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Diagnosis of injection system marine diesel engine with the use of the heat release characteristics

The paper presents the issues related to the diagnosis of injection system marine diesel engines, which are characterized by high unreliability. It was supported by the statistics of emergency events marine engines. It has been shown that the not only parameters of the diesel engine depends on the reliable operation of injection equipment but also the safety of navigation. This indicates the importance of diagnostics injection system, giving the ability to detect defects at the early stage of their development, in order to avoid failure. This has been demonstrated on the example of the injection system leak detection.

The article discusses the possibility of using in the heat release characteristics calculated based on the indicator diagram in the marine engine injection system diagnostics. It has been shown that the characteristics of heat release contain information about the condition of the injection systems, which enable to diagnose their failures. The obtained results allowed to select the diagnosis symptoms, useful in detecting faults in the injection system, from the characteristics of heat release.

Key words: *diagnosis, piston marine diesel engine, injection system, statistics damage, heat release characteristics, net of heat release characteristics, the intensity of the heat release.*

Diagnostyka układu wtryskowego silnika okrętowego z wykorzystaniem charakterystyk wywiązywania ciepła

W artykule przedstawiono problematykę związaną z diagnostyką aparatury wtryskowej silników okrętowych, które należą do najbardziej zawodnych układów funkcjonalnych tych silników. Poparte to zostało danymi statystycznymi zdarzeń awaryjnych silników okrętowych. Wykazano, że od niezawodnego działania aparatury wtryskowej zależą nie tylko parametry pracy silnika, ale także bezpieczeństwo żeglugi. Wskazuje to jak istotne znaczenie ma diagnostyka układów wtryskowych, dająca możliwość wykrywania uszkodzeń na wczesnym etapie ich rozwoju, aby nie dopuścić do awarii.

W artykule omówiono możliwość wykorzystania w diagnostyce układu wtryskowego silnika okrętowego charakterystyk wydzielania ciepła wyznaczanych w oparciu o wykres indykatorowy. Wykazano, że charakterystyki wydzielania ciepła zawierają informacje o stanie technicznym układów wtryskowych, umożliwiające diagnozowanie ich uszkodzeń. Uzyskane wyniki badań pozwoliły na wyłonienie z charakterystyk wydzielania ciepła symptomów diagnostycznych przydatnych w wykrywaniu uszkodzeń w układzie wtryskowym, co wykazano na przykładzie wykrywania nieszczelności układu wtryskowego.

Słowa kluczowe: *diagnostyka, okrętowy silnik tłokowy, modele wydzielania ciepła, charakterystyki wydzielania ciepła, ciepło wydzielone netto, intensywność wydzielania ciepła.*

1. Introduction

Improvement of the methods of diagnosis of marine diesel engines is a very important task to monitor engine operation, fault detection at an early stage of their formation, which contributes to improving the economics and safety of the ship. Ships reciprocating internal combustion engines are applied in the vast majority of the main propulsion of cargo vessels (over 80%), as well as drive marine generators set. When one talks about the need to equip with modern marine power systems and diagnostic equipment, it refers primarily to the diagnosis of marine engines.

On ships with conventional equipment, ie. without specialized diagnostic equipment, the current engine condition monitoring is based on the measured values of the parameters controlled. Diagnostic evaluation mainly includes processes: injection, combustion, cooling and lubrication of the engine.

Many marine power plant are equipped with portable diagnostic test for periodic diagnostic testing of engines. The measurements of the maximum cylinder pressure, compression pressure, medium pressure and indicated power are carried out.

On some ships, with high power plants stationary monitoring and diagnostics systems are installed, operating on-line. Some stationary systems are equipped with systems to measure the pressure in the fuel injection systems.

Evaluation of technical condition and state of the motor load is thus carried out in an indirect way, based on the known relationship between the parameters of the working processes, and states of the structure and the load test piece.

The reliability of the diagnosis, its uniqueness, the ability to determine the location of faults and their causes with this study depends largely on the knowledge and experience engineer officer, and has a very subjective nature. It should be noted that the conventional set of parameters controlled ships currently available are not sufficient for making a reliable diagnosis, especially in relation to fault location.

Practical implementation of diagnostic functions for machine crew (engineer officers) is not conducive to the frequent rotation of crews between ships. The efficiency of the diagnostic process is particularly unsatisfactory on modern building ships, with a complex structure and a highly automated design, on which also applies additional principle of limiting the number of members of the crew in engine-room.

