustrates an example of diagnosing a single cylinder of a two-stroke MAN engine using the D4.0HT system.

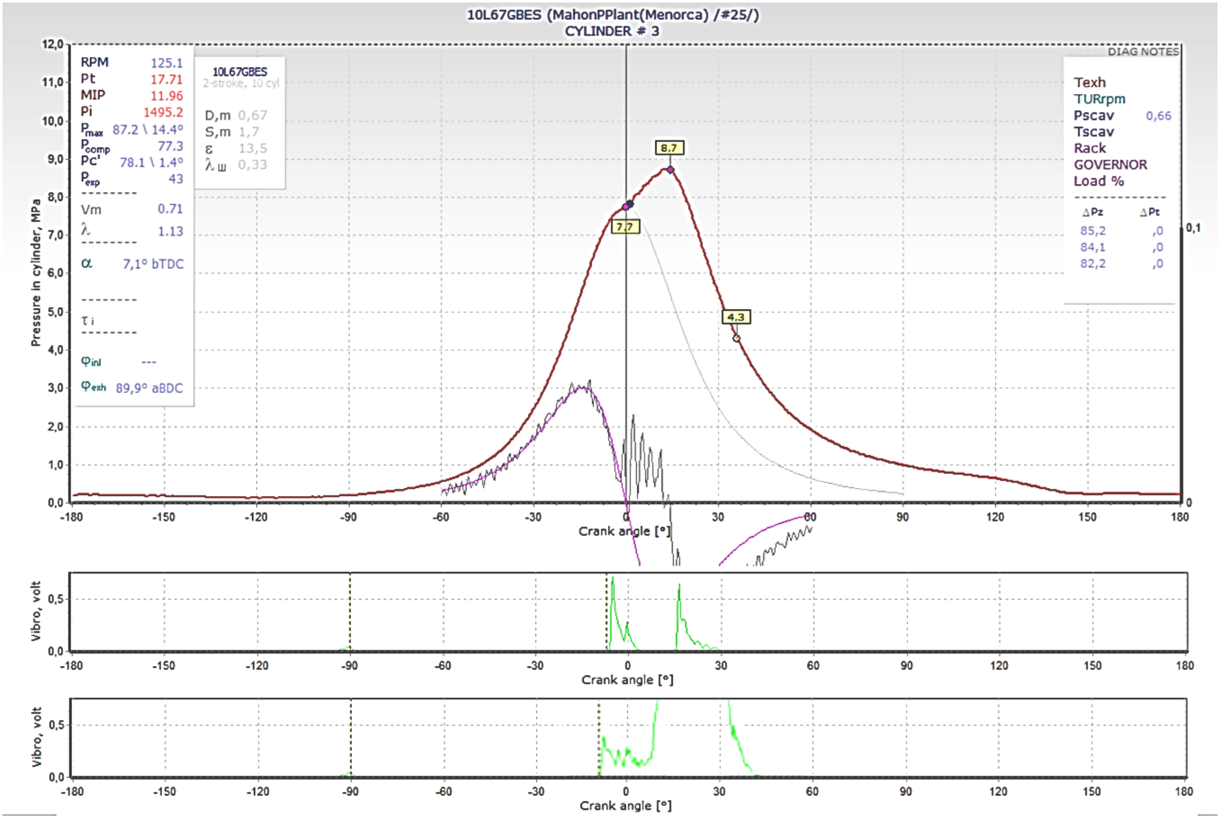

Fig. 3. Diagnosis of one cylinder of a two-stroke MAN engine using the D4.0HT system

The diagram $P(\varphi)$ (Figure 3.a) is analyzed in parallel with the vibro-diagrams of the fuel injectors Vinj(φ), Figure 3.b, and the high-pressure fuel pumps Vhpfp(φ), Figure 3.c. The vibro-diagrams were obtained using the Vibration sensor VS-20, see Table 1.

The injector vibro-diagram (Figure 3.b) also includes the closing pulse of the exhaust valve, which is a convenient feature of the D4.0HT system in practice, as it allows not only the actual fuel injection phases to be controlled but also the gas distribution phases using a single measurement point - the injector end face.

