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Research on the effect of low-sulphur marine fuels on the dynamic characteristics of a CI engine

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The implementation of low-sulphur, so-called modified marine fuels into operation requires prior laboratory engine tests to assess the energy, emission and structural effects of their usage. This type of research are carried out on the test bed of a diesel engine as a small-scale physical model that reproduces the adequate design and process (parametric) features of a full-size marine engine. Their key stage is to determine the energy characteristics of the engine in the steady state of operation determined on the basis of the analysis of the developed indicator diagram and the dynamic characteristics of the transient processes from idling to the reference steady state of load – and vice versa. In this way, the basic diagnostic parameters of the fuel usable quality are determined: the rate of pressure increase in the cylinder and the average deceleration of the engine crankshaft within the strenuous transient process. This article presents representative results of this type of research carried out on six different, low-sulphur marine fuels used to feed marine engines.

Key words: *low-sulphur marine fuels, engine tests, dynamic features*

1. Introduction

Experimental assessment of the impact of newly produced, low-sulphur marine fuels on the energy state of a diesel engine in terms of its performance, efficiency, dynamic characteristics and chemical emissivity of exhaust gases is a complex process [1, 2, 13]. It is the basis for making an operational decision regarding their further usage to feed full-size marine engines. It involves the need to carry out engine tests on specially adapted laboratory test beds in accordance with the developed methodology, as well as to perform a multi-criteria assessment of this impact using appropriate operations research tools [4–6]. As a result, it gives the possibility to build a ranking of the usable quality of the tested marine fuels according to the established diagnostic criteria (diagnostic parameters) [7, 14]. This type of research has been carried out for several years at the Marine Power Plant Department of the Gdańsk University of Technology on the test bed of a research CI engine as a small-scale physical model that maps adequate design and process (parametric) features of a full-size marine engine [7]. So far, six different low-sulphur marine fuels have been tested, the basic physical and chemical properties of which are listed in Table 1.

The key stage of the program of experimental research of a laboratory CI engine in the conditions of non-standard marine fuel feeding is the determination of dynamic features characterizing the combustion process, as well as transient processes enforced in a strictly defined alteration range of load and crankshaft rotational speed. In this way, two diagnostic parameters are determined (out of the ten criterion parameters of the ranking of marine fuels in usage quality), which are characterized by the greatest sensitivity to changes in the marine fuel used: the rate of in-cylinder pressure increase and the average engine crankshaft rotation delay in the transient process.

2. A rate of the in-cylinder pressure increase

A measurement of the pressure of the working medium in the cylinder in terms of an angle of the crankshaft rotation stands for a basis for the analysis and evaluation of energy processes worked out in the research engine Farymann Diesel D10, in the conditions of supply with various types of marine fuels. This is carried out in the states of steady engine load, using specialized measuring equipment (Fig. 1):

- Optrand Incorporated optical pressure sensor: AutoPSI-TC Sensor, 0–200 bar, 0.1 Hz to 20 kHz;
- two proximity (inductive) sensors, type PNP NO 5 mm: angular position and rotational speed of the crankshaft;
- DT9816 measurement card by Data Translation – for simultaneous recording control parameters (sampling frequency 10 kHz, resolution 16 bit), together with the QuickDAQ ver. 3.7.0.46 – for the direct acquisition of measurement data in online mode.

Computer application programs, developed in the MATLAB R2015b environment, for processing and analyzing the obtained results represent an important supplement to the measurement system. They enable averaging the recorded indicator charts, as well as determination of the magnitudes characterizing the working process worked out in the engine cylinder: average indicated pressure p_i, indicated power P_i, the maximum combustion pressure p_{max} and the rate of in-cylinder pressure increase $dp/d\alpha$.

The latter parameter, determined from the developed indicator diagram, makes it possible to evaluate the dynamic characteristics of the fuel combustion process in a diesel engine, in accordance with the known calculation

Table 1. Measurement results of elemental composition as well as energy and ignition properties of the considered low-sulphur marine fuels

Parameter	MGO	MDO	RMD 80/L	RMD 80/S	RME 180	RMG 380
The content of carbon C, % m/m	86.20	86.63	86.14	86.54	86.12	86.10
The content of hydrogen H, % m/m	11.10	11.20	11.72	11.75	11.80	11.90
The content of nitrogen N, % m/m	0.05	0.04	0.027	0.02	0.02	0.02
The content of sulfur S, % m/m	0.09	0.008	0.028	0.10	0.01	0.01
Gross calorific value, MJ/kg	46.20	45.68	46.01	45.41	46.19	46.03
Net calorific value, MJ/kg	43.23	42.70	43.04	42.44	43.20	43.08
Cetane number (CN)/calculated carbon aromaticity index (CCAI)	57.2	51	755	791	750	747
Density at 15°C, kg/m^3	827.1	820	872.7	885	878.7	884.5
Kinematic viscosity at 40°C (dist.)/50°C (res.), mm/s	2.99	2.37	77.83	16.48	165.30	308

