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Expert System for Diagnosis and Optimisation of Marine Diesel Engines

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Original scientific paper

The doctoral, thesis: “Expert System for Diagnosis and Optimisation of Marine Diesel Engines” is the result of many years of extensive practical and theoretical work on problems in the field of testing marine diesel engines and incorporating new technology during diagnosis. This work deals with problems of a complex analysis and testing a system of Diesel engine parameters, pointing out engine working cycle characteristics. The Expert system - EKSE has been developed to analyze and to research engine behavior especially regarding the working cycle and diagnostic system of engines and to optimize engine performance as well as increase efficiency. EKSE includes corrections of parameters under standard ambient conditions by a method developed on the basis of ISO standards. A diagnostic model has been developed for application in marine slow-speed, 2-stroke Diesel engines. A thermodynamic analysis of the working cycle has been carried out on the engines with direct injection. From the results, conclusions about the engine working cycle efficiency have been drawn, showing also the possibility of how to obtain optimizations. The most important results of combustion process have been compared using the correlations by Vibe and Watson-Piley-Marzouk. An expert system of diagnosis and control of Diesel engines gives results of the analysis of important parameters for a 2-stroke marine Diesel engine which serves as a basic technological know-how. EKSE could give best results during implementation on the newly developed, electronically controlled marine engines.

* Defended Doctoral Thesis (2004.)

Ekspertni sustav za dijagnostiku stanja i optimiranje rada brodskog dizelskoga motora

Izvornoznanstveni članak

Rad je rezultat višegodišnjeg praktičnog i teoretskog rada s brodskim Dieselovim motorima i usvajanja novih tehnologija pri dijagnosticiranju stanja motora. U radu se koristi osobno razvijeni programski paket EKSE koji sadrži analizu izmjerenih podataka i vrši dijagnostiku stanja motora. Posebno je razrađen termodinamički model radnog procesa dvotaktnih Dieselovih motora s ispušnim ventilom. Na temelju izvršenih analiza termodinamičkog ciklusa određuje se maksimalni koeficijent iskorištenja topline pomoću kojeg se vrši usporedba s ostalim ciklusima i određuju optimalne značajke motora. Analiza je obavljena na više tipova brodskih sporohodnih dvotaktnih Dieselovih motora. Razvojem računalne tehnologije i elektroničkim upravljanjem motora stvoreni su osnovni preduvjeti za kontinuirano praćenje rada statičkih i dinamičkih značajki i primjenu metoda optimiranja prikazanih u radu. Najbolje rezultate EKSE sustav će dati primjenom na novim generacijama, elektronički kontroliranih Dieselovih motora.

* Obranjena doktorska disertacija (2004.)

Keywords
Diagnosis of marine Diesel engine
Diesel engine
Expert system

Ključne riječi
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1. Introduction

En evaluation of engine technical condition and operating stability, which is obtained by means of measuring and monitoring essential engine working parameters, is one of the most important tasks during the engine exploitation process. Besides maintenance, it is necessary to inspect and eliminate all new conditions which lead to failure. For determining effects and correlations of engine characteristics, an expert system for diagnosis is used.

For the purpose of diagnosis, physical and chemical processes which occur inside the diesel engine are the basis for numerical simulation by which analyses of diesel engine are carried out.

Symbols/Oznake

D	- diameter of the cylinder, m - promjer cilindra
c_m	- mean piston velocity, m/s - srednja brzina stapa
m	- Vibe coefficient - Vibe koeficijent
N	- total number of heat transfer elements (surfaces) - ukupan broj površina za prijenos topline
n_a	- gas turbulence speed, 1/s - brzina plinskog vrtloga
p_{ck}	- compression pressure, Pa - tlak kompresije
c	- cylinder wall temperature, K - temperature stijenke radnog proctor
T_w	- cylinder wall temperature, K - temperature stijenke radnog proctor
X	- ratio of mass of fuel burned from start of combustion to the total mass of fuel injected during one cycle - udio izgorenog goriva od početka izgaranja
α_{pi}	- combustion start crank angle, °CA - kut koljenastog vratila pri početku izgaranja
α_{ti}	- combustion end crank angle, °CV - kut koljenastog vratila pri završetku izgaranja
β	- mode of burning rate - relativna količina izgorenog goriva u homogenoj fazi
c	- specific heat, J/(kg K) - specifični toplinski kapacitet
α	- heat-transfer coefficient, W/(m^{2}K) - koeficijent prijelaza topline fluktuacijska vrijednosti

The latest expert systems, of leading engine manufactures for electronically operated diesel engines are described. The systems described are based on standard procedures for measuring and examining engine which are most common in the exploitation process. Besides all mentioned possibilities of expert systems for diagnosis, a self-developed system EKSE deals with engine working cycles, determining efficiency rate and engine working parameters.

A thermodynamic process inside the combustion chamber is the basis for a study engine working process, Because of that: special attention is paid to combustion inside the engine cylinders.

The benefits of researching thermodynamic processes inside the engine with numerical simulations are:

- knowledge about process and its details,
- determining non-experimental parameters, (polytrophy exponent and local middle temperature of working matter inside cylinder),
- research of development of new values along constructive changes,
- research of development of the processes by changing working conditions, which is very expensive to be carried out in a experimental way,
- determining combustion speed and exchange process of the working medium from experimental indicator diagram,
- optimization and development of engine by obtaining optimal process and constructive characteristics,
- support for experimental and developing work.

Fuel energy efficiency between different cylinders of the same engine can vary; by comparing working processes it is possible to determine the most efficient. Also, corrections can be made by comparing engine working parameters and optimal parameters.

