



CONCEPTION OF DIAGNOSING SELF-IGNITION ENGINES FED WITH BIOFUELS IN OPERATION CONDITIONS

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Summary

The article deals with the question of diagnosing the high power self ignition (SI) engines fed with pro-ecologic fuels in an aspect of appearing operation problems. There has been presented the specific of action and techno-operation profile of the combustion engine foreseen as an investigations object. The preliminary conception of diagnostic investigations of the engine 7L35MC type produced in H. Cegielski - Poznan S.A. factory on MAN DIESEL A/S license has been demonstrated. The investigative problem and the main aims of undertaken diagnostic research have been formulated. Within this conception there has been taken into account an action model of the considered engine at an application of its diagnosing and controlling application. There has been also considered the proposal of investigation and diagnostic inference enabling an elaboration of the appropriate diagnosis about the engine technical state. Additionally, a way of the research organization as well as the specification of measuring equipment of the proposed diagnosing system diagnosing has been discussed.

1. Introduction

The results of preliminary investigations conducted by the authors as well as different publications [1,10,11,14,18,21,22] containing the research results concerning bio-fuels usefulnesses to feed SI engines lead to conclusion that the further continued investigations should be mainly directed into issues, as follows:

- qualification of the engine's energetic properties by assignment of such parameters (the coefficients) of its action like: maximum combustion pressure in cylinders (p_{max}), the indicated pressure (p_i), exhaust temperature (T_s),
- diagnostics application for identification of the engine's working spaces technical state, especially cylinders' bearing surfaces, pistons' heads, fuel injectors as well as cylinders' heads from the side of a combustion chamber.

We propose an application of diagnosing systems during engines' technical state evaluation, as follows: (fig. 8, 10, 11): a digital register and analyzer of vibration "SVAN 956", digital indicator of the cylinder pressure "the LEMAG the PREMETS" as well as the measuring videoendoskop "XLG3".

The scientific research aimed to evaluate a method of the energetic features estimation of self ignition engines feed with the palm oil as well as procedures of the identification of their technical state. Proposals in this regard have been introduced in point 3.

2. Profile of the research object

The worldwide crisis of shipbuilding industry in Poland extorted the necessity to search for the new sale markets by many country (and not only) manufacturers of marine machines and devices. The far performed changes of the production profile have been often necessary. A major polish producer of marine engines H. Cegielski - Poznan S.A. did not unfortunately avoid this problem. The factory specializes in production of licensed Wartsila as well as MAN the DIESEL A/S engines. Experiences gathered during a realization of the signed's contract along with Greece, on delivery several stationary energetic systems driven by low-speed two-stroke engines made it possible to take over the next order, from behind shipbuilding industry, this time for Germany. The contract signed-up in 2008 includes a delivery of the complete unit of a electric supply powering in the refinery PBB GmbH located in Brake [20]. A two-stroke low-speed engine of 7L35MC-S type produced on the license of MAN DIESEL A/S, adapted to feed with commercial biofuel - raw palm oil has been applied in he propulsion line of the electric power station. This is the first in the world the ecological electric power station, and gathered operation experiences will surely help to improve the propulsion engine's construction. It will also enable an application of different ecological fuels e.g. rapeseed oil, methylic spirit and even the animal tallow in the immediate future. Physical-chemistry properties of the applied biofuel has imposed a necessity of the engine's construction structure modification (elements of the engine's fuel feed system were adapted to have a contact with the fuel of a high acidic number equals 13-16 mgKOH / g), as well as the constructional form.

Currently the engine works on a crude palm oil at the parameters as follows:

Free fatty acids	max	7 %
Impurities	max	0.5 %
Water	max	0.5 %
Ignitron temperature	min	200 °C
Phosphorus	max	100 mg/kg
Acid number	max	14 mg KOH/g
Net calorific value	min	36 000 kJ/kg
Cetane number	min	36
Density	max	930 kg/m ³
Fluidity temperature		18 °C
Resistance to oxidation	100 °C min	8 std.
Viscosity	50 °C max	32 mm ² /s
Viscosity	70 °C max	20 mm ² /s

Sulfur	max	10 mg/kg
Ash	max	0.01 %

The engine's fuel system has been feed with the fuel come from chicken fat during starting the tested engine. This fuel also showed its usefulness to feed such kinds of diesel engines.

The MAN B&W engine of 7L35MC-S type is a 7-cylinder, low-speed, crosshead, two-stroke, high charged engine in a row configuration - fig. 1. A nominal engine's power of the piston stroke - 1050 mm and cylinder diameter - 350 mm equals 4520 kW, at the crankshaft rotational speed - $214,3 \text{ min}^{-1}$ and supercharged pressure - 0,27 MPa. The specific fuel consumption, within the load range burden 80-90% P_{nom} , does not exceed 179 g/kWh. It gives the general engine's efficiency about $\eta_o=54,7 \%$ taking into consideration that the net calorific value of the applied biofuel equals $W_d = 36770 \text{ kJ/kg}$. Figure 2 i 3 demonstrate the schematic diagram of the port-valve scavenging in the engine's cylinder system. The engine represents a propulsion unit for the alternating current generator of LEZ, St. Petersburg 4/5750 kW/kVA, 50Hz /11000kV type. The engine's basic parameters are introduced on the load profile - fig. 4.