A large amount of current duties performed by the engineer officers on the one hand, and the lack of appropriate diagnostic measures, on the other, do not facilitate the implementation of diagnostic tasks. Marine engines are technical objects with a high level of complexity (several tens of thousands of elements).

Each of these elements can characterize in technical terms even several parameters of the structure. Controlling the technical condition in this situation is very difficult. As a result, the functions of the machine crew vessels are often limited to removal during the voyage of the marine failure, to maintain the energetic autonomy of the vessel. Often these situations are the result of not detected in time damage. The number of failures could significantly reduce adequately devices and diagnostic methods.

Functional system of marine engine, which has basic influence on the quality of the work process, the economics of operation of the engine and its reliability is the injection system.

During running the marine engine, operational supervision the engine fuel supply system is reduced to operating current control operating parameters of as well as for periodic cleaning of fuel filters and centrifuges as well as tightness control the entire system. The main parameters on the basis of which engineer oversees the work of the engine fuel supply system are: pressure and temperature (viscosity) of fuel.

Regarding to the injection system condition of the injectors is checked periodically.

To evaluate the operation of the injection system are mainly used the following parameters:

a) operational (routinely measured):
 - the exhaust gas temperature, T_g,

b) read with indicator diagrams:
 - maximum combustion pressure, p_{max},
 - mean indicated pressure, p_i,
 - the angle where p_{max} occurs, referred to TDC, αp_{max}.

On some low-speed engines with high power, pressure are measured in injection systems. The main parameters determined on the basis of this measurement are:

- the maximum injection pressure fuel injectors, $p_{max\ inj.}$,
- injector opening pressure, $p_{ope\ injr.}$,
- the angle of injection period.

The parameters read on the basis of recorded pressure in injection system are indeed important diagnostic, but their measurement is difficult due to the limited sensors installation possibilities.

Injection system, for security reasons, must be leakproof. Injection piping commonly placed in special cases ("buffer zones"), which in the case of damage to the fuel pipe do not allow uncontrolled effluent of fuel to the engine room.

Therefore, it is advisable to search for such an effective method of diagnosing damages of the injection system, which does not require interference in the injection system. This a condition correspond to methods based on the analysis of the information contained in the indicator diagrams. This will be the indirect method to evaluation of the technical condition of injection equipment, which will cancel costly and unreliable measuring systems the pressure in the injection systems.

In order to obtain an effective method for the identification of major damages components in the injection system is needed in-depth analysis of indicator diagrams. This refers to the designation on the basis of the indicator diagram heat release characteristics, obtained based on the measurement of cylinder pressure the electronic indicator. Cylinder pressure transducers mounted on the indicator valves.

2. The fuel supply systems modern marine engines

Modern marine propulsion engines and generator sets are supplied mainly with heavy fuels (Heavy Fuel Oil, Residual Fuels), and the viscosity can be at a temperature of 100 ° C 1,4÷14 cSt for Marine Light Fuel Oil and 10÷55 cSt for Marine Fuel Oil. Lower viscosity fuels are used to for supplying the four-stroke medium speed engines, while the higher viscosity fuel - for supplying the low speed two-stroke engines.

Heavy fuel oil are contaminated with, inter alia, sulfur, water, compounds contained in seawater, bituminous materials (resins, hard asphalt) and solids. Such fuels require specific preparatory activities prior to injection into the engine.

Problems with using heavy residual fuels can be categorized as: storage and handling, combustion quality and burnability, contaminants - resulting in corrosion and damage to engine components.

Fuel supply to the combustion chamber of a piston engine performs injection system, which feeds the fuel at a certain time, properly atomized, in an amount corresponding to the instantaneous power requirement.

In contemporary marine engines still dominated traditional injection systems, constructed with the following elements:

- injection pump driven by the camshaft,
- high pressure fuel pipes,
- fuel injectors.

Injection pumps are displacement pumps, piston type, and typically each cylinder has a separate injection pump or a separate operating unit consisting of a cylinder, piston, non-return valve and drive mechanism piston. Variable maximum pressure in injection pipes can obtain a value from 40 to 100 MPa.