2. Characteristics of modern slow speed marine diesel engines to comply with IMO regulations

There are several methods to reduce exhaust gas emissions from marine engines which are accepted by Classification Societies. Primary methods are used to reduce up to 50 % of NOx from exhaust gases while fuel consumption has an economical rate. For a reduction of more than 50 % secondary methods are used, such as Selective Catalytic Reduction - SCR which reduces NOx from exhaust gases up to 90 %.

Marine engines have to apply IMO regulations for NOx emission limits. For this purpose, new fuel valves are developing. Measured by standard procedure ISO 8187 these fuel valves have compliance with allowed limit of 17.0 g/kWh, Figure 1.

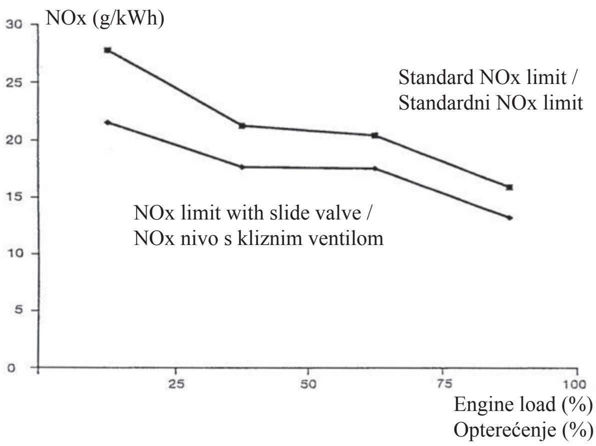

Figure 1. NOx level with and without using of new type of fuel valve (MAN B&W slide valve)

Slika 1. Razina NOx s i bez upotrebe novog tipa rasprskača (MAN-B&W klizni ventil)

One of the primary methods which provides 50 % reduction of NOx is water emulsification. Water is mixed with fuel and introduced into the cylinder by special fuel valve.

Intelligent operating of an engine is reached by means of reliable and flexible systems. A flexible system provides optimal fuel consumption and reduction of harmful emissions. For a system to be flexible, it must have developed injection system and electronically actuated exhaust valves system. Marine engine have to be protected from overload or insufficient maintenance.

Figure 2 shows marine engine system with electronically actuated high-pressure fuel pumps and exhaust valves.

air is low and the temperature of exhaust gases high, the monitoring and valuation system first receives all system condition characteristics, estimates optimal values and, in the end, acts on engine working parameters, such as early opening of exhaust valves or less fuel injection into the cylinders. In these cases, the operator is alarmed to take steps for establishing normal working conditions of an engine. Also, the system can recommend the following actions.

Diesel engines manufacturers have developed application program interface system which is installed and interacts between the engine and remote control system. It controls variable injection timing, variable exhaust valve closing, and changes fuel quality, control

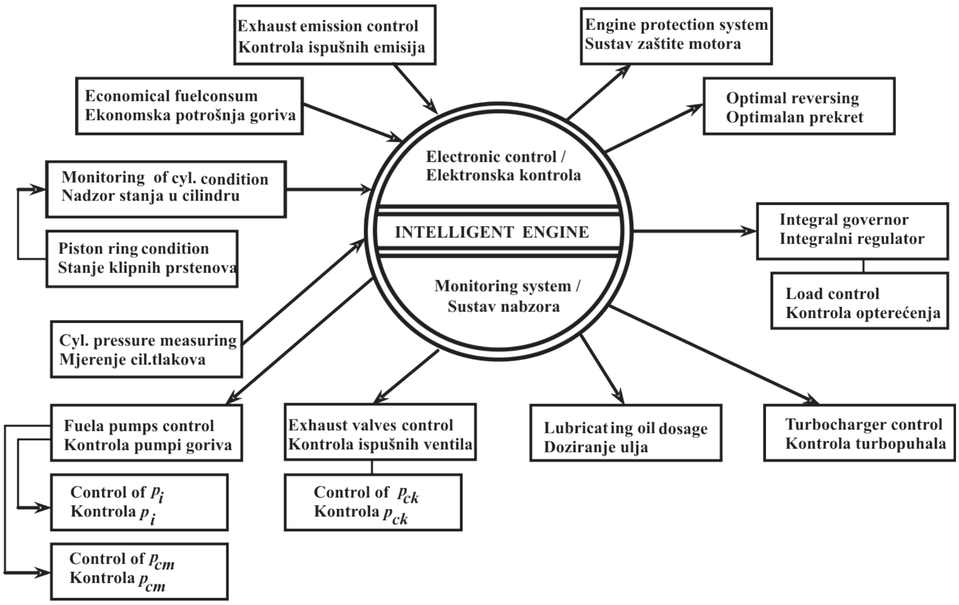

Figure 2. Principal conception of intelligent marine engine system
Slika 2. Princip zamisli inteligentnog brodskog motora

A control system is based on optimal working conditions for different engine loads and emission limits. Optimal reverse system and engine protection system use electronic systems to control it, while, a fuel system and exhaust emission control is operated from the bridge. A fuel pump and injection system, exhaust valves system, lubricating system and turbocharging system must all be controlled by the central part of Figure 2 describing the "brain" of the whole intelligent system made of an electronic control system which analyzes the main working parameters and control engine working cycles.

A monitoring and valuation system is always active. It receives all information on engine conditions automatically. If, for example, the pressure of scavenge

integrated cylinder liner cooling system and cylinder lubricating system, depending on the engine load.

3. Expert systems for diagnostics of marine diesel engines

With an expert system, it is possible to use all the benefits of automatic control and immediate intervention which brings more safety, less responsibility and amount of work. The technical crew on board ship controls a main and auxiliary engine, engine condition and organizes manning, technical support and maintenance.