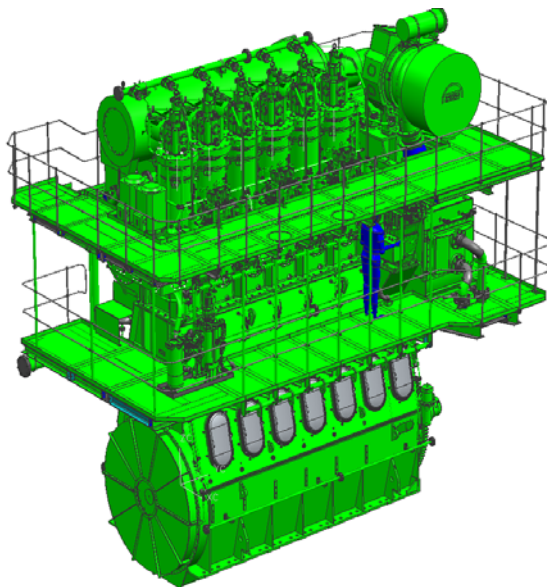


Fig. 1. General view of the 7L35MC-S engine

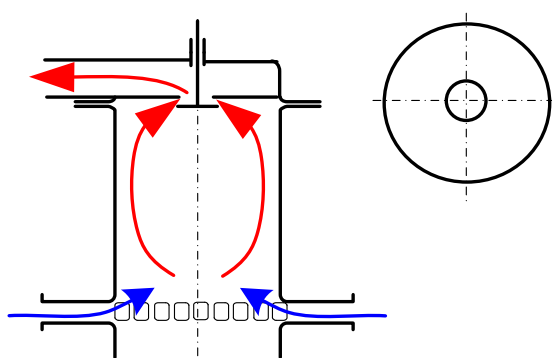


Fig. 2. Port-valve timing system of the 7L35MC-S engine a) flow diagram of the working medium, b) inlet (admission) ports.



Fig. 3. Exhaust outlet of the port-valve timing system of the 7L35MC-S engine
 a) exhaust valve stem, b) exhaust valve fungus in the low plate of the cylinder head.

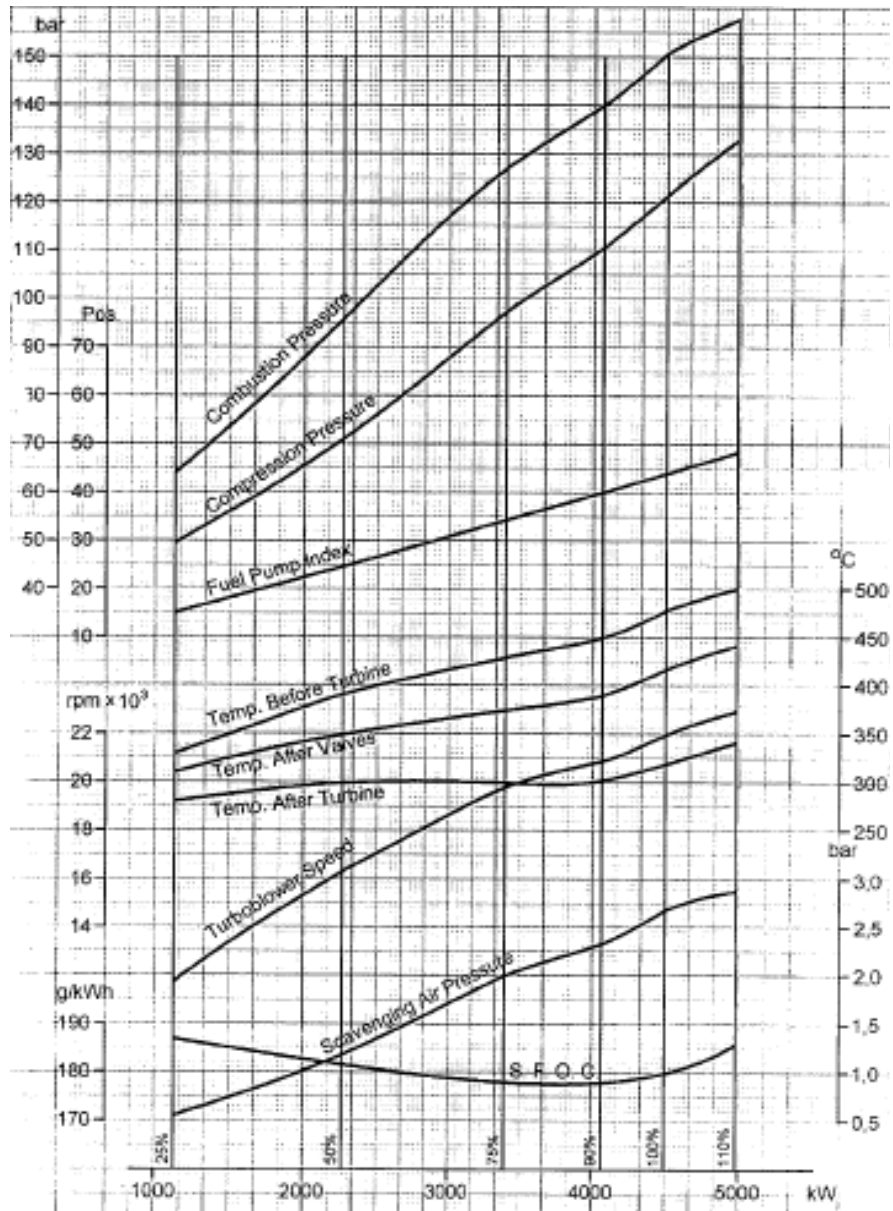


Fig. 4. Load profile of the 7L35MC-S engine

Basic technical parameters which characterize the whole energetic installation:

- Electric power: 4,5 MW;
- Thermal power in a steam and hot water: 3.5 MW;
- Efficiency of the electric energy production: 48%;
- The general efficiency of the electric and thermal energy production: 87%;