Energetic and economic indicators (parameters) of the engine, and the reliability of its operation largely depends on the operation of the injection system. On the one side an important factor will be constructional, technological and manufacture perfection of system components, especially the injection pumps and injectors, on the other hand, the proper conduct static regulation and proper exploitation.

It is believed that the most important quality parameters of the regulation of the conventional injection system is the beginning, end, and duration of fuel delivery by the pump and the injector expressed in degrees of crankshaft rotation. From these parameters, under the constant engine load, depends combustion process. To combustion process evaluate it uses dynamic parameters and economic indicators cycle.

In practice, sought the optimal injection advance angle, to achieve high diesel engine efficiency, for a given load.

3. Typical injection systems damages and their influence on the engine to operate

Statistical data showed [7], that almost 50% of all defects are defects marine engine fuel supply system, and the most common failure in relation to the injectors (41%) and the injection pump (38%).

Mileage and the quality of combustion are depends on the proper operation of the injection system and the exchange medium (intake air and exhaust outlet). Analyzing the reasons abnormal combustion, it is advisable to isolate the underlying factors affecting the working process - especially those caused by irregularities in the operation of the injection system.

Changing the injector opening pressure (C_{iop}) occurs due to the deterioration of the working properties of the springs. They lose their rigidity. It can also lead to subsidence of the springs, wear of the seat and nozzle needle, which in turn also leads to a decrease in the opening pressure of the injector. As a result occurs, a change of injection and combustion parameters, and consequently:

$$C_{iop} \Rightarrow (T_g\uparrow;\ p_{max}\downarrow;\ p_{max\ inj.}\downarrow) \Rightarrow (g_e\uparrow;\tau_c\uparrow) \qquad (1)$$

were:

T_g – temperature exhaust outlet,
p_{max} – maximum combustion pressure,
$p_{max\ inj}$ – maximum injection pressure,
g_e – specific fuel consumption,
τ_c – combustion time.

Significant changes are visible when the injector opening pressure decreases, relative to the rated value by more than ten percent. In practice, operating such changes are possible. Spring force may be reduced as low as 15 to 25% relative to the nominal value, after 100 to 500 hours of operation.

During operation, the injection holes are subject to wear and change their shape circular-cylindrical, and lose smoothness of the surface. This is mainly due to the large flow rate of fuel through the injection holes and the content of hard impurities in the fuel. This leads to changes in the shape of injected fuel streams.

As a result of wear the spray holes (W_{sh}) the change occurs injection and combustion parameters, and consequently:

$$W_{sh} \Rightarrow (T_g\downarrow;\ p_{max}\uparrow;\ p_{max\ inj.}\downarrow;\ u_c\downarrow) \Rightarrow (g_e\uparrow) \qquad (2)$$

were:

T_g – temperature exhaust outlet,
p_{max} – maximum combustion pressure,
$p_{max\ inj}$ – maximum injection pressure,
g_e – specific fuel consumption,
u_c – the out flow rate of fuel from the injector.

As a result of the abrasive, hard particles of impurities present in the fuel, surfaces of the pair piston-sleeve of the injection pump wear occurs.

Progressive wear, increase clearance between piston and sleeve pump causes a decrease in the hydraulic efficiency of the pump (η_h). Maximum injection pressure decreases and increases the average droplet diameter of fuel spray.

Part of the dose tapping by the fuel pump does not reach the cylinder, because the resulting leaks. Wear a injection pump (W_{ip}) thus leads to a change in injection and combustion parameters, and consequently:

$$W_{ip} \Rightarrow (\eta_h\downarrow;\ T_g\downarrow;\ p_{max}\downarrow;\ p_{max\ inj.}\downarrow;\ p_i\downarrow) \Rightarrow (g_e\uparrow;N_i\downarrow) \qquad (3)$$

where:

η_h – hydraulic efficiency of the injection pump,
T_g – temperature exhaust outlet,
p_{max} – maximum combustion pressure,
$p_{max\ inj}$ – maximum injection pressure,
g_e – specific fuel consumption,
p_i – mean indicated pressure,
N_i – indicated power.

During the exploitation of marine engines heavy fuels combustion also appears an often damage - clogging (carbonization) of injection holes (C_{ih}). The consequences of the occurrence of damage is different depending inter alia on the number of clogging holes relative to the unclog , and thus the change of total holes cross-section.