An expert system is used for combining maintenance procedures, from supply to install action on board. Because of that, an expert system has to be able dynamically to integrate different software for the purpose of using information on different maintenance procedures, and allow the crew to establish active cooperation with software. An expert system is expected to:

- control the engine,
- analyze working efficiency,
- hold diagnosis of engine condition,
- plan maintenance,
- handle and supply the spare parts.

4. EKSE - Expert system for diagnosis and optimization of marine diesel engine

With development of the electronically operated engines, a base is created for condition diagnosis and optimizing engine performances according to real time. Along side the computer techniques development, we have new measuring instruments. New pressure gauges and thermometers can withstand dynamic conditions and thermal loads.

EKSE is a self-developed set of software diagnostics system used for thermodynamic analyzes and performance testing of diesel engine, pointing out engine working cycle characteristics. The system combines:

- analysis of the engine condition from an expert system and suggestions for adjustments and service,
- calculation of the engine parameters according to ISO ambient conditions,
- visualization and automatic report of current observation and engine condition,
- optimization of the engine performances by means of thermodynamic analysis of the engine working cycles.

The advantage of this system, through analysis of the internal combustion engine indicator diagrams, is in receiving values of parameters which are difficult to measure and, also, essential to determine the efficiency rate and to optimize the working process, such as temperature of the combustion mixture inside the cylinder, provided heat energy and extracted heat energy, combustion speed, etc. The basic model of input information is the real values of measured parameters under the dynamic working condition.

An EKSE system consists of the constructive blocks:

- ISO - is software written in Fortran where the engine working parameters are corrected to ISO 3046 ambient conditions; also, it calculates engine load, engine efficiency, turbocharger efficiency, specific fuel consumption, compares referential values, and alarms if exceeding the limits with suggestions for causes and solutions.
- ARP (Analyze of Working Process) - is software written in Fortran which analyzes thermodynamic processes of the diesel engines
- DIJAGN.MOT - is software written in Turboprolog which serves for the malfunction diagnosis. Depending on the malfunction type, it gives possible causes and solutions.
- SERVICE.MOT - is software written in Turboprolog. It handles maintenance according to engine working hours and manufacturer suggestions.

Special attention is paid to optimizing the integral characteristic of the engine systems such as diesel engine. For this purpose different disciplines were applied such as thermodynamics, fluid mechanics, mechanics, numerical mathematics, optimizing theory, etc. Studying losses during the transformation of the chemical energy in to the mechanical work and inquiring the causes, a better way can be found to reduce fuel consumption. The exploitation efficiency rate of an engine is a ratio between the obtained mechanical work and the admitted chemical energy. It defines the fuel consumption.

Defining the course of combustion and exchange dynamics of the working mixture inside the cylinder, it is possible to make a prognostication of the process, define values that can't be found by the experiment, such as cylinder current middle temperature, polytrophic exponent, etc., and build the knowledge of engine process. All the above mentioned, features are used to make conclusions about diesel engine technical status, propriety of the engine and engine parts, and to define if the working process is an optimal one.

For the purpose of the doctoral thesis, the comparison has been made of Wärtsilä and MAN B&W low-speed diesel engines and the analysis of received values with EKSE software. From the received results, the proper development evaluation of the working process and indicated eventual differences and possibilities to optimize the process. Have been made Figure 3 shows the example for graphical presentation of the results made by the ISO software, where the working parameters are given in function with engine revolution speed.

5. Analyzing the engine working cycles with EKSE software

For the purposes of analysis of the IC engine thermodynamic process in the combustion chamber, a differential equation based on the first law of thermodynamics has been used, taking into consideration real parameters under quasi-steady conditions, applied to a closed thermodynamic system: the engine cylinder..

5.1 Heat release rate at Diesel engine working cycles

Fuel combustion rate ($\frac{dx}{d\alpha}$) in diesel engines working cycle which is essential for height pressure process in cylinder, can be expressed with a single Vibe function (1):

$$\frac{dx}{dt} = 6{,}908(m+1)\left(\frac{\alpha-\alpha_{pi}}{\alpha_{ti}}\right)^{m} e^{-6{,}908((\alpha-\alpha_{pi}/\alpha_{ti})^{m+1}} \cdot \frac{d\alpha}{dt}, \quad (1)$$

$$x = 1 - e^{-6{,}908((\alpha-\alpha_{pi})/\alpha_{ti})^{m+1}} . \quad (2)$$

Fuel combustion rate is:

$$\frac{dm_f}{dt} = \frac{dx}{dt} m_{f,proc} . \quad (2a)$$

Heat release rate is:

$$\frac{dQ_{comb}}{dt} = \frac{dx}{dt} m_{f.proc} H_d \eta_{comb} . \quad (2b)$$

5.2. Heat transfer to the wall of combustion

During analysis of the engine working cycle, heat transfer to cylinder walls has to be determined. Gas temperature is assumed to be time dependant and homogenous in all cylinder chambers.

Heat transfer from gas to cylinder walls is expressed by Newton equation:

$$\frac{dQ_{gub}}{dt} = \sum_{i=1}^{N} \alpha_{wi} A_{wi} (T_{ci} - T_{wi}) . \quad (3)$$

Cylinder wall temperature is:

$$T_w = \frac{T_{k1}A_{k1} + T_{g1}A_{g1} + T_{ci}A_{kc}(\alpha)}{A_{k1} + A_{g1} + A_{kc}(\alpha)} . \quad (4)$$