By analyzing the phases and shapes of the pulses in figure 3.b,3.c, it is possible to evaluate the technical condition of the injectors, high-pressure fuel pumps, and exhaust valve control system. The obtained data is used to adjust the Blitz-PRO online service.

Application of Digital Twins for advanced diagnostics and engine behavior prediction.

The Digital Twin of the Internal Combustion Engine is a numerical representation of a real engine that models various processes and parameters of engine behavior, depending on its type. These processes may include the operating processes in the engine cylinders, intake and exhaust manifold, engine wear due to friction and mechanical loading in engine parts, as well as vibrations and noise emissions. The application of Digital Twin technology for Internal Combustion Engine diagnostics has shown promising results, providing additional information on engine technical conditions. Furthermore, it can be used for simulating engine parameters for different engine operation programs, including the prediction of toxic and greenhouse gas emissions during engine operation.

In our study, we utilize the Blitz-PRO online service, which facilitates the creation and utilization of Digital Twins for Internal Combustion Engines [4]. This approach has been successfully applied in addressing diagnostics issues in marine diesel engines [5, 6].

For diesel engine the main component of greenhouse gases is CO_2, and its amount in exhaust gases obviously depends on the fuel consumption:

$$g_{\mathrm{CO_2}} = g_C b_b, \ \frac{g}{kW \times h}, \tag{5}$$

where g_{C} – carbon mass fraction in engine fuel;

b_b – brake specific fuel oil consumption.

Blitz-PRO also helps to estimate the following components of marine diesel engines exhaust gases toxic emissions: CO, soot, SO_x and NO_x.

The two-zone combustion model is used to predict separately the gas composition in the fresh charge and burned gases zones. Professor Zvonov's method for 18-components burned gases mixture is applied. The following constituents are considered: O, O_2, O_3, H, H_2, OH, H_2O, C, CO, CO_2, CH_4, N, N_2, NO, NO_2, NH_3, HNO_3, HCN.

The NO_x concentration is calculated for "thermal" nitric oxides (NO), according to Zeldovich. Three equations are:

$$\mathrm{N_2 + O \underset{K_{1r}}{\overset{K_{1p}}{\Leftrightarrow}} NO + N}, \tag{6}$$

$$\mathrm{N + O_2 \underset{K_{2p}}{\overset{K_{2n}}{\Leftrightarrow}} NO + O}, \tag{7}$$

$$\mathrm{N + OH \underset{K_{3r}}{\overset{K_{3p}}{\Leftrightarrow}} NO + H}, \tag{8}$$

where K_{1p}, K_{1r}, K_{2p}, K_{2r}, K_{3p}, K_{3r} – chemical reactions constants.

The kinetics of NO development is calculated as following:

$$\frac{d[\mathrm{NO}]}{d\tau} = \frac{2K_{1p}[\mathrm{N_2}][\mathrm{O}]}{1 + \dfrac{K_{1r}[\mathrm{NO}]}{K_{2p}[\mathrm{O_2}]}} \left(1 - \frac{[\mathrm{NO}]^2}{K_4[\mathrm{O_2}][\mathrm{N_2}]}\right), \tag{9}$$

$$K_4 = \frac{K_{1p}K_{2p}}{\mathrm{K}_{1r}\mathrm{K}_{2r}}. \tag{10}$$

For high-speed engines the final concentration of CO in exhaust gases is estimated as equivalent concentration at the combustion finish point. For medium-speed and low-speed diesel engines the following kinetic equation is used:

$$\frac{d[\mathrm{CO}]}{d\tau} = -K_{1C}[\mathrm{CO}][\mathrm{OH}], \tag{11}$$

where $K_{1c} = 7.1 \cdot 10^{12} \cdot e^{(-32200RT)}$ – reaction constant;

[CO], [OH] – CO and OH concentrations correspondently.