A typical consequence of this damage is primarily a change in the fuel injection parameters, including an increase maximum injection pressure ($p_{max\ inj.}$), but also the parameters of the combustion process:

$$C_{ih} \Rightarrow (p_{max\ inj.}\uparrow;\ T_g\uparrow;\ p_{max}\downarrow;\ p_i\downarrow) \Rightarrow (g_e\uparrow) \qquad (4)$$

where:

$p_{max\ inj.}$ – maximum injection pressure,
T_g – temperature exhaust outlet,
p_{max} – maximum combustion pressure,
p_j – mean indicated pressure,
g_e – specific fuel consumption.

4. Heat release model for the engine with direct injection

Development of modeling heat release piston engines occurred at the end of the sixties and the seventies of the last century, which was largely associated with the development of computer capabilities calculations and simulation research and the emergence of diesel engine new research opportunities.

In the diagnosis of piston engines are of particular interest in single-zone models based on indicator diagrams as a source of information [3, 5, 11, 12, 14]. Indicator diagrams are commonly used in research and diagnostics combustion piston engines conducted both in the laboratory and supplies. This also applies to tests carried out in the country [1, 2, 6, 8, 9, 13, 14].

Commonly used for diesel engines with direct injection is a Krieger and Borman model [5].

The starting point for each model of heat release is the principle of conservation of energy in the form of the first law of thermodynamics, which is for an open system can be written as follows:

$$đQ_{sp} = dU + đW + đQ_{ch} + \sum đm_i h_i \qquad (5)$$

or in the form of heat release dynamics equations in the time domain:

$$\frac{đQ_{sp}}{d\tau} = \frac{dU}{d\tau} + \frac{đW}{d\tau} + \frac{đQ_{ch}}{d\tau} + \frac{d}{d\tau}\sum đm_i h_i \qquad (6)$$

were:

$đQ_{sp}$ –the heat transported (by combustion of fuel),
dU – change in internal energy of the mass in the system
$đW$ – the work produced by the system
$đQ_{ch}$ – the cooling heat loss,
$đm_i$ – flows in and out of crevice regions; piston ring blow-by and direct injection of fuel into the cylinder
h_i – the enthalpy flux across the system boundary
τ – time.

Due to difficulties in calculating the cooling heat and charge loss as a result of gas blow-by, for diagnostic purposes it is appropriate to use the net heat release characteristics, which is an sum of the internal energy and the work.

It is assumed that the cooling heat loss, will be the same for each cylinder, and will have little effect on the character of the course of heat release characteristics.

The formula for Q_n net heat evolution is obtained by transformation of equation (5) to the form:

$$đQ_n = đQ_{sp} - đQ_{ch} - \sum đm_i h_i = dU + đW \qquad (7)$$

Assuming that the gas is ideal and neglecting the exhaust and crevice loss, equation (5) takes the form [10]:

$$đQ_n = \frac{\kappa}{\kappa - 1} p\,dV + \frac{1}{\kappa - 1} V dp \qquad (8)$$

were:

κ = const – isentropic exponent,
V – volume of the cylinder,
p – pressure of the cylinder.

The instantaneous volume V of gas in the cylinder can be expressed as the sum:

$$V = V_s - V_{sx} + V_c + V_z + V_{px} \qquad (9)$$

were:

V_s – displacement volume cylinder
V_{sx} – cylinder volume corresponding to the distance traveled by the piston from a BDC
V_c – clearance volume
V_z – change the volume of the cylinder due to wear and impact assembly,
V_{px} – the apparent change in the volume of the cylinder due to gas blow-by (function road of the piston).

If it were accepted $V_z = 0$ and $V_{px} = 0$, the current volume of gas in the cylinder is given by:

$$V = V_s - V_{sx} + V_c \qquad (10)$$

After dividing the equation (10) by the stroke volume V_s we get volume in dimensionless form:

$$v = 1 - v_{sx} + v_c \qquad (11)$$

Dividing equation (6) by the displacement volume cylinder the intensity of the heat release q, written in the form:

$$q = \frac{đQ_n}{V_s d\alpha} = (\kappa - 1)^{-1}\left[v\frac{dp}{d\alpha} + \kappa p\left(\frac{dv}{d\alpha}\right)\right] \qquad (10)$$

5. Example use the heat release characteristics to the leak injection pump detection

The research was conducted in the laboratory on a stand with the marine engine SULZER type 3AL25 / 30, loaded with the self-excited synchronous generator GD8-500-50 type. The stand also includes a central computer system measurement and registration of the parameters this diesel engine.