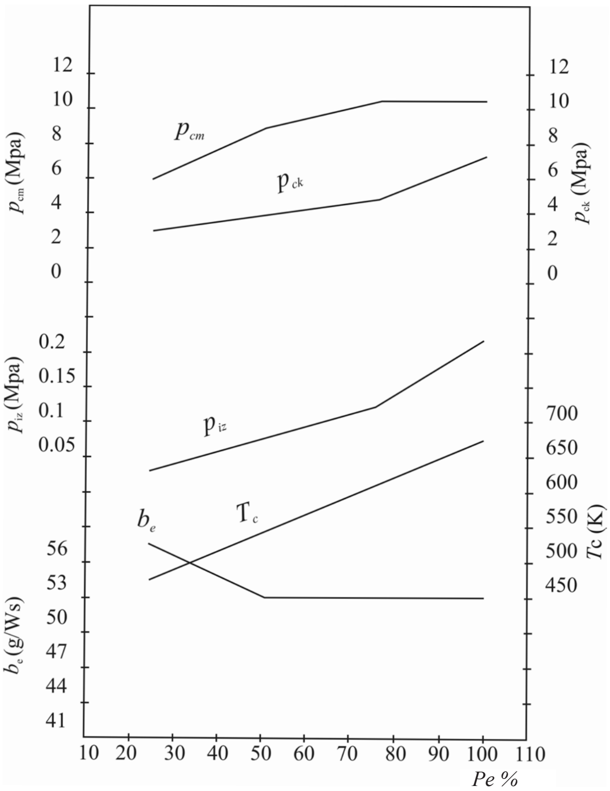

Figure 3. Example of the results from ISO software (6S70MC MAN B&W)

Slika 3. Primjer rezultata programa ISO (6S70MC MAN B&W)

We have:

$$\frac{dQ_{gub}}{d\alpha} = \sum_{i=1}^{N} \alpha_{wi} A_{wi} (T_{ci} - T_{wi}) \frac{1}{\omega} . \quad (5)$$

Heat transfer is determined by the following:

- the combustion chamber geometry,
- the fresh mass on cylinder inlet,
- engine speed in relation to time duration of hot gas and surface of cylinder liners.

For calculation of heat loss by convection, mean temperatures of piston, cylinder liner, cylinder head and valves have been used. Heat transfer coefficient according to Woschni is calculated by Hausen equitation for Nusselt number for convective heat transfer in turbulent pipe flow. Heat transfer coefficient according to Woschni is:

$$\alpha_w = 0{,}0132 D^{-0,2} p^{0,8} T^{-0,53} w^{0,8} \ \ \mathrm{W/m^2K} , \quad (6)$$

where the units to be entered are:

D(m), p (bar), T (K), w (m/s)

When the mass velocity in engine, is determined the first factor represent the velocity due to the piston movement and in-cylinder turbulence during suction, and the second factor represent the velocity due to combustion:

$$w = c_1 c_m + c_2 \frac{V_0 T_1}{p_1 V_1}(p - p_{ck}), \quad (7)$$

where coefficients for various phases of the engine process are:

$c_1 = 6{,}18+0{,}417\dfrac{c_u}{c_m}$ - mass exchange phase,

$c_1 = 2{,}28+0{,}308\dfrac{c_u}{c_m}$ - high pressure phase,

$c_2 = 3{,}24 \cdot 10^{-3}$ m/sK - for direct injection diesel engine,

c_u - gas velocity at diesel engine with direct injection,

$$c_u = D \cdot n_{a,} \quad (8)$$

$$c_m = \frac{S \cdot n_m}{30}\,. \quad (9)$$

6. Description of measuring equipment and methods

Figure 4 shows a schematic measuring chain for engine indicating. The system is equipped with two parallel A/D converters and has a total frequency up to 2x500 kHz, with 12-bit transformation. Such high frequency of this height also enables controlling of signals from crankshaft angle sensor.

Indicating pressure in all cylinders as the function of an engine crankshaft angle was measured for different engine speeds and loads. Rotating speed of crankshaft is measured indirectly i.e. by period of time elapsed between angle marks. The same pressure sensor is moved along all cylinders and mounted on an indicating valve during unchanged engine working regime. The cylinder pressure for the same load was measured by a special permanently mounted pressure sensor on the sixth cylinder through a charge amplifier Kistler type.

Regarding dissipation of successive engine processes, a sequence of up to 50 successive processes on all cylinders with angle sensor with 2048 divisions was measured, which gives total amount of pressure data by cylinder 2048 x 50 = 102.400 data/sequence. In fact total number of data stream for all cylinders, with additional data from permanently mounted sensor and rotating speed of crankshaft is (6+1+1) x 2048 x 50 = 819.200 data by regime. For thermodynamic analysis of working process, the mean value of measured pressure is taken from 50 processes at the same crankshaft angle.

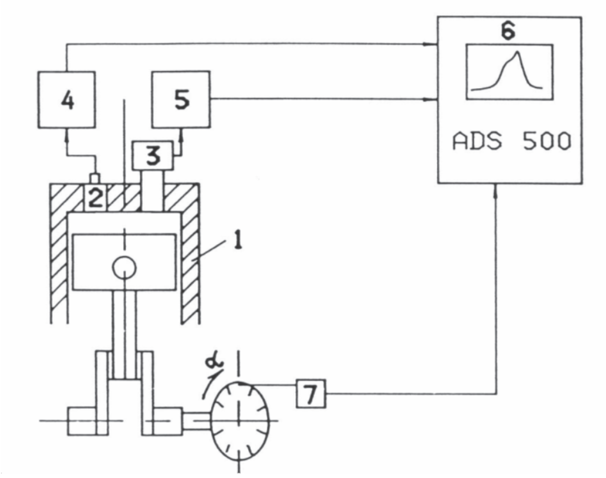

Figure 4. Scheme of measuring chain for cylinder pressure indicating 1. Engine; 2. Pressure sensor on cylinder ("Kistler" 7061); 3. Pressure sensor on engine indicating valve ("Kistler" 7061); 4. Charge amplifier ("Kistler" 5007); 5. Charge amplifier ("Kistler" 5011); 6. Analog-digital converters with measuring system ADS 500; 7. Crank angle encoder ("Leine-Linde")