The volumetric rate of soot concentration is given by the Razleitsev mechanism:

$$\frac{d[\mathrm{C}]}{d\tau} = \left(\frac{d[\mathrm{C}]}{d\tau}\right)_{kin} + \left(\frac{d[\mathrm{C}]}{d\tau}\right)_{pol} - \left(\frac{d[\mathrm{C}]}{d\tau}\right)_{burn} - \left(\frac{d[\mathrm{C}]}{d\tau}\right)_{vol}, \tag{12}$$

where:

$\left(\dfrac{d[C]}{d\tau}\right)_{kin}$ – kinetic soot formation rate (in the flame);

$\left(\dfrac{d[C]}{d\tau}\right)_{pol}$ – core polymerization of fuel droplets rate;

$\left(\frac{d[C]}{d\tau}\right)_{burn}$ – burning of the soot particles rate;

$\left(\frac{d[C]}{d\tau}\right)_{vol}$ – change in soot concentration rate due to cylinder volume change.

$$\left(\frac{d[\mathrm{C}]}{d\tau}\right)_{kin} = B_{1soot}\frac{q_{fuel}}{V}\frac{dx}{dt}, \tag{13}$$

$$\left(\frac{d[\mathrm{C}]}{d\tau}\right)_{burn} = B_{3soot}k_{\mathrm{O}_2}\sqrt{n}\,p[\mathrm{C}], \tag{14}$$

$$\left(\frac{d[\mathrm{C}]}{d\tau}\right)_{vol} = B_{4soot}\frac{6n}{V}\frac{dV}{df}. \tag{15}$$

Kinetic soot formation rate from fuel injection period:

$$\left(\frac{d[\mathrm{C}]}{d\tau}\right)_{pol} = B'_{2soot}\delta_d\frac{q_{fuel}}{V}\cdot$$

$$\cdot\frac{1-\exp\left(-\left(\frac{\sqrt{K_{ev}\left(\tau-\tau_{inj.start}\right)}}{d_{32}^{\mathrm{inst}}}\right)^{n_{disp}}\right)}{\tau_{inj}}. \tag{16}$$

Kinetic soot formation rate after injection end:

$$\left(\frac{d[\mathrm{C}]}{d\tau}\right)_{pol} = B''_{2soot}\delta_d\left(1-x_{inj.end}\right)\cdot$$

$$\cdot\frac{n_{disp}q_{fuel}}{2V\left(\tau-\tau_{inj.end}\right)}\left(\frac{\sqrt{K_{ev}\left(\tau-\tau_{inj.start}\right)}}{d_{32}^{inst}}\right)^{n_{disp}}\cdot, \tag{17}$$

$$\cdot\frac{1-\exp\left(-\left(\frac{\sqrt{K_{ev}\left(\tau-\tau_{inj.start}\right)}}{d_{32}^{inst}}\right)^{n_{disp}}\right)}{\tau_{\mathrm{inj}}}$$

where $B_{1soot}, B'_{2soot}, B''_{2soot}, B_{3soot}, B_{4soot}$ – coefficients;

δ_d – droplets core size;

d_{32}^{inst} – diameter fuel droplets for given portion of fuel;

K_{ev} – constant of evaporation;

$\tau_{inj.start}$, $\tau_{inj.end}$ – injection start and stop timings;

$x_{inj.end}$ – burned fuel fraction at the injection end;

n_{disp} – coefficient of droplets distribution;

[C] – volumetric concentration of the soot.

As an example the Blitz-PRO's online service results of engine emissions prediction depending on the fuel injection advance are shown in figure 4, 5, 6. We considered the maximum continous rating (MCR) operating point of marine low-speed engine MAN 6S60MC.