An important element of this measurement system is an electronic indicator UNITEST 2008, in which to measure the pressure in the cylinders were used 6353A24 Kistler sensors with transmitters 6961A250 type (item 1 in Figure 1) and sensors to measure pressure in the injection system's Optrand Autopsie type-S C922A8 type transducers (item 2 in Figure 1).

Fig. 1. The research with the engine SULZER 3AL25 / 30 - view on one of the cylinder cover with converters installed with an electronic indicator co-operating: 1 - 6353A24 Kistler sensor for the measurement of cylinder pressure; 2 - sensors for measuring pressure in the injection system's Optrand AutoPSI type-S

The object of the study was the four-stroke ship's diesel engine 3 AL 25/30 Sulzer. On the second cylinder, injection pump leak was simulated. The simulation was carried out by dropping a small amount of fuel to the fuel pump overflow space.

In research the engine was indicated and based on the received indicator diagrams determined heat release characteristics. The paper presents selected results for the three load: 150 kW, 200 kW and 250 kW, which corresponds to the values of the mean indicated pressure (pi), respectively, 8.3 bar, 10.1 bar, 12 bar and accounts for 40%, 50% and 60% of the rated load of the engine.

Figures 2, 3 and 4 show the designated functions of the heat release for the three specified above loads - the engine ran without damaging the injection pump and with simulated damage.

The effect of a leaks pair precision of injection pump is to reduce the amount of fuel per cycle, which causes a decrease of indicated pressure, indicated power and a decrease in the value of q_{max} and Q_{max}, in cylinder supplied defective with injection pump.

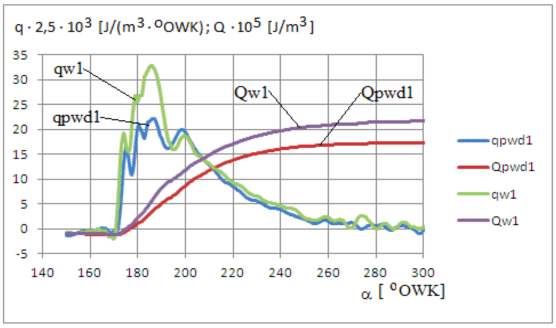

Fig. 2. Comparison of q and Q characteristics for the standard condition (reference condition) and the of leakage in the injection pomp, for the load 60% nominal load the engine. The parameter values for the reference condition: p_i = 12,0 bar, q_{max} = 65,6 · 10^3 J/(m^3 · °OWK), Q_{max} = 21,8 · 10^5 J/m^3. The parameter values for the failure simulation: p_i = 9,96 bar, q_{max} = 4,44 · 10^3 J/(m^3 · °OWK), Q_{max} = 17,3 · 10^5 J/m^3

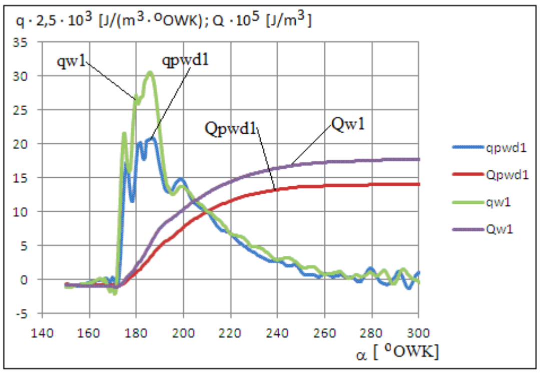

Fig. 3. Comparison of q and Q characteristics for the standard condition (reference condition) and the of leakage in the injection pomp, for the load 50% nominal load the engine. The parameter values for the reference condition: p_i = 10,1 bar, q_{max} = 6,12 · 10^3 J/(m^3 · °OWK), Q_{max} = 18,0 · 10^5 J/m^3 . The parameter values for the failure simulation:
p_i = 7,94 bar, q_{max} = 0,417 · 10^3 J/(m^3 · °OWK), Q_{max} = 14,1 · 10^5 J/m^3

Since the test engine runs at a constant speed, the load take other cylinders of the engine. As it is apparent from the graphs in Figures 2 to 4 for such damage the characteristic is also a change the angle of the curve Q in the initial period of the rise, as shown in Figure 5.