The introduced installation is characterised with the highest standard in a range of the environment protection fulfilling the EU requirements within the scope of the Best Accessible Techniques so called BAT (Best Available Technology) - which marks:

- Obtainment of the minimum efficiency of the electric power production with delivered chemical energy in a liquid, in the range of 40 - 45 %;
- Obtainment the associated efficiency (the cogenerative) of the electric power and warmth production (in the form of low-pressure steam from the warmth delivered to the waste-heat boiler as well as in the form of hot water from the warmth delivered to heat exchangers of the cooling cycles HT and LT), in the range of 75-90 %;
- Limitation of dustiness to the level of 20 mg/m³, by means of the electrofilter application;
- Limitation of SO₂ emission, by means of the low-sulphur fuel application;
- Limitation of NO_x emission, by means of the SCR system application;
- Limitation of CO and hydrocarbons emission, by means of OxyCat system application;
- Limitation to minimum of the water dirt, by means of an application of the closed cooling systems of oil and water medias as well as restrictive fulfilling the German norms within this range.

The Competitive Committee of XIII International Energetic Market ENEX 2010 rewarded the project with medal for the innovation and applied technical solutions in an acknowledgement of the innovation of the applied solutions in Brake electric power station.

The operation parameters of the power station as well as the positive opinion of the German customer caused the interest of different investors in this solution. At present HCP realizes the next contract on an equipment delivery of two electric power stations at the power of 13 MW (the engine plus generator and TCS) on English market. The engines will be fed with the rapeseed oil. The electric power stations have to be ready before the next Olympiad (the location on the suburbs of London, in Beckton and Southall).

There is also considered the electric power station building at the power of 32 MW for Ireland - animal fat will be the fuel here, and also building the identical electric power station, how there is in Brake, in Poznan on HCP terrains.

The engine of Brake electric power station overworked about 3500 hours till January 2010. The engine has been twice subjected a technical state evaluation (after 1868 and 3462 overwork hours) since the statement-receiving tests carried out in 24 March 2009.

It is worth pointing out the HCP signed the service contract with German customer in Brake assuring the maintenance of the system's proficiency and its disposability by the period of two years. There is expected that the contract realization will permit on gathering additional experiences and help in selection of optimum solutions in the next projects.

3. Conception and diagram of the research performance

A control of an operation process of any SI combustion engine requires, among other things, controlling both its technical states and energetic states during operation. Moreover, the energetic states controlling may be worked out only during the engine's action (running). In case of a SI engine, the controlling process consists in well ordered impact on the engine's



constructional structure parameters, controlling devices and the direct user (the controlling system), according to principles, programmes and algorithms accepted by the decision-maker. They should be adapted to the executed tasks, of which undertaking requires the regard of limitations (H), criteria function (F) as well as the results of diagnosing in the form of diagnoses (D), or diagnoses and also the prognoses (P), or diagnoses and also the possible origins (genesis G), or the full diagnoses (it means together diagnoses, prognoses and origins), generated by the diagnosing system (SDG). Such a situation is pictured in form of diagram introduced in fig. 5 [6]. The above mentioned task $Z = \langle D_Z, W_R, t \rangle$ could be interpreted as the correct action consisting in production of the required power in engine's cylinders - in general - the engine's functioning (D_Z), in definite operation conditions (W_R) and in the settled time (t). The controlling process should assure a rational engine's action, which consists in the proper energy transforming in the form of warmth and work. Consequently, the engine's overall efficiency does not deviate considerably from the optimum value of the overall efficiency that could be possible to obtain for the considered engines' types. Moreover, a technically dry friction does not occur within the engines' most significant tribologic systems. The only mitigated solid friction is acceptable. A rational action of this engines does not lead to premature damages of its elements (pistons, piston rings, main and crank bearings etc.), causing the unserviceable states, especially characterised with extensive disturbances of constructional structure, so called the breakdowns.

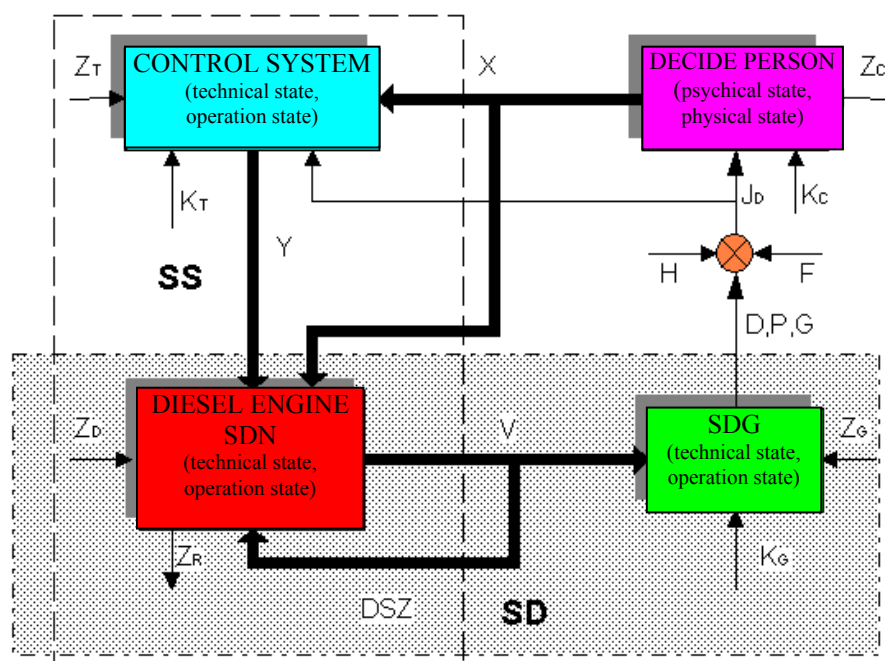


Fig. 5. Simplified model of combustion engine operation with regards to diagnosing and controlling in time of operation [6]: D - diagnosis, DSZ - destructive feedback, F - criterion function, G - genesis, H - operational limitation, J_D - decision information, K_C - disturbances while making operational decisions, K_D - disturbances of the system being under diagnosis (SDN) and simultaneously under control (ST), K_G - disturbances of diagnosing system (SDG), K_T - disturbances of controlling system, P - forecast, SD - diagnostic system (SDN and SDG), SS - control system, V - vector of initial processes, X - vector of decision, Y - vector of control, Z_C - power supply of a decision maker, Z_D - supplied power, Z_G - power supply of a diagnosing system, Z_R - lost power, Z_T - power supply of a controlling system.