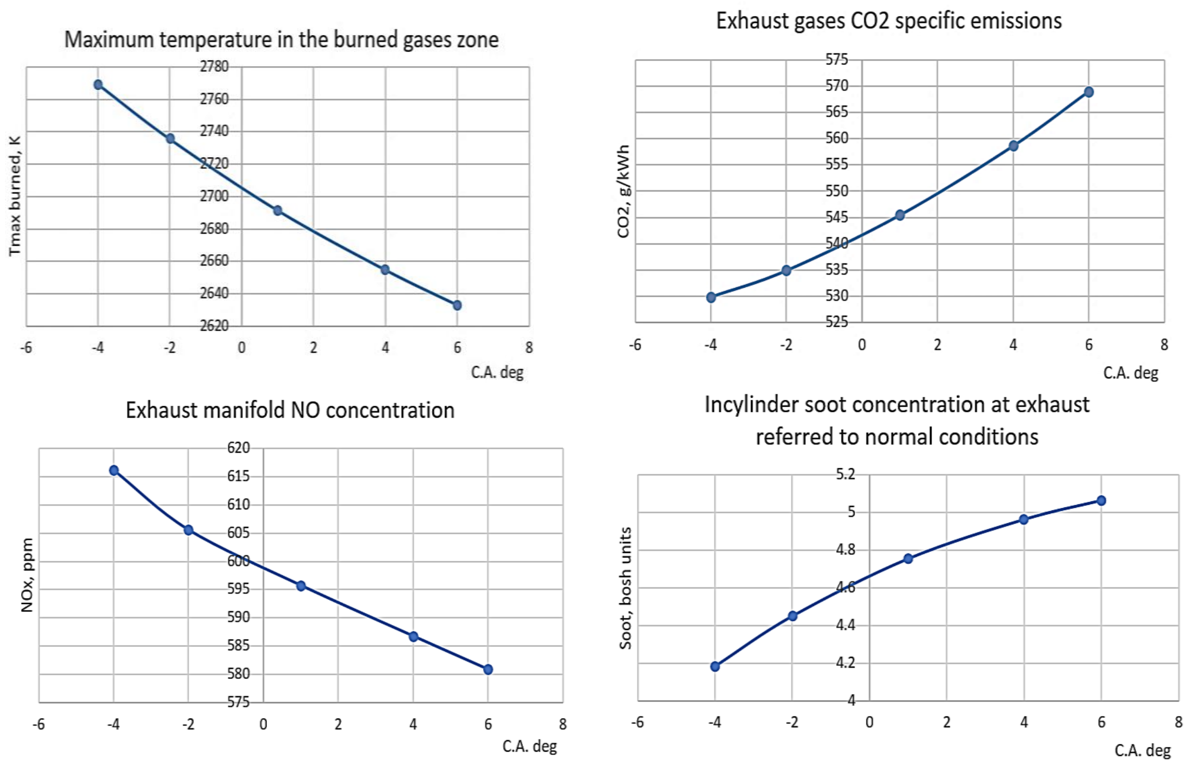

Fig. 4. Maximum temperature in the burned gases zone, CO_2 *and* NO *specific emissions, soot concentration at different fuel injection timing*