As it is apparent from the graphs shown in Figure 5, for diagnostic purposes leak of the injection apparatus can be used not only Q_{max}, and q_{max} but also increase/ decrease the value of the net heat generated (pd_{1Q}) in the first phase of the rise (for angle α_{pd1Q}), relative to the reference value, and increase/decrease of the maximum heat release due to the damage (pd_{1q}) relative to the reference value.

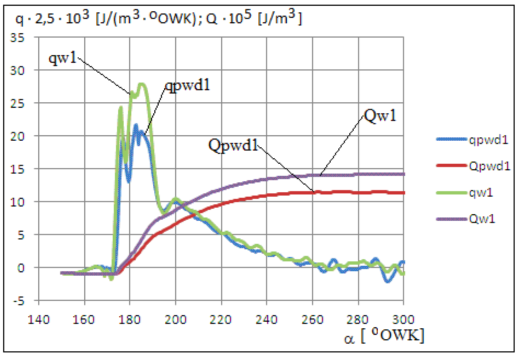

Fig. 4. Comparison of q and Q characteristics for the standard condition (reference condition) and the of leakage in the injection pomp, for the load 40% nominal load the engine. The parameter values for the reference condition: p_i = 8,27 bar, q_{max} = 5,58 · 10^3 J/(m^3 · °OWK), Q_{max} = 14,3 · 10^5 J/m^3 . The parameter values for the failure simulation: p_i = 6,63 bar, q_{max} = 4,33 · 10^3 J/(m^3 · °OWK), Q_{max} = 11,5 · 10^5 J/m^3

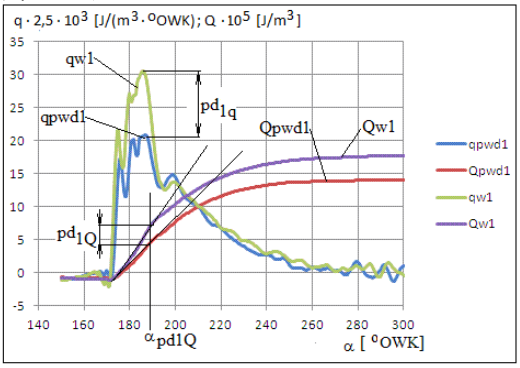

Fig. 5. Symptoms of leakiness injection system for the example shown in Figure 3: pd_{1q}, pd_{1Q} - examples of diagnostic parameters, α_{pd1Q} - angle determining the value pd_{1Q}

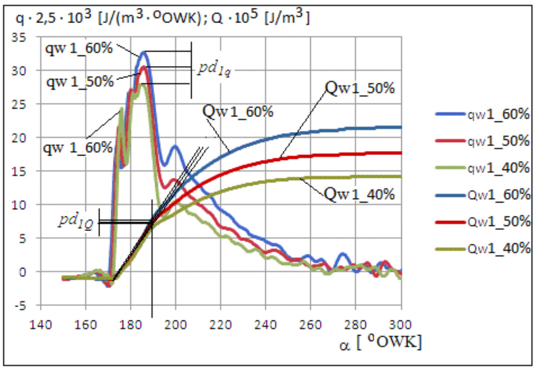

Fig. 6. Load effect diesel engine on the reference value (without damage) parameters pd_{1q}, pd_{1Q}

It should be noted that on the value of the parameter pd_{1q} significantly affect load engine level and impact the load engine on the pd_{1Q} value is small, as shown in Figure 6. In addition to the value pd1q, in contrast to the parameter pd_{1Q} significantly influences the error designate TDC of the piston. Therefore, due to the nature of the parameter pd_{1Q} its use for diagnostic purposes as compared with the parameter pd1q seems appropriate.

CONCLUSIONS

The results show that, with a net heat release characteristics damage to the injection system can be detect. This allows you to opt out for the diagnostic use, the measurement and analysis of the pressure in the injection system.

Course of heat release characteristics q and Q react primarily on the intensity of the fuel dosage to the cylinder and the value of the fuel dosage per cycle.

For the simulated injection pump failure (leakage) characteristic is pronounced the drop in the value of the maximum heat release rate (q_{max}) and the maximum value of the net heat release (Q_{max}).