The result of foregoing considerations is that the credibility of diagnosis should be taken into account during undertaking operation decisions [2,6,7]. In case of a determined fact that

the diagnosing system (the *SDG*) has been in full operation readiness (in the full serviceable state and acted without fail) during diagnostic investigations and diagnosis elaboration about the engine's technical a diagnosis pertinence should be taking into account [2,6]. The additional result is that the rational regard of the diagnostics within the control process of combustion engines requires the accomplishment of a diagnostic identification of the individual engines, in which the information enabling the construction of suitable diagnostic models of these engines should be worked out. This task requires also a diagnostic process identification aiming an obtainment of the information defining a specific of this process. The information got has the essential meaning, because the course of this process influences on the diagnosis' credibility, indeed (alternatively on the pertinence) about the technical state of individual combustion engines. The process can be viewed variously, but it goes without saying that the process is created by the realizations, as follows: always:

- diagnostic investigation,
- diagnostic inference.

In general, a diagnostic inference is usually created by the inferences: signal, measuring, symptomatic, structural and operational [2]. A schematic diagram of such an inference is introduced in fig. 6.

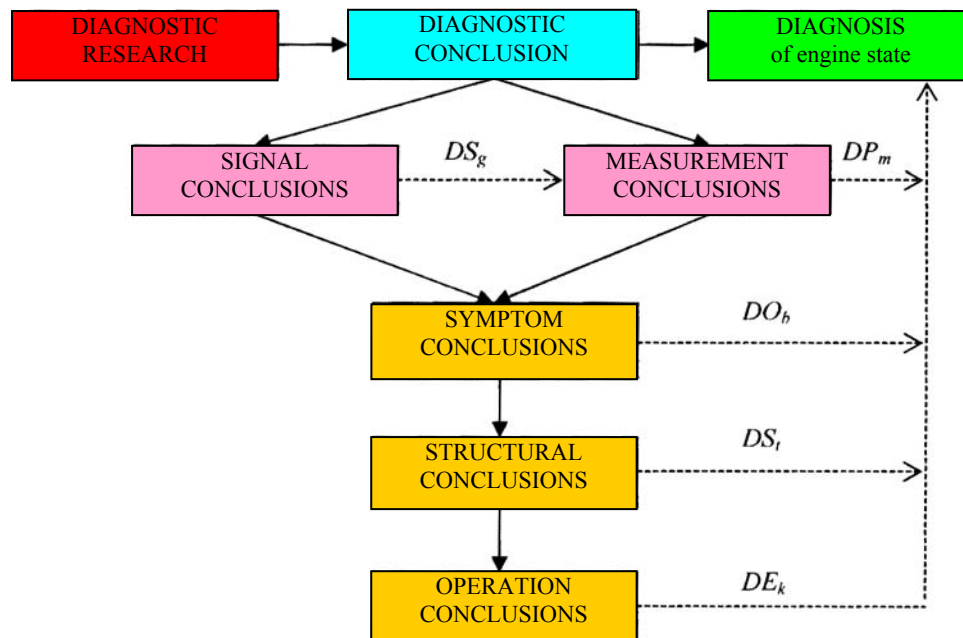


Fig. 6. Diagram of diagnostic inference enabling elaboration of a diagnosis about technical state of an engine (*SDN*) and simultaneously about making operational decision: engine of „full ability”, „partial ability” or „disability” for employment in compliance with its destination: DS_g - signal diagnosis, DP_m - measurement diagnosis, DO_b - symptom diagnosis, DS_i - structure diagnosis, DE_k - operation diagnosis.

As far as the introduced diagnosing conception is concerned the diagnosing process has go the values (states), which represent a diagnostic investigation and specified kinds of the inference, and the time of these kinds duration reflects realizations of these states. Therefore, this is the process of the following class: discreet in states and continuous in time. From the research which have been carried out so far results that this process can be recognized as the semimarc one [7,8,9].

The mistakes made within every kind of mentioned above inferences can accumulate. Moreover, the more states *SDN* are contained in a diagnostic task the greater mistakes are. The more exact diagnosis is necessary (it means a diagnosis at the larger credibility) the

mistakes meaning is greater. These facts cause, that only three states class *SDN* are considered: full fitness, partial (incomplete) fitness and unfitness.

4. Research apparatus

4.1. General description of the research apparatus

Permanent modernizing and enlarging the possibility of the measurement-diagnostic systems applied within the energetic system driven with combustion piston engines enables widening functions of the control system of control including, except standard measurement of the operation parameters, also the functions of measurement and registration:

- pressure in an engine's cylinders,
- vibration generated by the chosen points of an engine's constructional structure (the head, turbocompressor's frame),
- vision of internal spaces.

Schematic diagram of the designed diagnosing system, taking into account the constructional form of 7L35MC-S engine as well as the accessible investigative apparatus, is introduced in figure 7.