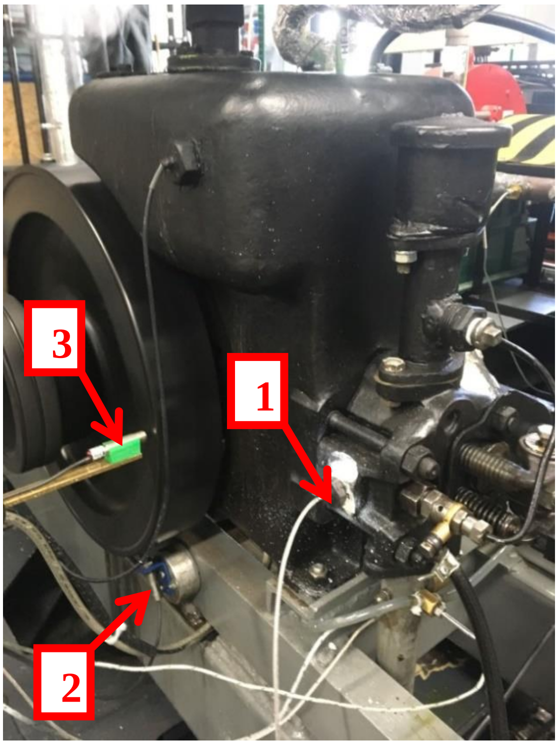

Fig. 1. Measuring sensors on the Farymann Diesel D10 research engine: 1 – in-cylinder pressure, mounted in the side wall of the cylinder head, 2 – proximity sensor, crankshaft angle position (TDC), mounted in a plane perpendicular to the flywheel, 3 – proximity sensor, crankshaft rotational speed, mounted in a plane parallel to the flywheel

formula for the intensity of heat release in the combustion chamber dQ/dα [11, 12][1]:

$$\frac{dQ}{d\alpha} = \frac{1}{\kappa-1} \cdot V \cdot \frac{dp}{d\alpha} + \cdot \frac{\kappa}{\kappa-1} \cdot p \cdot \frac{dV}{d\alpha}, \frac{kJ}{^{o}CA} \quad (1)$$

where: κ – specific heat ratio of the working medium c_p/c_v, V – combustion chamber volume, p – in-cylinder pressure, α – angle of the crankshaft rotation.

The above equation, after appropriate transformation, can be used to determine the formula on the rate of in-cylinder pressure increase dp/dα in the form:

$$\frac{dp}{d\alpha} = \frac{\kappa-1}{V} \cdot \frac{dQ}{d\alpha} - \kappa \cdot \frac{p}{V} \cdot \frac{dV}{d\alpha}, \frac{MPa}{^{o}CA} \quad (2)$$

In turn, knowing that the total amount of heat released in the process of complete combustion Q depends on the injected fuel dose m_{fuel} and its net calorific value NCV:

$$Q = m_{fuel} \cdot NCV, kJ \quad (3)$$

equation (1) can be written in the expanded form:

$$\frac{dp}{d\alpha} = \frac{\kappa-1}{V} \cdot NCV \cdot \frac{dm_{fuel}}{d\alpha} - \kappa \cdot \frac{p}{V} \cdot \frac{dV}{d\alpha}, \frac{MPa}{^{o}CA} \quad (4)$$

where: NCV – fuel calorific value, kJ/kg, m_{fuel} – fuel dose for one engine work cycle, kg/cycle.

The first component of the right-hand side of equation (4) takes into account the time (angular) characteristics of the injection of a specific fuel dose $dm_{fuel}/d\alpha$ and its calorific properties NCV. That means that the direction of changes in the rate of in-cylinder pressure increase is consistent with the direction of changes in the energy potential of the applied type of feeding fuel. The second component of the right-hand side of equation (4) characterizes the work of compression performed by the thermodynamic system, which can be proved using the general isentrope equation [10, 12].