Slika 4. Shematski prikaz mjernog lanca za određivanje tlaka u cilindru 1. Motor; 2. Osjetnik tlaka na glavi ("Kistler" 7061); 3. Osjetnik tlaka na indikatoru ("Kistler" 7061); 4. Pojačalo ("Kistler" 5007); 5. Pojačalo ("Kistler" 50011); 6. Analogni/digitalni konverter sa njernim sustavom ADS 500; 7. Kutni marker ("Leine-Linde")

7. Corrections of input values

Tests of pressures inside cylinders were made. On the sixth cylinder, a difference was found during the expansion stroke. For the purpose of the comparison on the sixth cylinder two pressure gauges were connected. Pressure gauge connected to the indicator valve showed lower pressures than the one connected to the cylinder head. The difference is shown in Figure 5. After the analyses, a malfunction on the indicator valve was found.

All values are within allowed tolerances. During the compression stroke total heat exchange (UX) is 0 while, during the expansion strokeil is UX=1, which confirms that all heat is in concerned. In some tests maximal variation was 2 %.

During the measurements it was confirmed that the angle difference between cylinders is equal to the theoretical crank shaft angle with tolerance of +/- 0.06 ºCA. Because of various crank shaft twisting stresses on the journals, real angle tolerance is greater. Regarding revolution angle, the referential flywheel angle is obtained by means of integration of the revolution speed, after running the harmonic analyses and syntheses. It was assumed that flywheel rotates at constant speed.

Figure 6. shows the effect of the angle correction because of the various crank shaft twisting stresses, and course of the heat developed in cases when corrections are in considered and not considered.

An extensive observation has been made about the real gas dissociation process and gap losses (due to imperfect cylinder sealing that occurs during the high pressured process). Dissociation occurs when high temperatures are reached during the power stroke. Dissociation can be detected with heated losses. Percentage of dissociated combustion products and heat losses, which are associated with dissociation, increase if the cylinder temperature increases. As the temperature depends on the mixture composition, then the dissociation limit will depend on scavenging air composite. Slow-speed diesel engines which were tested, work with scavenging air composite above 1; therefore, the dissociation is not significant.

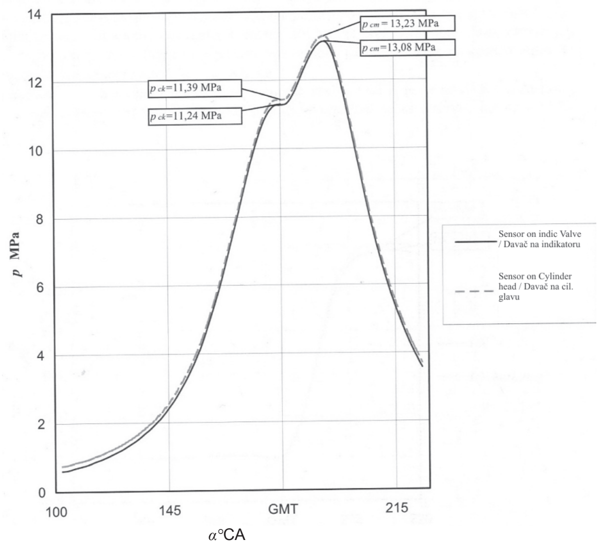

Figure 5. Sixth cylinder pressure diagram at 100 % load. Measured simultaneously with pressure gauge connected to the indicator valve and the cylinder head

Slika 5. Razvijen cilindarski tlak na 6. cilindru pri 100 % opterećenja. Mjeren istovremeno davačima uz cilindar i na indikatorskom pipcu.

Comparing the pressures which are obtained when taking into account real gases with dissociation and ideal gases without dissociation, a great difference has been noticed when maximal pressure occurring (pressures of ideal gases without dissociation were lesser up to 4 %). The effect of dissociation and real gases has an inverse course of action when maximal temperatures and pressures, and maximal scavenging air composite coefficient are reached. Very similar results are obtained when analyzing indicator diagrams. Nevertheless real gases with dissociation or not are considered. Therefore, most commonly used are the ideal undissociated gas properties.

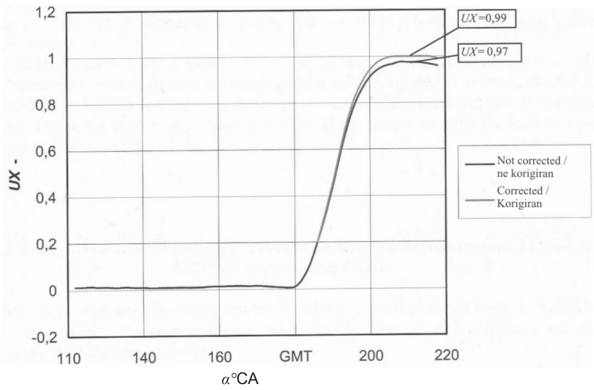

Figure 6. Total admitted heat when calculated with and without correction of the angle on sixth cylinder at 100 % load.

Slika 6. Ukupna dovedena toplina u slučaju proračuna s korekcijom i bez izvršene korekcije kuta na 6. cilindru pri 100 % opterećenja -6S70MC.

8. Example of data from working cycle analysis

Heat release rate *dX/dα* or combustion law shows intensity of combustion and quality of working cycles. A more or less extended diagram shows that the engine is more or less thermally loaded. On this example, it is seen that combustion is completed within 30 ºCA. Deviation of measured parameters during compression is visible on diagram.