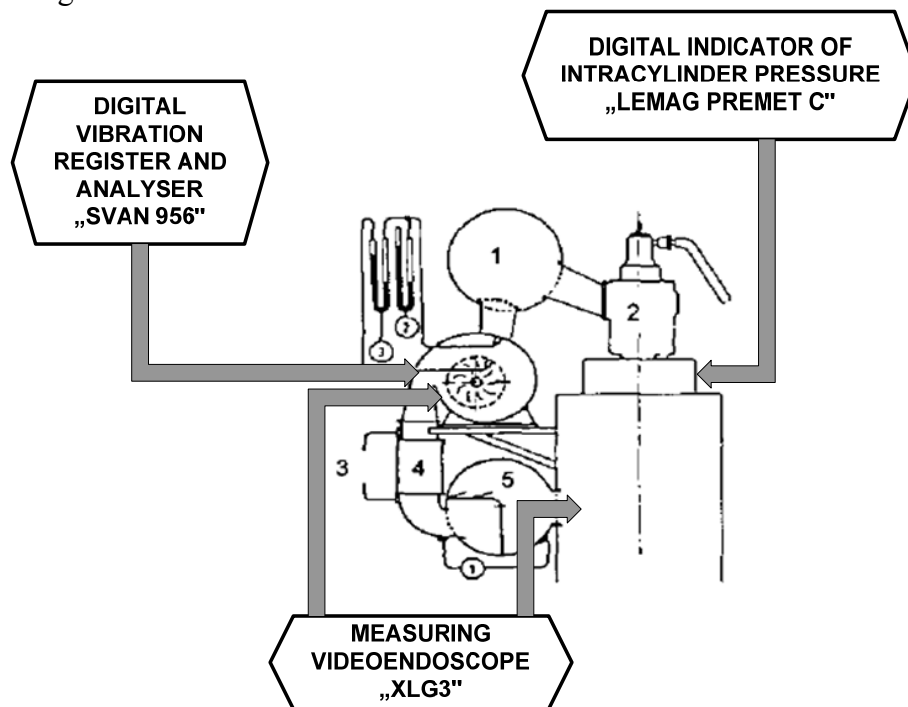


Fig. 7. Schematic diagram of 7L35MC-S engine along with diagnosing system's elements
 1 – exhaust-storage cell, 2 – outlet valve, 3 – turbocompressor, 4 – scavenging air cooler, 5 – scavenging air-storage cell.

4.2. Digital indicator of the pressure in engine's cylinders

A selective indicating the engine's cylinders during a steady running on representative and settled ranges of the engine's load represents the basis of a realization of the parametric diagnostic investigations. Developed indicator diagrams are created by means of the specialist electronic indicator "LEMAG PREMET C" (fig. 8). The diagrams represent the courses of pressure alterations in the engine's cylinders in terms of an angular position of the crankshaft. Moreover, a crankshaft's angular position on the indicator diagram is related to the piston's



IDC (inner dead centre) - fig. 9a. Such diagrams are then overlaid each other, averaged and compared in terms of a load's inequality of the engine's individual cylinders - fig. 9b. It has got relocation on the spectrum of torsion vibration of the engine's output shaft deciding about the lifespan of elements transmitting a torque to the power receiver. If the cylinders' pressure measurements were associated with the vibration measurements generated from the engine's head during hittings the co-operating constructional elements of valve timing and fuel apparatus the more precise and deeper formulation about the engine's governing state would be possible.

The results of cylinders' indicating will be also used in a trends analysis to evaluate alterations of the engine's technical state in different stages of the usage process and to elaborate rational operation decisions.

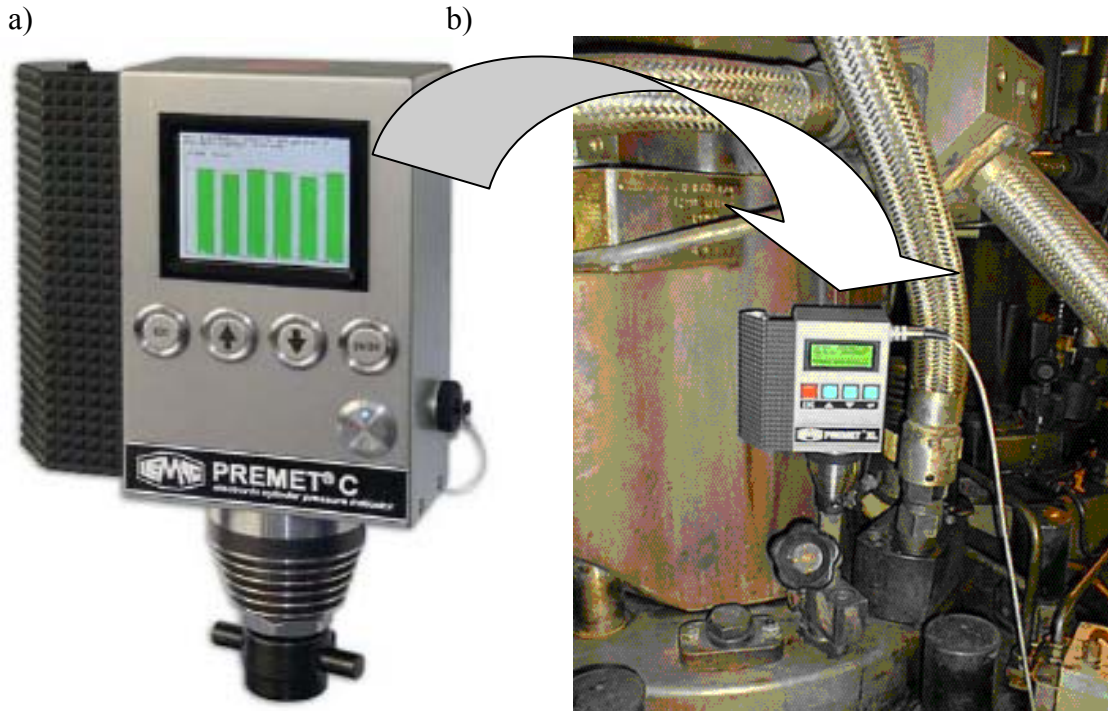


Fig. 8. Digital indicator of the engine's intracylinder pressure „LEMAG PREMETS C” [23]
 a) complete indicator along with adapter, piezoelectric Kistler sensor (0-25,0 MPa) and projector LCD, b) the way of indicator installing on the RTA48TB engine.