Electronic cylinder indication brings a completely new information quality in the aspect of assessing the dynamic characteristics of the fuel combustion process in a research diesel engine, despite the known metrological weaknesses of this method[2], used mainly in the diagnostics of high-power engines – land and marine. On the basis of a properly smoothed (e.g. by synchronous averaging) course of variation of the working medium in-cylinder pressure as

[1] Since it is not possible to directly (by measurement) determine the course of heat release in the process of fuel combustion in the cylinder of a diesel engine, it is recreated by calculation, by means of an analytic-empirical model derived from the first law of thermodynamics. A course of the in-cylinder pressure alteration during the valves closing period stands for the input parameter of this model. It is recorded during the experimental tests of the engine. But the rate of net heat release (amount of heat released as a result of combustion reduced by heat losses penetrating the walls of the combustion chamber, heat for fuel heating and evaporation, as well as the heat of thermal dissociation of the fuel vapor) constitutes the model output parameter.

[2] They result from the following problems:
- the need for the manufacturer to ensure sufficient exam susceptibility of the engine, in the sense of its standard equipment with cylinder indicator valves (most modern high-speed and even medium-speed engines do not meet this condition);
- the need to ensure a steady, nominal load during the engine testing (this is easy to fulfill for engines driving generating sets, while for engines of the ship's main propulsion system it is difficult because their cylinders indication requires constant sailing conditions);
- significant measurement uncertainty resulting from errors in determining the piston TDC and fluctuation rotational speed of the crankshaft;
- deformations of the working medium in-cylinder pressure course caused by changes in the geometry of the indicator cock passage as a consequence of its contamination or wear, as well as imperfection of the measuring transducers used (temperature drift).

a function of an angle of the crankshaft rotation p = f(α), it is possible to determine the courses of the first and second-order derivatives (Fig. 2). They provide key diagnostic information regarding the quality of the working process (combustion):

- the angular position of the crankshaft at which the pressure in the cylinder reaches its maximum value – the zero point of the first-order derivative dp/dα;
- the angular position of the crankshaft at which fuel self-ignition occurs – the zero point of the second-order derivative $d^2p/d\alpha^2$;
- dynamics of the combustion process – maximum of the first-order derivative $(dp/d\alpha)_{max}$.

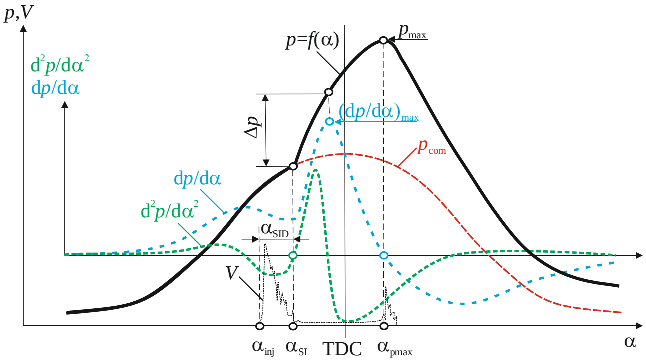

Fig. 2. The method of using the 1st and 2nd order derivative of the cylinder pressure function p = f(α) to evaluate the dynamic features of the fuel combustion process in a diesel engine: p – working medium in-cylinder pressure, p_{com} – air in-cylinder pressure during the "clean" compression process (without self-ignition), V – vibration signal forced by the injector, generated from the cylinder head (vibration acceleration envelope), α – angle of the crankshaft rotation (°CA), α_{inj} – angle of the fuel injection beginning, α_{SI} – fuel self-ignition angle, α_{max} – angle of the maximal combustion pressure

In assessing of the combustion process dynamics, more complex indicators are also applied. For example, Kozaczewski proposed in his monograph the so-called dynamic impulse D_{comb}, defined as a product of the maximum of the first-order derivative $(dp/d\alpha)_{max}$ and the pressure increase until this maximum Δp [8]:

$$D_{comb} = \Delta p \cdot \left(\frac{dp}{d\alpha}\right)_{max} \tag{5}$$

While analyzing the impact of the rate of in-cylinder pressure in a diesel engine, its two aspects should be considered: the efficiency of the realised working process and the strength of the engine structure. In general, the compromise principle of maintaining the highest possible dp/dα values while preventing excessive pressure pulsations in the cylinder space and the so-called knocking combustion, with all the further effects of this negative phenomenon on the engine reliability [8].