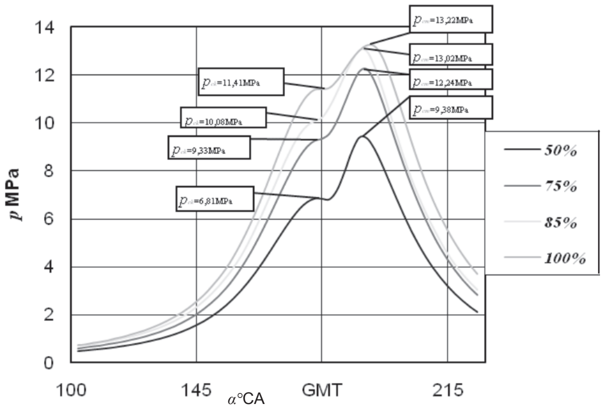

Figure 7. Pressure developed in 6th cylinder for 50 %, 75 %, 85 % and 100 % load on 6S70MC engine

Slika 7. Razvijeni cilindrski tlakovi na 6. cilindru pri 50 %, 75 %, 85 % i 100 % opterećenja na motoru 6S70MC.

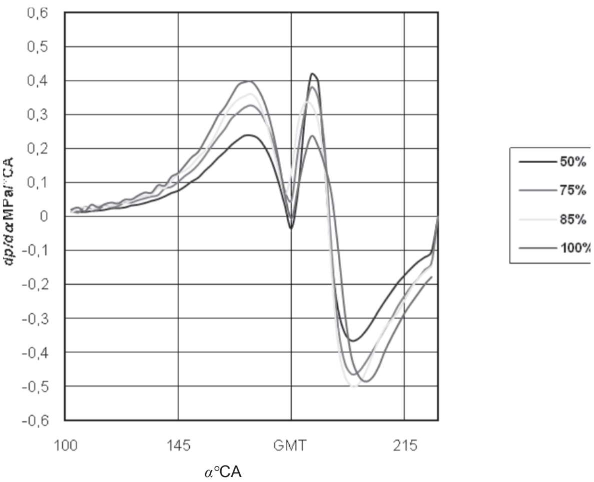

Figure 8. Rate of pressure rise in 6th cylinder

Slika 8. Brzina porasta tlaka u 6.cilindru

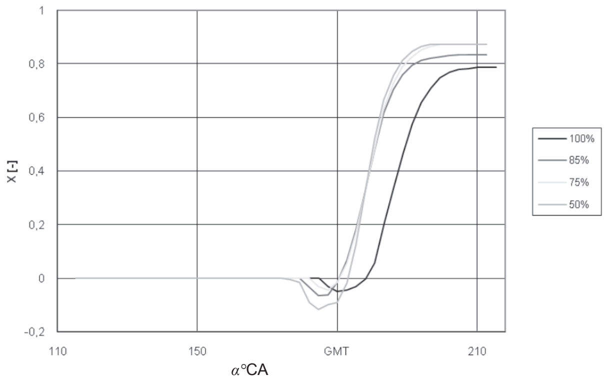

Figure 9. Cumulative heat release at different loads

Slika 9. Usporedba iskorištenih toplina različitih opterećenja

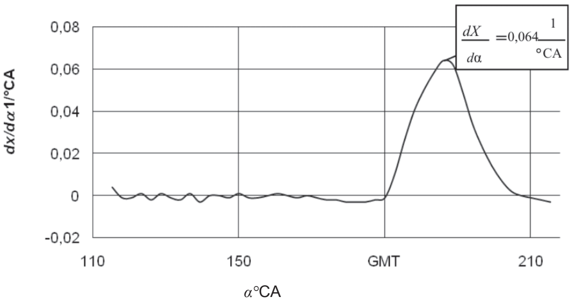

Figure 10. Heat realease rate $dX/d\alpha$ for 6th cylinder at 100 % load

Slika 10. Brzina izgaranja $dX/d\alpha$ za 6. cilindar pri 100 % opterećenja

In experimentally examined engines, the results confirm very prolonged fuel injection and because of that, prolonged mixture inflammation. While trying to reduce formation of harmful particles in exhaust emissions, engine manufacturers had to determine the start of injection angle of 1-2 °CA before TDC.

The causes of rapid combustion at the beginning of injection are:

- at the end of compression, stroke air is compressed to temperatures high enough for ignition,
- fuel which is atomized and overheated is brought into the combustion space,
- evaporation rate is linearly proportional with temperature,
- chemical reaction rate is increased exponentially with temperature.

Injection rate and the cylinder charge temperature influence the homogenous combustion phase. Shorter injection time results in harder, but more economic engine work. During homogenous combustion phase, a rapid heat developing occurs and because of that there is a rapid initial pressure increase.

At end of the combustion phase, there must be no additional injections, because it causes incomplete burning of fuel, increased temperatures of exhaust gases and thermal loading of the engine parts.

Combustion rate curve will vary regarding the injected fuel characteristic, disposable oxygen in the combustion chamber and the energy content of mixing process.

Correct formation of mixture and combustion in diesel engines provides silent engine operation with a pressure increase rate of the pre-mixed combustion phase within the limits allowed. Correct design of combustion chamber, good air eddying results in fumeless, complete and just in time combustion, with the lowest air to fuel ratio. In this way optimal combustion is obtained with advantageous thermal and mechanical stress of engine parts.

From a combustion rate diagram, it is noticeable that there is a rapid increase of cylinder pressure if the top of a curve is extremely high. The cause of that is longer ignition delay in ignition phase due to the low temperatures and low compression ratio. If such combustion occurs it is necessary to either shorten delay of ignition phase or reduce the amount of injected fuel during that phase. Fuel with high cetin number, increase of compression ratio or increase of cylinder temperature will shorten the period of ignition delay. Fuel injection system can be designed to inject a smaller amount of fuel just before the injection of main fuel amount.

9. Combustion analysis according to Vibe and Watson-Piley-Marzouk correlations

Analysis of engine working cycle has been performed by determine the heat release rate from measured indicated pressure, described in [5].