On the basis of simultaneous measurements of pressures in cylinders, crankshaft rotational speed and vibration generated from cylindrical heads there is possible determination of the engine working spaces' diagnostic parameters, as follows:

- maximum compression and combustion pressure,
- average indicating pressure of individual cylinders,
- indicating power of individual cylinders as well as the whole engine,
- intensity of pressure growth in cylinders $dp/d\alpha$,
- angles of the injector's opening and closing,
- angles of an occurrence of the fuel self-ignition in a cylinder,
- angles of cylinder valves' opening and closing.

a)

b)

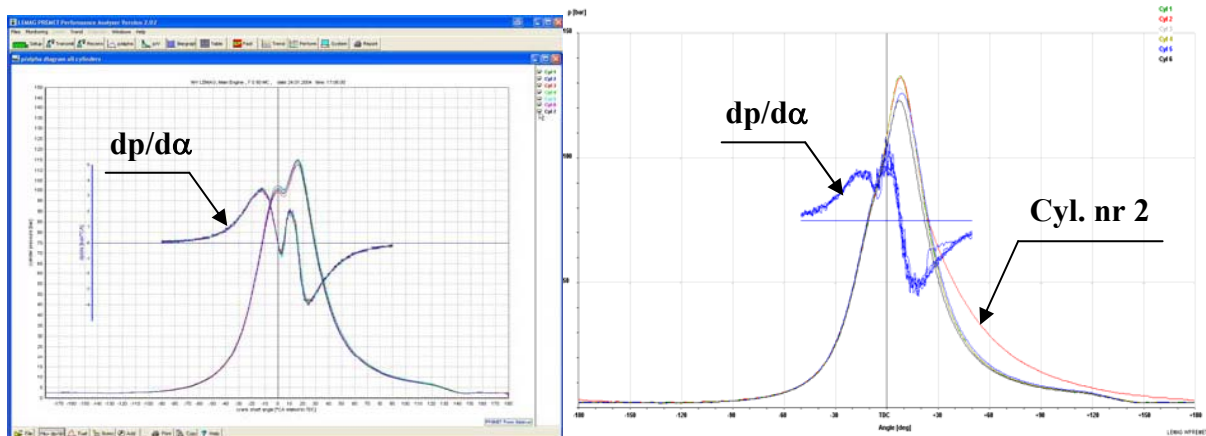


Fig. 9. View of the computer screen after starting-up an analyzing program of the indicator
 a) analysis of the intensity of pressure growth in cylinders, b) overlaid indicator diagrams – fuel afterburning during expansion process worked out in cylinder number 2 (disturbances within the atomization process, leakage of the injector sprayer).

A convenient menu of the analysing indicator programme enables working out the functions, as follows:

- display of a course of the cylinder heads vibration's envelope on a background of the intracylinder pressure course in terms of the crankshaft rotation angle,
- quick presentation of all the measured and computed parameters' values in the form of tables as well as developed graphs and bar graphs, and also the comparison of their values to the average values for the engine,
- comparison of the indicator diagrams of any cylinders of a studied engine, as well as the gathered data of different engines of the same type.

There is possible to carry out the analysis of the engine's technical state on the basis of assigned diagnostic parameters, as follows::

- assessment of the engine cylinders' tightness,
- assessment of the load equability of individual engine cylinders,
- assessment of the control quality of the injection unit,
- assessment of the performance of the whole engine,
- assessment of the engine's and propulsion system's mechanical losses,
- forecasting the time of the engine's correct running,
- precise readjustment of the engine to the work on partial loads, which leads to limitation of fuel consumption even by 30%.

4.3. Digital vibration register and analyzer

A fatigue strength of the material of constructional structure's elements stands for one of the parameters which has got the most essential impact on a combustion engine's lifespan. A multiple alterations of mechanical and thermal loads during an engine's work might cause serial springy and plastic deformations of the constructional elements. They represent the reason of a formation of variable internal tensions, until the fatigue cracks occur (high - and low-cycle fatigue). A vibration resulting from the stability loss of the engine's mechanical unit stands for the most frequent reason of fatigue cracks of a combustion piston engine. With regard to a special construction's complexity of the combustion piston engine, as a fluid-flow machine at the periodic action, there is possible appearing the resonance phenomenon of all the vibration's forms: torsion, longitudinal and transverse. The huge variety and

changeability of the occurred extortions (and disturbances), at a lack of sufficient information about the frequencies of proper (own) vibration of constructional parts causes the opinion that the state of an operational vibration diagnostics of combustion piston engines is still discontent, because only few engine's components are susceptible on this method of a technical state's evaluation. Nevertheless, many scientists dealing with a diagnostics of combustion piston engines of a large power (particularly marine diesel engines) undertake trials to make a spectral analysis of all the vibration's forms for the technical state's evaluation of chosen constructional elements of the engine. It would concern, among others, cylinder liners - longitudinal and transverse vibration [19], fuel injectors and working spaces - a crankshaft's torsion vibration [3,4,5,17], cylindrical valves (clearances) - the transverse vibration of a head [15], turbocompressors (bearing and blading system) - longitudinal and transverse vibration of the rotor [16].