An average rate of the in-cylinder pressure increase of the engine with a pre-combustion chamber is much lower than in the engine with direct fuel injection [6]. However, regardless of the engine construction, the limit value of dp/dα should not exceed 0.8–1.0 MPa/°CA in the entire range of the load alterations. Hence, this is recommend to apply a calculation formula that takes into account the need to maintain appropriate proportions of pressure increase in the cylinder during the period of fuel self-ignition delay and the period of kinetic combustion [6]:

$$\left(\frac{dp}{d\alpha}\right)_{\alpha_{SI}-\alpha_{pmax}} - \left(\frac{dp}{d\alpha}\right)_{\alpha_{inj}-\alpha_{SI}} \leq 0.25\ \mathrm{MPa}/\ {}^{o}\mathrm{CA} \tag{6}$$

A different approach to the issue of determining a rate of the in-cylinder working medium pressure of the research engine was adopted, treating this value as a diagnostic parameter characterizing the usable quality of marine fuels. It was assumed that the most destructive for the mechanical system of the engine are the local maxima of the first-order derivative of the pressure in the cylinder, occurring during the period of kinetic combustion $\alpha_{SI} - \alpha_{pmax}$. Hence, only the highest instantaneous value of the pressure increase of the working medium in this period was adopted for further diagnostic evaluation (Fig. 3):

$$\sup\left(\frac{dp}{d\alpha}\right)_{\alpha_{SI}-\alpha_{pmax}} = \sup\left(\lim_{\Delta\alpha\to 0}\frac{p(\alpha+\Delta\alpha)-p(\alpha)}{\Delta\alpha}\right) \tag{7}$$

Table 2 lists numerical values of a rate of the in-cylinder pressure increase of the engine fed with the tested marine fuels.

Table 2. Calculation results of a rate of the in-cylinder pressure increase of the engine fed with the tested marine fuels

Parameter	**MGO**	MDO	RMD 80/L	RMD 80/S	RME 180	**RMG 380**
dp/dα MPa/°CA	**0.6406**	0.6130	0.4947	0.5600	0.4817	**0.4693**

Analyzing the numerical data presented in Table 1, it can be concluded that the most favorable course of the combustion process in the dynamic aspect ("soft" engine operation) was obtained when the engine had been fed with RMG380 fuel, for which the rate of in-cylinder pressure increase was equal dp/dα = 0.4693 MPa/°CA. The most unfavorable combustion course ("hard" engine operation) – when powered by MGO fuel, for which dp/dα = 0.6406.

3. Angular acceleration and deceleration of the crankshaft in transient processes

In the second stage of testing marine fuels, examinations of research diesel engine dynamics are carried out in transient processes. They are worked out within the established range of the engine load variability [6]. These processes are initiated (enforced) by changes in the armature current intensity of the generator loading the engine. The processes are forcedly carried out in about 1–2 s (of a course similar to a unit stroke). In this way, further diagnostic parameters are determined: angular acceleration within the process of the engine crankshaft acceleration and angular deceleration in the process of its deceleration as observable effects, respectively: accumulation and dissipation of kinetic energy stored in the rotary power train unit.

These parameters primarily reflect the inertia of the accelerated and decelerated mechanical system of the entire power train unit, which results from moments of the masses inertia within the engine reciprocating and rotational motion and the rotating masses of the drive line along with the power receiver.