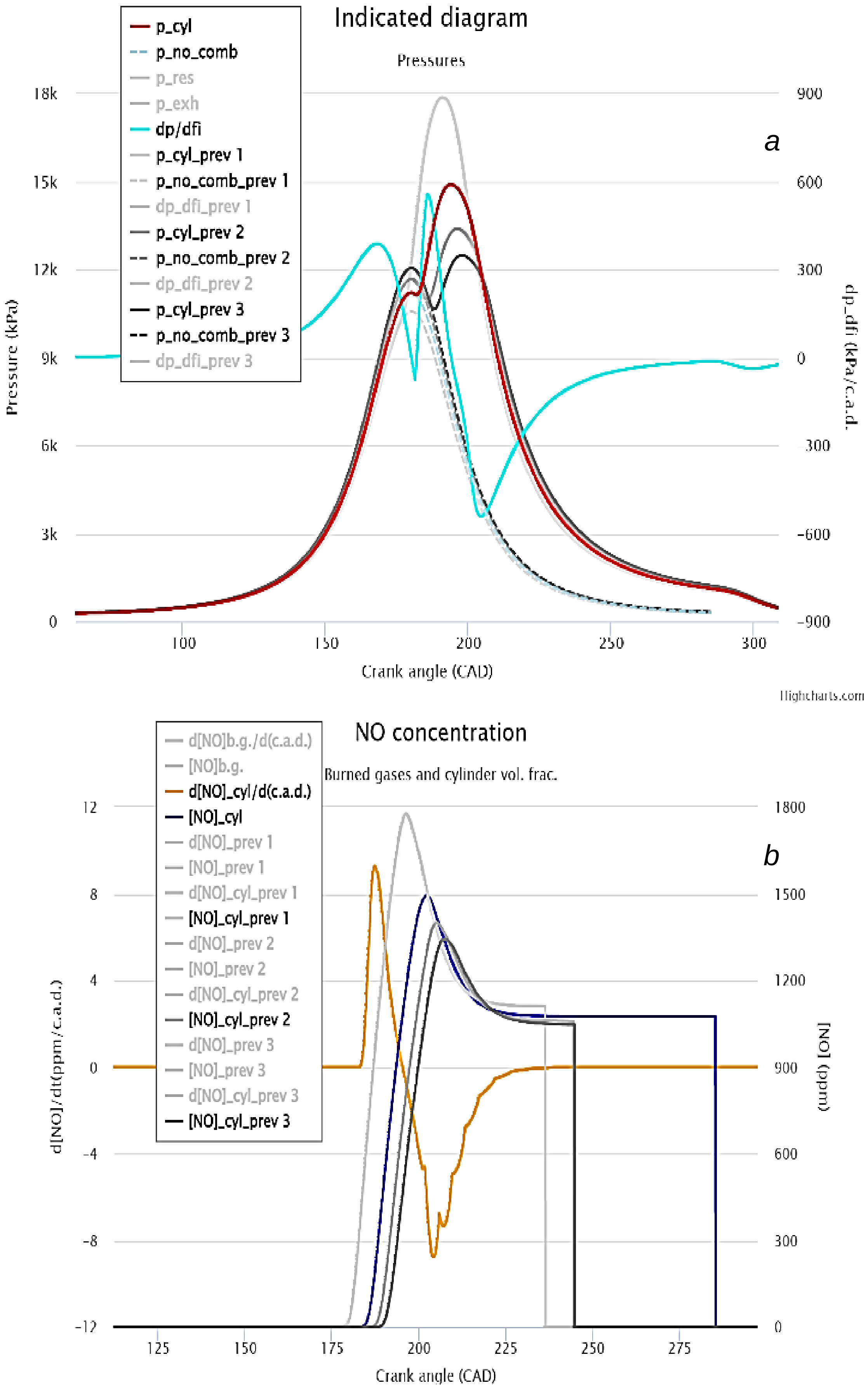

Fig. 5. P(deg) (a), P(V) (b), of MAN 6S60MC engine at different fuel injection timing