On the basis of so far reached results, there can be concluded that in case of the considered 7L35MC-S engine the measurement and spectral-correlational analysis of the vibration signal generated with a turbocompressor running represents the most promising method of a complex evaluation of its technical state. An attractiveness of the spectral analysis confirms its common applying in diagnostics of whirling machines. It induces the measuring devices' manufacturers to construct the more and more perfect vibration's registers and analyzers which give a possibility of the following trends of values' alterations of the spectrum parameters in different characteristic frequency bands, for the well-known and recognizable states of operation unfitness [24].

It is foreseen, that in the first stage of diagnostic investigations of the 7L35MC engine's turbocompressor a single-channel digital vibration measuring instrument SVAN 956 type equipped with the function of frequency analysis (FFT function - Fast Fourier Transform function) of spectrum amplitudes of the recorded vibration signal will be applied- fig. 10.



Fig. 10. Digital vibration register and analyser „SVAN 956” [24]
1 – piezoelectric sensor of vibration’s acceleration, 2 – laser tachometer probe.

It is equipped with DYTRAN piezoelectric acceleration sensor 3185D type. A magnetic connection of the sensor makes it possible a quick exchange of the measurement place which has got the very essential meaning in case of variable and limited conditions of the measurement's realization. Three independent measuring profiles applied in the analyzer



permit selecting three filter sets and time-constants for the simultaneous measurement of vibration's acceleration, velocity and displacement within the frequency range from 0,5 kHz to 20 kHz (limited with a transfer band of the applied transducer). Thanks to the large power of a signal processor the simultaneous narrow-band analysis FFT, the simultaneous frequency analyses within the octave- and tercial-bands as well as the simultaneous analysis of vibration envelope are possible during the measurement realization. The analyzer's capacious memory (32 MB) enables recording a time history of the measurement within unsteady processes (turbocompressor rotor's acceleration and deceleration) for an observation of the level alterations and frequency spectrum during measurements: root-mean-square value (RMS), peak value (PEAK), peak to peak value (PEAK-PEAK), maximum root-mean-square value (MAX). There is also accessible the register's version equipped with a function of whirling machine balancing, which requires the rotational speed measurement (laser tachometer probe - from 1 to 99999 min^{-1}) with a simultaneous vibration measurement.

4.4. Measuring videoendoscope

A visual examination o internal space of marine diesel engines with the use o endoscopies is currently the basic method of technical diagnosis. The surface structure of the construction material is seen as if through a magnifying glass during the examination which enables detections, identification and quantitative assessment of the malfunctions and material defects, eventually leading to the quick assessment of the level of deterioration and fouling of the constructional elements while the engine is excluded from the motion. They do not usually generate observable alterations of the diagnostic parameters' values. Depending on the method of observation and image processing o a surface under examination we can distinguish a classic optical endoscopy utilizing rigid (lens based) boroscopes and flexible fiber glass fiberscopes and dynamically developing digital endoscopy utilizing highly sophisticated videoendoscopes fitted with high resolution micro cameras – fig. 11.

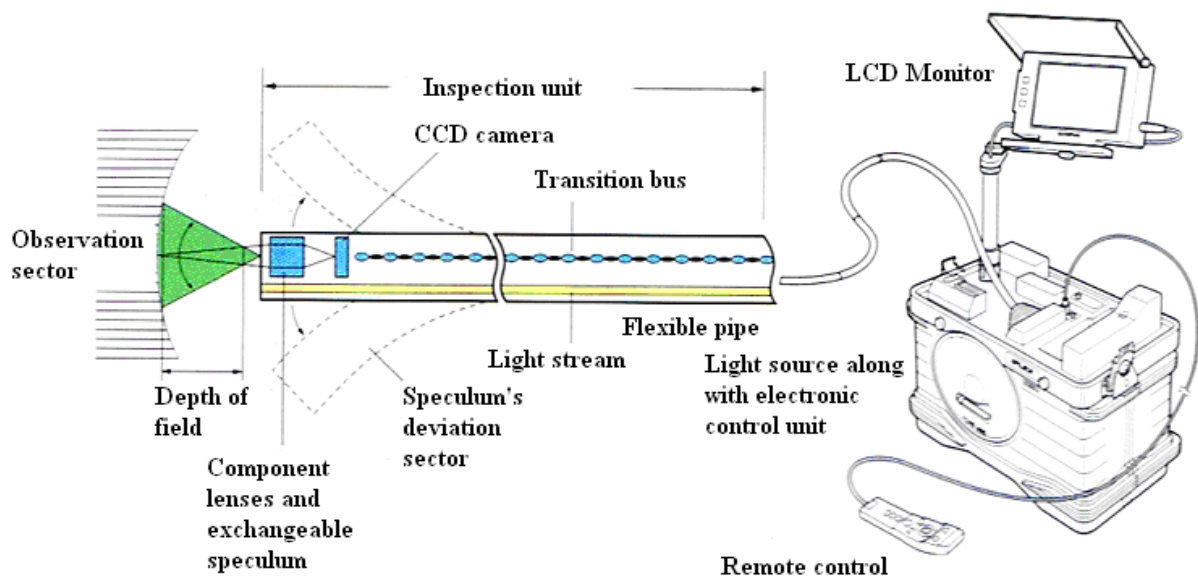


Fig. 11. Schematic diagram of a videoendoscope [25]

A CCD camera processes optical image into an electronic one which is digitally transmitted via a bus into a color LCD unit. This solution generates new diagnostic



possibilities such as the ability of qualitative assessment of the surface deterioration (the possibility to measure the detected structural changes – defects, discolorations, contrast etc.). Because producers of marine machines and devices give permissible values of the surface defects of the most vulnerable construction elements the precise assessment of the real dimensions of the defect represents a key diagnostic issue.