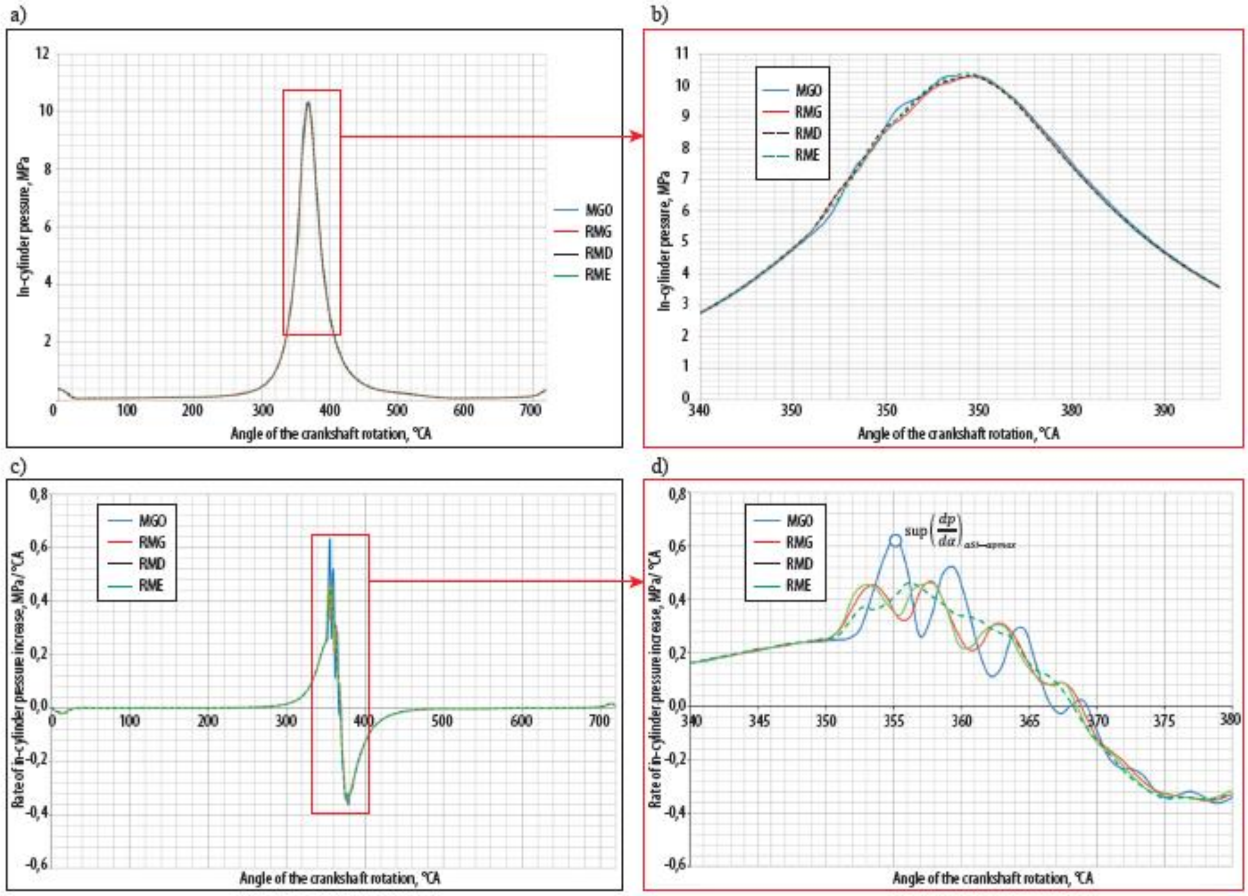

Fig. 3. Developed indicator diagram p = f(α) of the Farymann Diesel D10 research engine in the conditions of feeding with the tested marine fuels: a) assembly diagram; b) magnification of the graph p = f(α) in the area of the piston TDC; c) the course of the derivative dp/dα for the entire engine cycle; d) magnification of the derivative dp/dα for the period of kinetic combustion [6]

It also results from dynamic features of the power supply and control system engine, including the calorific properties of the feeding fuel used.

According to Newton's second law of dynamics, in the transient operating states of the considered power train unit with a CI engine, there are specific alterations in the kinetic energy of the rotating masses, which result from the following relationship [3, 9]:

$$\pm J \cdot \frac{d\omega}{d\tau} = M_e - M_{load} = M_i - M_m - M_{load} \qquad (8)$$

where: J – mass polar moment of inertia of the rotating masses of the engine and generator, ω – angular velocity of the propulsion unit, M_e – effective (useful) torque of the engine, M_i – indicated torque developed by the engine, M_m – torque of the mechanical losses within the whole power train unit, M_{load} – load torque (DC generator).

On the other hand, the indicated torque M_i, which is directly proportional to the mass flow rate of the feeding fuel $\dot{m}_{fuel}$, its net calorific value NCV and thermal efficiency of the engine thermodynamic cycle η_{th}, and inversely proportional to the rotational speed of the crankshaft n, can be calculated from the following formula:

$$M_i = \dot{m}_{fuel} \cdot NCV \cdot \eta_{th} \cdot \frac{1}{2 \cdot \pi \cdot n} \qquad (9)$$

while the indicated engine power – from the formula:

$$P_i = 2 \cdot \pi \cdot n \cdot M_i = \dot{m}_{fuel} \cdot NCV \cdot \eta_{th} \qquad (10)$$

Thus, in order to increase or decrease the engine power, the mass flow rate of the feeding fuel to the combustion chamber for each transient rotational speed of the crankshaft must be, respectively: greater or lesser than during the operation of the power train unit, with the same rotational speed over a fixed range.

As a result, while analyzing dynamic characteristics of the engine in the transient process, the dependence on the acceleration (deceleration) time of the crankshaft from the rotational speed n_1 to n_2 (and vice versa) can be expressed in the form:

$$\tau_{a(d)} = \frac{\pi}{30} \cdot J \cdot \int_{n_1}^{n_2} \frac{dn}{|M_d|} \qquad (11)$$

where: $M_d = M_i - M_m - M_{load}$ – dynamic torque (accelerating or decelerating) on the engine output shaft.