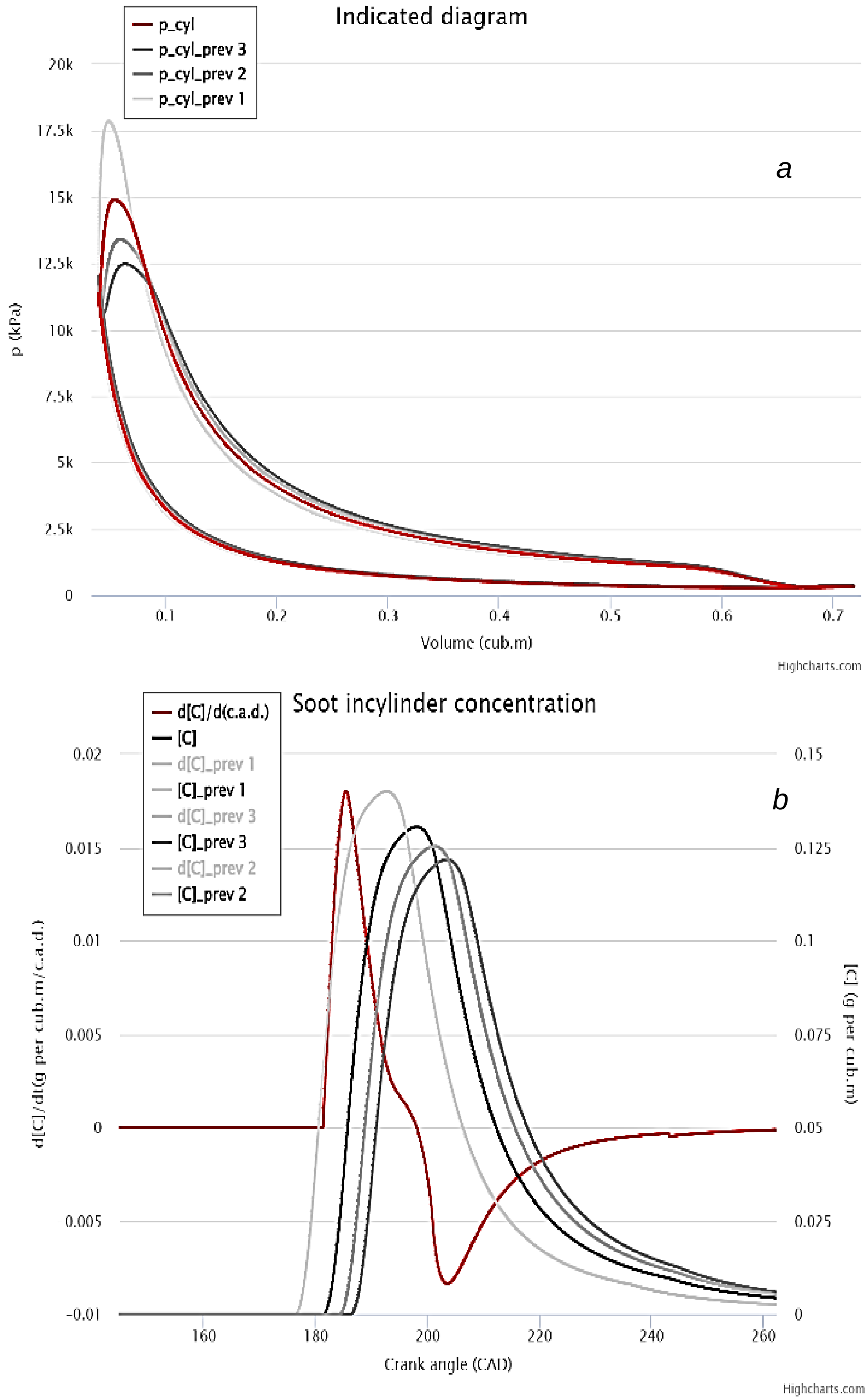

Fig. 6. NO *concentration (a), Soot concentration (b) of MAN 6S60MC engine at different fuel injection timing*

Conclusion

The analysis of emissions concentrations of CO_2, NO, and soot during advanced marine diesel engine diagnostics using the D4.0HT system and Blitz-PRO online service showed that earlier fuel injection timing resulted in decreased CO_2 specific emissions and soot, but increased concentration of nitrogen oxides (NO). These findings suggest that careful consideration of fuel injection timing can influence emissions performance in accordance with current IMO requirements. Numerical analysis of these values can aid in the selection of an appropriate operational strategy that takes into account current IMO requirements, engine power, and fuel consumption rate, thereby optimizing engine performance and emissions control.

References:

1. IMO Strategy on reduction of GHG emissions from ships, International Maritime Organization [Electronic resource].– Access mode: https://www.imo.org/en/OurWork /Environment/Pages/IMO-Strategy-on-reduction-of-GHG-emissions-from-ships.aspx . – 04.07.2023. 2. ANNEX 11. Resolution MEPC.304(72) Initial IMO strategy on reduction of GHG emissions from ships, International Maritime Organization, URL: https://wwwcdn.imo.org/ localresources/en/KnowledgeCentre/IndexofIMOResolutions/ MEPCDocuments/MEPC.304(72).pdf (date of access: 04.07.2023). 3. Minchev D. Marine Diesel Engines Operating Cycle Simulation for Diagnostics Issues / D. Minchev, R. Varbanets, N. Aleksandrovskaya, L. Pisintsaly // Acta Polytechnica.-2021.-vol. 3, №61.- P. 428–440. doi:10.14311/AP.2021.61.0435. 4. Minchev, D. Blitz-PRO User's manual [Electronic resource] / D. Minchev. – Access mode: http://blitzpro.zeddmalam.com/application/index/signin – 04.07.2023. 5. Heywood, J.B. Internal Combustion Engine Fundamentals/ J.B. Heywood.- McGraw-Hill Education. – 2018. - 51p. 6. Píštěk, V. Acoustic identification of turbocharger impeller mistuning-A new tool for low emission engine development/ V.Píštěk, P.Kučera, O.Fomin, A.Lovska// Applied Sciences. – 2020. - vol.10(18). doi.org/10.3390/app10186394.