Another important advantage is the high resolution of the image reaching several hundred thousand pixels which ensures sharpness even under poor illumination – fig.12. A digital recording of the image as videoinformation in e.g. JPEG can be transmitted on long distances (cellular networks, the internet). This allows a multilateral didactic (training an exchange of experience) or specialized consultation aiding the process of diagnostic reasoning.

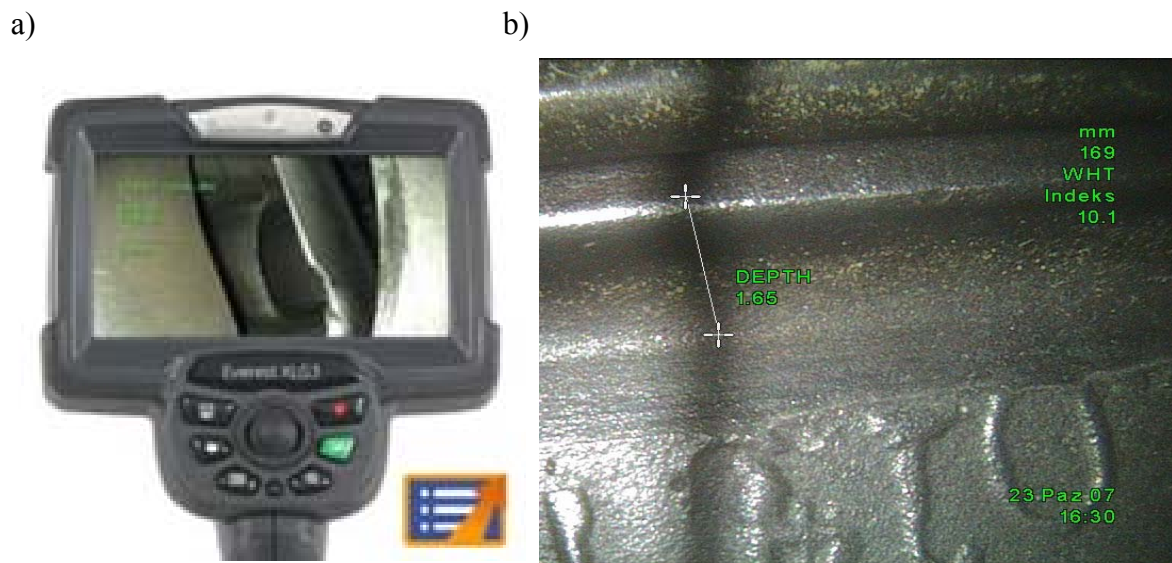


Fig. 12. Digital recording of the image by means of measuring videoendoscope XLG3 [12,25]
 a) panoramic LCD projector, b) depth's measurement of the concave surface profile with the „Shadow” method.

5. Summary. Final remarks and conclusions

Biofuels application at the defined physical-chemistry properties requires the adaptation of the engines' constructional structure to the biofuels which have to feed them. There has been affirmed the relationship between the applied biofuel and constructional structure of the engine, representing the investigation, which is fed with this fuel.

A two-stroke, low-speed engine of 7L35MC type produced on licence of MAN DIESEL A/S Company, adapted to biofuelling with a raw palm oil has been undertaken as an investigation object.

There is a possibility of widening the measuring offer of universally applied control system by means of, except standard measurements of operation parameters also, functions of the measurement and registration:

- pressure in the engine's cylinders,
- vibration generated by the selected points of the engine's constructional structure (cylinder head, turbocompressor frame),
- image of the engine's internal spaces.

The measuring possibilities of the specialist electronic indicator "LEMAG PREMETS" (fig. 8) have been characterized. It is designed and foreseen to create a developed indicator diagrams which represent courses of the pressure alterations in the engine's cylinders in terms

of crankshaft angular position. Moreover, the crankshaft angular position on a developed indicator diagrams is related to the piston's IDC.

There has been also paid an attention within the proposed investigations on usefulness of a multi-channel vibration meter "SVAN 956" type, equipped with the function of frequency analysis (FFT function) of the spectrum amplitudes of the recorded vibration signal (fig. 10). The vibrometer is additionally equipped with a piezoelectric acceleration sensor DYTRAN 3185D type.

One of the most up-to-dated videoendoscope, namely a measuring videoendoscope "XLG3" type, foreseen to diagnostic investigations has been presented. This kind of endoscope is equipped with miniature digital camera CCD, at high resolution (fig. 11), which processes an optical image into an electronic one. Its digital record is transformed by the sonde (broadcasting rail) on the LCD colorful monitor.

An application of the above mentioned diagnostic devices is necessary with regard to need to obtain the credible information concerning not only energetic aspects and potential contamination of a natural environment with toxic substances, but also aspects within the range of wear and tear process of the engine fed with biofuels and the same its reliability and durability.

It results from the gathered information about MAN Diesel 7L35MC-S engine wearing (affects its reliability and durability), that a technical diagnostics has to be necessarily applied. It should be expected, that diagnosing systems like mentioned: digital vibration register and analyzer "SVAN 956", digital indicator of the pressure in engine's cylinders "LEMAG PREMETS C" as well as the measuring videoendoscope "XLG3" applied together with classic diagnosing systems which provide contemporary self ignition engines represent interesting possibilities to incorporate information about technical shape of biofuelled engines.

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