The greater the value of the dynamic torque M_d and the smaller the value of the mass polar moment of inertia of the rotating masses J and the smaller the range of changes in the crankshaft rotational speed $n_2 - n_1$, the shorter the time of the transition process $\tau_{a(d)}$. The dynamic torque, positive or negative, can also be generated during the transient process enforced by changes in the engine load torque (generator driving torque). In such a situation, there are two options for implementing this process:

- during engine running on the external speed characteristics (line A-B in Fig. 4), while maintaining a constant fuel dose per engine work cycle m_{fuel} (constant fuel rail setting l_{fuel}), taking into account its correction, which results from the speed characteristics of the injection unit. Deceleration or acceleration is caused, respectively: by increasing or decreasing the load torque M_{load};
- during the running of the engine on the regulator characteristics with the rotational speed changing in the range of the regulator's astatic operation[3] (line B-C in Fig. 4). The fuel dose is changed as a result of an impact of the rotational speed controller on the fuel rail of the injection pump. Deceleration represents a result of the simultaneous increase in the load torque M_{load} and the fuel dose per cycle m_{fuel}, while acceleration – a simultaneous decrease in M_{load} and m_{fuel}.

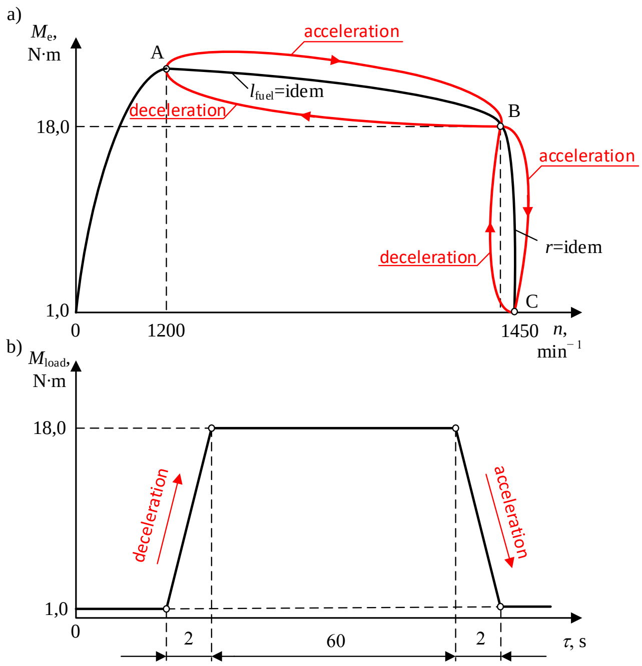

Fig. 4. Characteristics of the realised transient processes of the research engine: a) alteration of the effective torque of the engine in the process of acceleration and deceleration; b) the nature of the applied excitation: A-B – external speed characteristics (fuel rail setting – the amount of injected fuel per one engine cycle, l_{fuel} = idem), B-C – control characteristic (setting the rotational speed controller, r = idem)

The formulas (8)–(10) also result in an important methodological conclusion in the field of testing marine fuels. Well, the time of acceleration and deceleration of the engine crankshaft depends additionally on the net calorific value of the feeding fuel NCV. The higher the NCV value, the shorter the engine crankshaft acceleration time and the longer the deceleration time. Thus, by registering the rotational speed of the engine crankshaft in a given range and the nature of the load variation, it is possible to determine the average value of the angular acceleration (deceleration) $\Delta\omega_{a(d)} = |\Delta\omega|/\Delta\tau$ in the transient process and, on this basis, to assess the impact of the marine fuel applied on the dynamic characteristics engine and the entire powertrain.

[3] The so-called "slip" of the rotational speed controller.

Figure 5 shows the representative time courses of the research engine load (power of the generator), enforcing the process of acceleration and deceleration of the power train unit, and the corresponding time courses of the crankshaft rotational speed as a response to the applied inputs of the dynamic process. The method of determining the angular acceleration and deceleration of the crankshaft in the considered transient processes is graphically illustrated in Fig. 6. First, the recorded courses of rotational speed of the engine crankshaft should be smoothed and averaged[4], and then the differential quotients $\Delta\omega/\Delta\tau$ should be calculated for successive instantaneous time values implementation of the transition process. In the next step of the calculations, it is necessary to determine the beginning and ending times of the transient process τ_b and τ_e. It is assumed that these are the characteristic zero points of the $\Delta\omega/\Delta\tau$ course, for which limit values of the crankshaft rotational speed n_b and n_e are determined. On this basis, it is possible to calculate the average values of the engine crankshaft angular acceleration and deceleration in the specified time interval of the acceleration and deceleration process:

$$\left(\frac{d\omega}{d\tau}\right)_{a(d)} \approx \left(\frac{\Delta\omega}{\Delta\tau}\right)_{a(d)} = \left(\frac{\Delta n}{\Delta\tau}\right)_{a(d)} = \frac{|n_b - n_e|}{\tau_e - \tau_b} \tag{11}$$