Bibliography (transliterated):

1.IMO Strategy on reduction of GHG emissions from ships [International Maritime Organization]. Available at: https://www.imo.org/en/OurWork/Environment/Pages/IMO-Strategy-on-reduction-of-GHG-emissions-from-ships.aspx (accessed 04.07.2023). 2. ANNEX 11. Resolution MEPC.304(72) Initial IMO strategy on reduction of GHG emissions from ships[International Maritime Organization]. Available at:: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.304(72).pdf (accessed 04.07.2023). 3. Minchev, D., Varbanets, R., Aleksandrovskaya, N., Pisintsaly, L. [Marine Diesel Engines Operating Cycle Simulation for Diagnostics Issues]. Acta Polytechnica, 2021, vol. 3, no.61, pp. 428–440. doi: 10.14311/AP.2021.61.0435. 4. Minchev, D. Blitz-PRO User's manual. Available at: http://blitzpro.zeddmalam.com/application/index/signin (accessed 04.07.2023). 5. Heywood, J.B. Internal Combustion Engine Fundamentals [McGraw-Hill Education]. London, 2018. 51p. 6. Píštěk, V., Kučera, P., Fomin, O., Lovska A., [Acoustic identification of turbocharger impeller mistuning-A new tool for low emission engine development]. Applied Sciences, 2020, vol. 10(18). doi.org/10.3390/app10186394

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РОЗШИРЕНІ МЕТОДИ ДІАГНОСТИКИ ДЛЯ СУДНОВИХ ДИЗЕЛЬНИХ ДВИГУНІВ: ДОСЯГНЕННЯ ВІДПОВІДНОСТІ ІМО ЩОДО ДЕКАРБОНІЗАЦІЇ

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Анотація. У цій роботі розглядаються апаратно-програмні методи для моніторингу робочих параметрів морських дизельних двигунів та методи математичного моделювання в режимі он-лайн (цифрові двійники) для розрахунку викидів CO_2, NO_x, сажі та інших шкідливих забруднювачів. Демонструється, що вимірювання та аналіз вібраційних діаграм двигуна паралельно з діаграмами газового тиску у циліндрах дозволяє оцінити фактичний час подачі палива та розподіл газів. Отримані дані використовуються для уточнення математичної моделі робочого процесу двигуна, яка визначає показники двигуна та його потужність, а також викиди шкідливих речовин, що потрібно контролювати відповідно до поточних вимог Міжнародної морської організації (ІМО). Автори набули досвіду використання розглянутих апаратнопрограмних методів для діагностики морських двигунів під час експлуатації. Описані апаратні та програмні методи були впроваджені у систему реального часу для діагностики морських двигунів. Система розроблена на основі сучасного двохядерного контролера з високою продуктивністю та низьким споживанням енергії, що включає в себе високошвидкісний АЦП, здатний моніторити робочий процес з роздільною здатністю 0,1 градуса обертання колінчастого вала для всіх типів морських головних та допоміжних двигунів. Система також використовує бездротову технологію передачі даних. Сучасний смартфон або планшет на платформі Android/iOS є обчислювально-графічною частиною системи. Ця система реального часу дозволяє використовувати всі переваги паралельного аналізу тиску та віброакустичного аналізу, включаючи визначення ключових робочих параметрів, визначення положення верхньої мертвої точки та оцінку фаз подачі палива та розподілу газів. Крім того, вона використовує переваги використання цифрового двійника – он-лайн математичної моделі робочого процесу циліндра двигуна. Зазначені рішення покращують якість діагностики та, в кінцевому підсумку, підвищать ефективність експлуатації морських двигунів, зменшуючи витрати на їх експлуатацію та збільшуючи період безвідмовної роботи.

Ключові слова: діагностика; двотактний двигун; датчик вібрації; паливна форсунка; випускний клапан; індикаторні параметри двигуна.