Combustion in cylinder is described as heat transferred to the cylinder charge. Combustion rate or heat release in function of time is expressed by equation:

$$\frac{dQ_g}{d\alpha} = f(\alpha, m_g, \lambda, n_m, p, T, ...) = f(\alpha, k) \quad (10)$$

Combustion rate can be expressed by empirical equation:

$$\frac{dQ_g}{d\alpha} = 6{,}901 \cdot \eta_{izg} \cdot m_{g,pr} \cdot H_d \cdot (m+1) \cdot \cdot \gamma^m \cdot \exp(-6{,}901 \cdot \gamma^{m+1}) \quad (11)$$

Relative combustion angle:

$$\gamma = \frac{\alpha - \alpha_{pi}}{\alpha_{ki} - \alpha_{pi}} \quad (12)$$

Diesel engine combustion process is divided into two phases:

- in homogenous combustion phase (*hf*), fuel vapour mixture with air is burned with high velocity, thus resulting in very steep pressure and temperature rise in cylinder,
- in diffusion combustion phase (*df*), where combustion rate is slow and limited by fuel droplets vaporization rate.

By superposition of two Vibe functions which start simultaneously, but with different duration and exponent *m,* we can get double Vibe function:

$$\frac{dQ_g}{d\alpha} = 6{,}901 \cdot \eta_{izg} \cdot m_{g,pr} \cdot H_d \cdot \begin{bmatrix} \beta \cdot (m_{hf}+1) \cdot \gamma_{hf}^{mhf} \cdot \\ \cdot \exp(6{,}901 \cdot \gamma_{hf}^{mhf+1}) + \\ +(1-\beta) \cdot (g_{df}+1) \cdot \gamma_{df}^{mhf} \cdot \\ \cdot \exp(-6{,}901 \cdot \gamma_{df}^{mhf+1}) \end{bmatrix}, \quad (13)$$

$$\beta = \frac{Q_{g,hf}}{Q_g}, \quad (14)$$

where equation (14) is a descriptor of the burning rate, equal to cumulative fuel burnt in premixed burning phase as a fraction of the total fuel injected.

Watson-Piley-Marzouk correlation is used to describe both the homogenous phase with Vibe-like function, and diffusion phase by using the Vibe function. Both functions begin at ignition point and combustion lasts for 125 °CA.

$$\frac{dQ_g}{d\alpha} = \frac{\eta_{izg} \cdot m_{g,pr} \cdot H_d}{125} \cdot \begin{bmatrix} \beta \cdot c_{hf1} \cdot c_{hf2} \cdot \tau^{c_{hf1}-1} \cdot \\ \cdot (1-\tau^{c_{hf2}})^{c_{hf2}-1} + (1-\beta) c_{df1} \cdot \\ \cdot c_{df2} \tau_{c_{df2}-1} \cdot \exp\left(-c_{df1} \cdot \tau^{c_{df2}}\right) \end{bmatrix}, \quad (15)$$

where:

$$\tau = \frac{\alpha - \alpha_{pi}}{125} \text{ - relative combustioning time,} \quad (16)$$

β, C_{hf1}, C_{hf2}, C_{df1}, C_{df2}- constants are empirical functions of ignition delay and air-fuel ratio at combustion completion.

To control NO_x, relative ratio β of fuel combustion in homogen phase is calculated. The calculated value of coefficient β for MAN B&W and Wärtsilä engines are shown in the following table.

Figure 11 shows the combustion rate expressed with Vibe and Watson-Piley-Marzouk correlation. Measured value has been compared with calculated value.

Table 1. Relative ratio of fuel combusted in premixed phase for MAN B&W- 6S70MC engine

Tablica 1. Relativna količina izgorenog goriva u homogenoj fazi izgaranja kod MAN B&W- 6S70MC motora

Load	50 %	75 %	85 %	100 %
β	0,58333	0,5645164	0,565218	0,5238097

Table 2. Relative ratio of fuel combusted in premixed phase for Wärtsilä engine serie RTA

Tablica 2. Relativna količina izgorenog goriva u homogenoj fazi izgaranja kod Wärtsilä –RTA motora

Engine type	RTA62U	RTA62U	RTA62U	RTA72U	RTA84U
Load	40 %	60 %	100 %.	100 %	100 %
β	0,567214	0,53284	0,587230	0,584552	0,62565

Oscillation due to gas fluctuation in indicating channel can be seen on combustion rate curves. For exact measurements, the sensor at the cylinder head has to be installed as close as possible, to the cylinder chamber. For indicating pressure measurements, piezoelectric sensor with stabile crystal structure and wide range of temperature operation has been used.

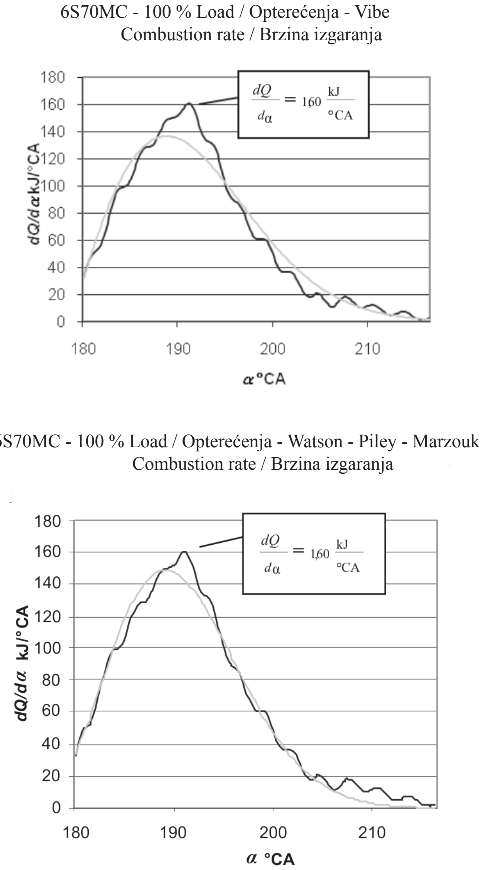

Figure 11. Example of result obtained by Vibe and Watson-Piley-Marzouk correlation