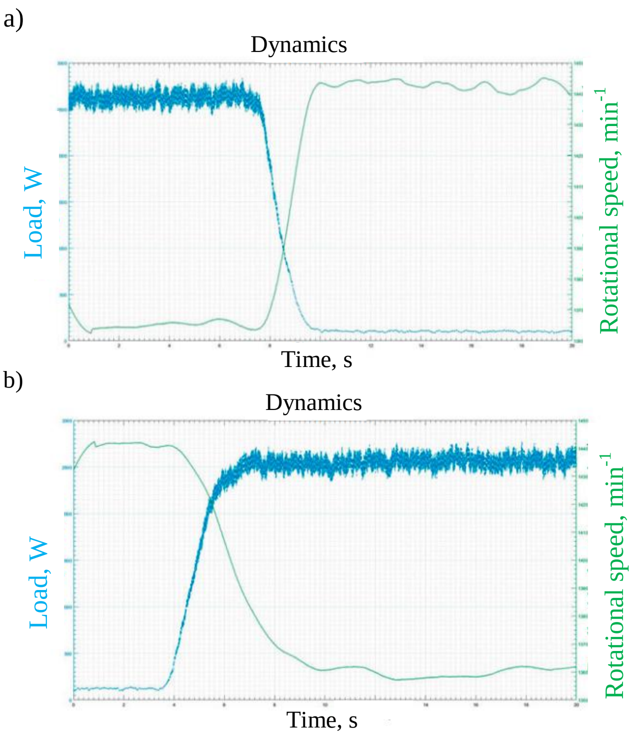

Fig. 5. Time courses of the load and crankshaft rotational speed of the research engine in the acceleration (a) and deceleration (b) processes [6]

Table 3 lists the numerical values of diagnostic parameters determined by this method. Since the direction of their changes is the same, only the average angular deceleration of the engine crankshaft $(\Delta\omega/d\tau)_d$ was selected for further analyzes of the usable quality of the tested marine fuels.

[4] Repetition of the transient process at least 4–5 times under the same thermal conditions.

Table 3. Calculation results of the angular acceleration and deceleration of the engine crankshaft fed with the tested marine fuels in the transient processes of acceleration and deceleration

Parameter	MGO	**MDO**	RMD 80/L	RMD 80/S	RME 180	**RMG 380**
$(\Delta\omega/\Delta\tau)_a$ $1/s^2$	0.210	**0.420**	0.021	0.032	0.042	**0.025**
$(\Delta\omega/\Delta\tau)_d$ $1/s^2$	0.095	**0.165**	0.033	0.043	0.032	**0.030**

The numerical data presented in Table 3 show that a much more advantageous solution, from the point of view of the marine engine motion dynamics, is the application of distillation fuels for its feeding, which is in line with the expectations. The best dynamic features in the transient process were shown by the engine being fed with MDO distillate fuel, for which the average angular deceleration of the crankshaft was $(\Delta\omega/\Delta\tau)d = 0.165$ $1/s^2$, and the worst – by the engine fed with residual fuel RMG380, for which $(\Delta\omega/\Delta\tau)d = 0.030$ $1/s^2$.

4. Final remarks and conclusions

By comprehensively analyzing the obtained numerical values of diagnostic parameters characterizing the usable quality of low-sulphur marine fuels in terms of the dynamic characteristics of the diesel engine powered by them, it can be generally concluded that while distillate fuels have a beneficial effect on the dynamics of transient processes, their impact on the dynamics of the combustion process is already definitely less favourable ("hard" engine running).