The changes in the value of the maximum net heat release (Q_{max}) are comparable to the decrease in mean indicated pressure pi.

For the diagnostic purposes leak of the injection apparatus can be used not only Q_{max}, and q_{max} but also increase / decrease the value of the net heat release (pd_{1Q}) in the first phase of the rise (for the angle α_{pd1Q}), relative to the reference value.

Nomenclature/*Skróty i oznaczenia*

g_e specific fuel consumption/jednostkowe zużycie paliwa

N_i indicated power/moc indykowana

p pressure of the cylinder/ciśnienie w cylindrze

p_i mean indicated pressure/średnie ciśnienie indykowane

p_{max} maximum combustion pressure/maksymalne cisnienie spalania

$p_{max\ inj.}$ maximum injection pressure/maksymalne cisnienie wtrysku

q intensity of the heat release/intensywność wydzielania ciepła

Q_{ch} cooling heat loss/ciepło chłodzenia

Q_n net heat/ciepło netto

Q_{sp} heat transported (by combustion of fuel)/ciepło spalania

T_g exhaust gas temperature/temperature gazów wylotowych

U internal energy/ energia wewnętrzna

W work/praca

αp_{max} the angle where p_{max} occurs, referred to TDC/kąt dla którego uzyskano ciśnienie maksymalne wyrażony wzgledem GMP

η_h hydraulic efficiency of the injection pump/sprawność hydrauliczna pompy wtryskowej

κ isentropic exponent/wykładnik izentropy

τ_c combustion time/czas spalania

Bibliography/*Literatura*

[1] Ambrozik A., Sobociński R., *Analiza procesu spalania tłokowego silnika spalinowego na podstawie wykresu indykatorowego.* Prace Instytutu Transportu Politechniki Warszawskiej, 1983, nr 21. (2)

[2] Ambrozik A., Łagowski P., *Wybrane metody sporządzania charakterystyk wydzielania ciepła w silnikach spalinowych.* Jurnal of KONES, 2005, Vol. 12, No 1-2. (3)

[3] Heywood J.B., *Internal combustion engine fundamentals.* McGraw-Hill Company, 1988. (33)

[4] Lyn W.T., *Calculations of the Effect of Rate of Heat Release on the Shape of Cylinder-Pressure Diagram and Cycle Efficiency.* Proc. ImechE, 1960, No1. (59)

[5] Kriger R.B., Borman G. L., *The Computation of Apparent Heat Release for Internal Combustion Engines.* Proc. Diesel Gas Power, ASME 1966.(56)

[6] Michalecki M., *Badanie procesu wydzielania ciepła w dwusuwowym wysokoprężnym silniku na podstawie wykresu indykatorowego.* Zeszyty Naukowe Politechniki Gdańskiej, Mechanika V, 1973. (68)

[7] Piaseczny L., *Ocena niezawodności okrętowych silników spalinowych w aspekcie tworzenia ich systemów diagnostycznych i obsługowych.* Materiały Konferencji Naukowo-Technicznej, ITEO AMW, Gdynia 1992. (78)

[8] Polanowski S., *Studium metod analizy wykresów indykatorowych w aspekcie diagnostyki silników okrętowych.* Zeszyty Naukowe AMW, Nr 169 A, Gdynia 2007.(84)

[9] Polanowski S, Pawletko R., *Acquisition of diagnostic information from the indicator diagrams of marine engines using the electronic indicators.* Journal of KONES Powertrain and Transport, Vol. 18(3)/2011.(86)

[10] Rychter T., Teodorczyk A., *Modelowanie matematyczne roboczego cyklu silnika.* PWN, Warszawa 1990. (93)

[11] Schweitzer P., *The Tangent Method of Analysis of Indicator Cards of Internal Combustion Engines.* Bulletin nr 35. Pennsylvania State University, September 1926.(96)

[12] Sothern J.W.M.: *Marine diesel oil Engines, A manual of marine oil engine practice.* 5th edition, 1999, Vol. 1. (99)

[13] Staś M.J., *Preparation of diesel engine indicator diagrams for cycle calculations.* Materiały Konferencji KONES 1999. (101)

[14] Wajand J., *Możliwości wykorzystania wykresów indykatorowych do określenia przebiegu wydzielania ciepła w cylindrze silnika spalinowego.* Silniki spalinowe, 1966, nr 2. (111)

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