Slika 11. Primjer rezultata dobivenih pomoću Vibe i Watson-Piley-Marzouk korelacija

10. Comparison of results obtained by different methods for analysing of Diesel engine working cycles

Verification of different methods has been carried out by comparison of important parameters obtained from the analysis of combustion process. During comparison it is important to take into consideration correlation between different parameters with mode of burning rate β, pressure rise $dp/d\alpha$ and shape factors (C_{p1}, C_{p2}, C_{d1}, C_{d2} depending on combustion chamber conditions), parameters that are important to determining the quality of engine combustion process.

Mode of the burning rate (β) gives us the mass of the fuel burnt during premixed (homogenous) combustion phase. Greater β gives harder combustion process and more NO_x emissions.

From obtained results it is obvious that at both engines, MAN B&W and Wärtsilä, there are harder engine working cycles at lower load.

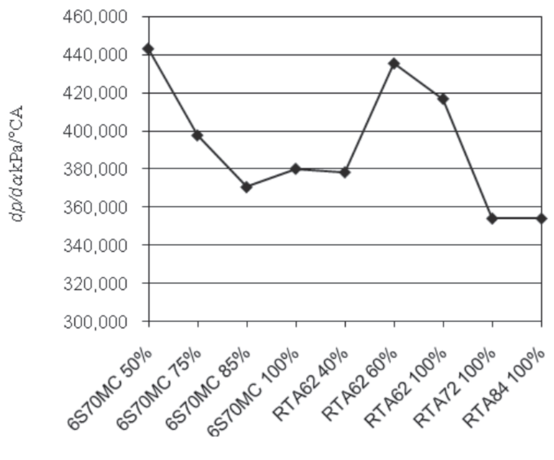

Figure 12. Pressure increase rate obtained by EKSE

Slika 12. Porast tlaka dobiven programom EKSE

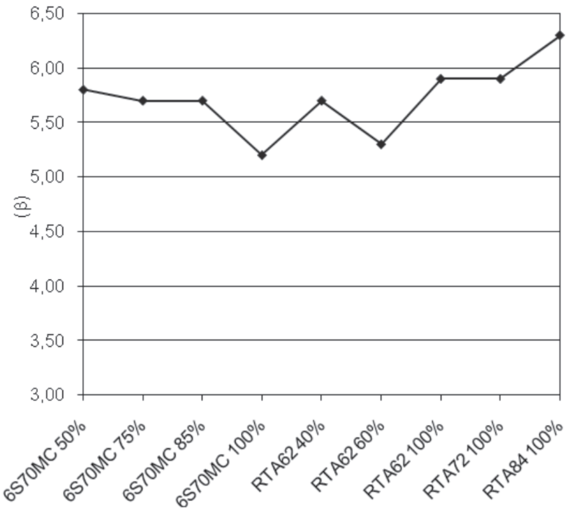

Figure 13. Mode of the burning rate during pre-mixed phase (β) obtained by Vibe and Watson-Piley-Marzouk correlations

Slika 13. Relativna količina izgorenog goriva u homogenoj fazi (β) dobivena analizom prema korelaciji Vibe and Watson-Piley-Marzouk

In general, at engines with higher displacement we have lower pressure rise.

This paper gives us a good indication in analyzing working cycles, and in the future subject parameters will be deeply analyzed as key factors. Parameters (β, C_{p1}, C_{p2}, C_{d1}, C_{d2} will be deeply analyzed as key factors that influence pollutant emission.

11. Conclusion

The doctoral of science thesis: “Expert System for Diagnosis and Optimisation of Marine Diesel Engines” deals with problems of a complex analysis and testing a system of Diesel engine parameters The program package EKSE – Expert System for Diagnostics and Optimizing of Marine Diesel Engines is developed by the first author. In this study a thermodynamic analysis of engine working cycles for few slow speed direct injection marine diesel engines was made. Testing was performed on MAN-B&W MC and Wärtsilä RTA two stroke, slow speed marine propulsion diesel engines.

Data provided by measurement were corrected due to the phase angle between various cylinders. Engine cylinder pressure is measured, related to the crankshaft angle. By using the working cycle analysis program a relevant values for diagnostic of engine working process and analysis of causes of increase and decrease of NO_x forming rate were obtained. Relevant values are: working mixture temperature in the engine cylinder, pressure rise rate, used and lost heat in the cylinder and combustion rate. These relevant values may be influenced by the start of injection, compression ratio, timing of opening and closing of exhaust valve, scavenge air pressure, heat transfer and air to fuel ratio.

Results of analyses of working process obtained by EKSE program package, were compared with the results of analysis gained by using the Vibe and Watson-Piley-Marzouk correlations. Good match of measured and numerically simulated values is noticeable.

To have a better insight to the thermodynamic problem in the future development of expert diagnostic system for marine diesel engines, the analysis of working process used in this paper is of the at most importance. Delay of the ignition is a very important data for the evaluating of the influence of pre-mixed combustion to the complete combustion in the engine and to the NO_x emissions.

Analyses performed provide useful engine condition diagnostics, pointing to incorrect operation of engine system or its parts. By analyzing the working process and comparing it with optimal values, it will be possible to influence opening and closing of exhaust valves, start of injection, cooling media temperature, correct acting of injector, etc.

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