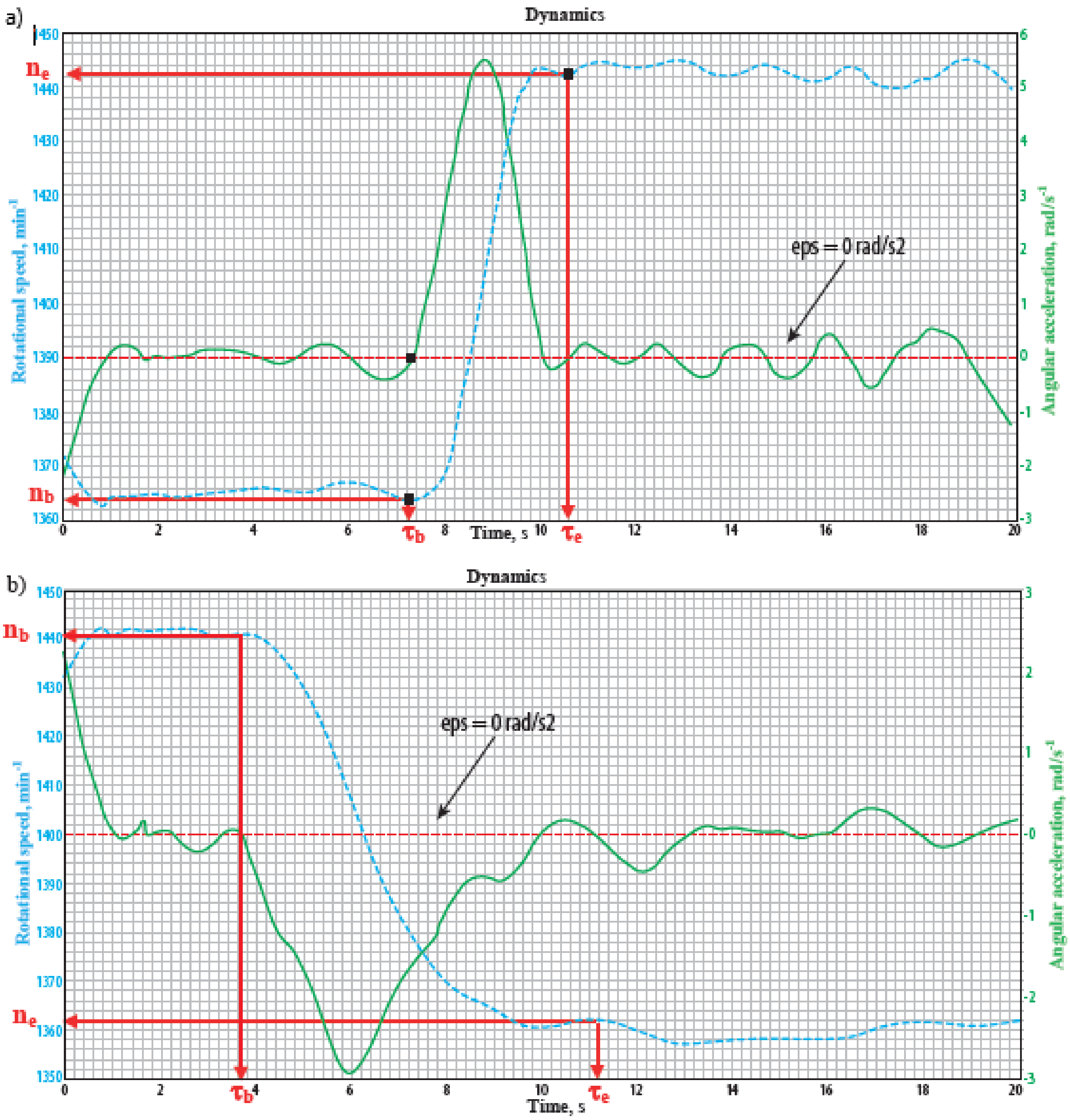

Fig. 6. Time courses of the research engine rotational speed and crankshaft acceleration in the acceleration (a) and deceleration (b) processes – the method of determining the limit values of the crankshaft rotational speed n_b and n_e [6]

The opposite is true for residual fuels. It turns out that the combustion process is milder for them ("soft" engine running), with a slightly slower response of the engine's mechanical system to the given load alterations. In the case of marine main propulsion engines, this kind of inertia is not of great importance in practice.

Moreover, considering the obtained results of the conducted examination of the engine dynamic features in the context of the currently built ranking of the usable quality of newly produced, modified marine fuels, additional methodological conclusions can be drawn:

– The type of feeding fuel has a significant impact on the considered dynamic parameters of the IC engine, that stands for the basis for treating them as key diagnostic parameters in a multi-criteria ranking of the usable quality of the tested fuels, not only marine ones;
– The engine crankshaft angular acceleration and deceleration might represent stimulant parameters of such a ranking, in which the increase or decrease of their values is perceived as, respectively: an increase or a decrease in the evaluation of the fuel usable quality;
– The attitude to similar classification the rate of in-cylinder pressure is more complex. Taking into account the marine engine durability it should be treated as a destimulant of the ranking. But, in more in-depth and detailed analyses, should be treated as the ranking nominant. It can be assumed that the optimal value of this parameter should be in the range of, for example, 0.2–0.8 MPa/°CA In such a situation, exceeding both the lower limit of the range, which means a reduction in the working process efficiency, and the upper one, indicating too “hard” engine work that leads to excessive loads on its mechanical system, means a reduction of the fuel usable quality rating. It has been established that in treating this parameter as a destimulant, it is assumed that the same marine engine power is achieved with its “softer” running – which is more desired.

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